CCI Land Surface Temperature

User Requirements Document

WP1.1 – DEL-D1.1

Ref.: LST-CCI-D1.1-URD v3
Date: 17-May-2023
Organisation: Consortium CCI LST

Signatures

	Name	Organisation	Signature
Written by	Freya Aldred[1], Elizabeth Good[1], Claire Bulgin[2] & Nick Rayner[1]	[1]Met Office [2]U. Reading	
Reviewed by	Claire Bulgin	U. Reading	
	Jérôme Bruniquel	ACRI-ST	
Approved by	Darren Ghent	U. Leicester	
Authorized by	Simon Pinnock	ESA	

Change log

Version	Date	Changes
1.0	14-Dec-2018	First version
1.1	21-Feb-2019	Updated version taking into account RIDs raised by ESA
2.0	31-Mar-2021	Added Sections 8 and 9, updated Section 10 with new requirements, added Appendices C, D, E and F. There are also a few minor text amendments to other sections in relation to these added sections (e.g. adding references to the new Sections 8 and 9).
3.0	15-May-2023	Added new Section 10 with recommendations from the 2022 User Workshop and updated Sections 1 and Section 11 (formerly Section 9) to reflect these new requirements.

Applicable Documents

Identity	Reference
AD-01	LST_cci (2023) 2022 User Workshop Report, Reference LST-CCI-UWR-D5.3 v1.0

Table of Content

1. EXECUTIVE SUMMARY ---------- 1

2. PURPOSE AND SCOPE ---------- 13

3. EXISTING USER REQUIREMENTS FOR SATELLITE LST PRODUCTS ---------- 15
3.1. Establishing LST as an Essential Climate Variable ---------- 15
3.1.1. GCOS Requirements ---------- 15
3.1.2. LST Climate Change Initiative ---------- 16
3.2. LST User Requirement Summary ---------- 17
3.2.1. NASA white paper on LST ---------- 18
3.2.2. NCDC workshop ---------- 18
3.2.3. LST User Exploitation Document ---------- 19
3.2.4. Sentinel Convoy for Land Applications ---------- 20
3.3. LST User Requirements from ESA Data User Element GlobTemperature ---------- 21
3.3.1. ESA Data User Element GlobTemperature ---------- 21
3.3.2. GlobTemperature User Requirements for Climate ---------- 23

4. DEFINING REQUIREMENTS FOR LST_CCI ---------- 25

5. JOINT LAND WORKSHOP ---------- 27
5.1. Satellite LST for Climate Applications Questionnaire ---------- 27
5.1.1. Introduction ---------- 27
5.1.2. Current Data Use ---------- 27
5.1.3. LST Applications ---------- 28
5.1.4. Concerns Regarding LST ---------- 28
5.1.5. Requirement Priorities ---------- 29
5.1.6. Merged Products ---------- 29
5.1.7. Clouds ---------- 30
5.1.8. Error and Uncertainty ---------- 30
5.1.9. Ideal Dataset ---------- 31
5.2. Results and Analysis ---------- 31
5.2.1. Current Data Use ---------- 31
5.2.2. LST Applications ---------- 31
5.2.3. Concerns Regarding LST ---------- 32
5.2.4. Requirement Priorities ---------- 33
5.2.5. Merged Products ---------- 34
5.2.6. Clouds ---------- 34
5.2.7. Error and Uncertainty ---------- 34
5.2.8. Ideal Dataset ---------- 35
5.3. Summary ---------- 36

6. USER REQUIREMENTS QUESTIONNAIRE ---------- 37
6.1. Context ---------- 37
6.2. Questionnaire Overview ---------- 38
6.2.1. Introduction ---------- 38
6.2.2. General Information ---------- 38
6.2.3. LST Applications ---------- 38
6.2.4. Current Data Use ---------- 38
6.2.5. Concerns Regarding LST ---------- 38
6.2.6. Data Specification ---------- 39
6.2.7. Data Format and Metadata ---------- 39
6.2.8. Quality Control ---------- 39
6.2.9. Error and Uncertainty ---------- 39

6.2.10. Validation and Inter-comparison ---40
6.2.11. Clouds ---40
6.2.12. Comments ---41
6.3. Questionnaire --- 41
6.3.1. Introduction ---42
6.3.2. General Information ---43
6.3.3. LST Applications ---44
6.3.4. Current Data Use ---45
6.3.5. Concerns Regarding LST ---48
6.3.6. Data Specification ---49
6.3.7. Data Format and Metadata ---53
6.3.8. Quality Control ---56
6.3.9. Error and Uncertainty ---57
6.3.10. Validation and Inter-comparison ---61
6.3.11. Clouds ---62
6.3.12. Comments ---63
6.4. Results and Analysis --- 63
6.4.1. General Information ---63
6.4.2. LST Applications ---65
6.4.3. Data Use ---67
6.4.3.1. Use of LST Data for Climate Applications 67
6.4.3.2. Use of CCI ECV Datasets for Climate Applications 69
6.4.3.3. Intended Use of Data Products 70
6.4.4. Concerns Regarding LST ---72
6.4.5. Data Specification ---74
6.4.5.1. Spatial Domain 74
6.4.5.2. Time of Observation 75
6.4.5.3. Dataset Length and Resolution 76
6.4.5.4. Data Quality 79
6.4.5.5. Specification Priorities 81
6.4.5.6. Data Processing Level 82
6.4.6. Data Format and Metadata ---83
6.4.7. Quality Control ---86
6.4.8. Error and Uncertainty ---87
6.4.8.1. Current use of Uncertainty Information 87
6.4.8.2. Barriers to using Uncertainty Data 89
6.4.8.3. Uncertainty Information Requirements 90
6.4.9. Validation and Inter-comparison ---93
6.4.9.1. Current use of Validation and Inter-comparison Data 93
6.4.9.2. Barriers in using Validation and Inter-comparison Data 93
6.4.9.3. Validation and Inter-comparison Requirements 94
6.4.10. Clouds ---95
6.4.11. Comments ---98
6.5. Summary ---100
6.5.1. General information ---100
6.5.2. Applications ---100
6.5.3. Data Use ---100
6.5.4. Concerns regarding LST ---101
6.5.5. Data specification ---101
6.5.6. Data Format and Metadata ---101
6.5.7. Quality Control ---102
6.5.8. Error and Uncertainty ---102
6.5.9. Validation and Inter-comparison ---102
6.5.10. Clouds ---103

7. INTERVIEWS WITH THE CLIMATE RESEARCH GROUP ---------- 104
7.1. Context ---------- 104
7.2. Discussion Structure ---------- 104
7.3. Results and Analysis ---------- 105
7.3.1. UCS 1 Interview: Global and Regional Trends in LST (Met Office Hadley Centre) ---------- 105
7.3.2. UCS 2 Interview: Assimilating Greenland ice sheet surface ice temperature into atmosphere and ice sheet models (DMI) ---------- 106
7.3.3. UCS 3 Interview: Surface Urban Heat Island (University of Hamburg) ---------- 107
7.3.4. UCS 4 Interview: Biosphere/Atmosphere Exchange (MPI) ---------- 108
7.3.5. UCS 5 Interview: Inter-comparison and integrated use of LST_cci and other products in urban climate studies (MeteoRomania) ---------- 109
7.3.6. UCS 6 Interview: Integration of LST_cci products into a Surface Energy Balance Model (LIST) ---------- 110
7.3.7. CRG partner Interview: Production of Drought, Urban Heat and Frost Monitoring Maps (MeteoSwiss) ---------- 111
7.3.8. CRG partner Interview: Using LST-Air Temperature as a Measure of Vegetation Stress (CMUG / Met Office Hadley Centre) ---------- 112
7.4. Summary ---------- 114

8. FEEDBACK FROM THE 2020 USER WORKSHOP ---------- 116
8.1. LST_cci User Workshop 2020 ---------- 116
8.1.1. Workshop Attendance ---------- 116
8.1.2. LST user feedback ---------- 117
8.1.2.1. General Discussions: Padlet Discussions and Zoom Chat 118
8.1.2.2. Uncertainties Discussion Session 120
8.1.2.3. User Requirements Discussion Session 122
8.1.2.4. Climate Services Discussion Session 125
8.1.2.5. Future Role of LST in Climate Monitoring Discussion Session 127

9. FEEDBACK FROM EARLY LST_CCI DATA USERS IN PHASE I ---------- 129
9.1. Requirements identified from the LST_cci CAR v1 ---------- 129
9.1.1. Dataset accuracy, stability and precision ---------- 129
9.1.2. Data set artefacts and issues ---------- 129
9.1.3. Data file issues and recommendations ---------- 130
9.1.4. Other recommendations ---------- 130
9.2. Requirements identified from other CCI projects ---------- 131

10. FEEDBACK FROM THE 2022 USER WORKSHOP ---------- 132
10.1. LST_cci User Workshop 2022 Overview ---------- 132
10.2. LST_cci User Workshop 2022 Outcomes ---------- 132

11. REQUIREMENTS OF SATELLITE LST FOR CLIMATE APPLICATIONS ---------- 139
11.1. Summary Requirements and Recommendations ---------- 140
11.1.1. Data Format and Accessibility ---------- 140
11.1.2. Product Types ---------- 145
11.1.3. Data Specification ---------- 147
11.1.3.1. Coverage and resolution 147
11.1.3.2. Quality 149
11.1.3.3. Priorities 150
11.1.4. Quality Control ---------- 151
11.1.5. Error and Uncertainty ---------- 153
11.1.6. Validation and Inter-comparison ---------- 155
11.1.7. Clouds ---------- 156
11.1.8. Other requirements ---------- 158
11.2. Requirements ---------- 159

BIBLIOGRAPHY ---------- 170

List of Figures

Figure 6-1: Summary of responses to Q.4: Would you be interested in being contacted about any of the following? ---- 65

Figure 6-2: Summary of responses to Q.7: Please select the primary climate application from the list for which you use or intend to use LST data. This is the application we would like you to have in mind when you answer the rest of the survey. Secondary applications / interests can be selected in the following question. You may also submit multiple responses for different primary applications if you wish. ---- 66

Figure 6-3: Summary of responses to Q.8: Please indicate from the list below if you use LST data for any other applications. Multiple boxes can be checked, but please have in mind the primary application selected above when completing the remainder of the survey. ---- 67

Figure 6-4: Summary of responses to Q.9: Do you currently use LST data for climate-based applications? ---- 68

Figure 6-5: Summary of responses to Q.10: Which satellite LST datasets do you currently use for your primary application? ---- 68

Figure 6-6: Summary of responses to Q.11: What level of LST data do you use? ---- 69

Figure 6-7: Summary of responses to Q.12: Do you use any of the GlobTemperature datasets for your primary application? ---- 69

Figure 6-8: Summary of responses to the following questions: Q.13: Do you use any of the other CCI Essential Climate Variable (ECV) data products for your primary application?; Q.14: Do you use these in conjunction with LST data? ---- 70

Figure 6-9: Summary of responses to a) Q.34 and b) Q.37: Q.34: Do you currently use, or intend to use, data from the GlobTemperature project?; Q.37: Do you currently use, or intend to use, data from the ESA CCI project (LST or otherwise)? ---- 71

Figure 6-10: Summary of responses to Q.15: Do you intend to use any of the new CCI ECV datasets? ---- 71

Figure 6-11: Summary of responses to Q.30: Please select any dataset types you might be interested in. ---- 72

Figure 6-12: Summary of responses from Q.16: Please rank the top 3 main concerns or barriers (if any) you experience using LST (with 1 being the most important, and 3 the least). The key indicates the rank selected (#1, #2 or #3). ---- 73

Figure 6-13: Summary of responses (a) from Q.17: Over what spatial domain do you require LST data for your primary application? This is summarised on the right (b) as a percentage of responses for global, regional, and local scales, where regional includes equatorial, mid latitudes, Polar Regions, continental, and country. ---- 74

Figure 6-14: Summary of responses to questions: Q.18: At what time of day do you require LST observations (tick as many time slots as are applicable)? And Q.19: Are the times selected above UTC or local time? ---- 75

Figure 6-15: Summary of responses to Q.20: What is the minimum length of dataset that you require? Number of responses are shown as columns referencing the left axis, with the cumulative percentage overlaid as a line referencing the right axis. The cumulative percentage indicates the percentage of respondents who would be satisfied by each successive requirement. ---- 77

Figure 6-16: Summary of responses to Q.21: At what spatial resolution do you require LST data? Number of responses are shown as columns referencing the left axis, with the cumulative percentage overlaid as a line referencing the right axis. The cumulative percentage indicates the percentage of respondents who would be satisfied by each successive requirement. ---- 78

Figure 6-17: Summary of responses to Q.22: At what temporal resolution do you require LST data? Number of responses are shown as columns referencing the left axis, with the cumulative percentage overlaid as a line referencing the right axis. The cumulative percentage indicates the percentage of respondents who would be satisfied by each successive requirement. ---- 79

Figure 6-18: Summary of responses to Q.23: What are your requirements for LST Accuracy – the degree of conformity of the measurement to the accepted 'true' value? Number of responses are shown as columns referencing the left axis, with the cumulative percentage overlaid as a line referencing the right axis. The cumulative percentage indicates the percentage of respondents who would be satisfied by each successive requirement. ---- 80

Figure 6-19: Summary of responses to Q.24: What are your requirements for LST Precision – closeness of agreement between independent measurements of a quantity under the same conditions? Number of responses are shown as columns referencing the left axis, with the cumulative percentage overlaid as a line referencing the right axis. The cumulative percentage indicates the percentage of respondents who would be satisfied by each successive requirement. ---- 80

Figure 6-20: Summary of responses to Q.25: What are your requirements for LST Stability – consistency of LST measurements from a given satellite product over time (kelvin per decade)? Number of responses are shown as columns with regards to the left axis, with the cumulative percentage overlaid as a line with regards to the right axis. The cumulative percentage indicates the percentage of respondents who would be satisfied by each successive requirement. ---- 81

Figure 6-21: Summary of responses to Q.26, Q.27 and Q.28: Which is more important for your primary application? ---- 82

Figure 6-22: Responses to Q.26 (a) and Q.28 (b) regarding priorities, broken down by required spatial domain, see Figure 6-13b. ---- 82

Figure 6-23: Summary of responses to Q.29: What level of LST data do you require? This question was answered by 57 respondents. ---- 83

Figure 6-24: Summary of responses to Q.31 (a) regarding ability to use NetCDF format and Q.32 (b) covering barriers preventing use of the data. Q.31: Data products within the LST_cci project will be provided in NetCDF format, would you be able to use these for your application right now? Q.32: What are the barriers preventing you using NetCDF data? ---- 84

Figure 6-25: Summary of responses to Q.35: (a) shows the number of responses for each impact category as a bar chart (left axis), with the cumulative percentage of responses shown as a line (right axis); and Q.36 (b) indicating the file format changes likely to have the greatest impact on current GlobeTemperature data users. Q.35: As a current or future user of GlobTemperature data, what is the likely impact of incorporating a product that conforms to the CCI data standards, with the differences described above? Q.36: Which one of the possible changes from the GlobTemperature harmonised format would have the largest impact? ---- 85

Figure 6-26: Summary of responses to Q.38 (a) shows the number of responses for each impact category as a bar chart (left axis), with the cumulative percentage of responses shown as a line (right axis); and Q.39 (b) indicating the file format changes likely to have the greatest impact on current CCI ECV data users. Q.38: As a current or future user of CCI ECV products, what is the likely impact of incorporating a product that conforms to the GlobTemperature harmonised format, with the differences described above? Q.39: Which one of the possible changes from the CCI standard format would have the largest impact?-- 85

Figure 6-27: Summary of responses to Q.40: Please rank the order of importance of these flags for your application (with 1 being the most important and being the least important).-------------------------------- 86

Figure 6-28: Summary of responses to the following questions: Q.42: Would you make use of Quality Level data on a pixel level should it be provided? Q.43: Would you make use of Quality Level data on a file level should it be provided? Both questions received 54 responses in total.-- 87

Figure 6-29: Summary of current use of uncertainty information. (a) Answers two questions: Q.44: Do you use uncertainty information? And Q.46: Have you used a dataset that is provided with uncertainty information broken down into different components: random, locally systematic, and large scale correlated uncertainties? (b) Describes the components used by those who selected 'yes' to Q.46, in response to questions: Q.47: Which components have you made use of in your work? And Q.48: Which of the uncertainty components did you use? -- 88

Figure 6-30: Summary of propagation of uncertainties when generating higher level products (a) or assimilating LST (b). (a) Shows responses to questions: Q.50: Do you generate higher level products from the LST data provided, for example averaging over longer time periods or larger spatial scales? And Q.51: Do you propagate the relevant uncertainty information in this process? (b) Shows responses to questions: Q.52: Do you assimilate LST data into a model or other system? And Q.53: Do you propagate the relevant uncertainty information in this process? --- 89

Figure 6-31: Summary of barriers experienced in using uncertainty data (a) and uncertainty components (b). This is in response to the following questions: (a) Q.45: What are the barriers in preventing you from using it? And (b) Q.49: What were the barriers preventing you from using the uncertainty components? -- 90

Figure 6-32: Summary of responses to the following questions: (a) Q.55: Would you like uncertainty estimates broken down into different components (random, locally systematic and large-scale systematic) in addition to a total uncertainty? And (b) Q.57: Which components would you need to use? ------------ 91

Figure 6-33: Summary of intended use of uncertainty data (Q.54), partitioned by the requirement for total uncertainty budget only, and the provision of uncertainty components (Q.55). Q.54: For what purposes would you like to use uncertainty data? Q.55: Would you like uncertainty estimates broken down into different components (random, locally systematic and large-scale systematic) in addition to a total uncertainty?--- 92

Figure 6-34: Summary of responses to the following questions: (a) Q.59: Do you consider validation and inter-comparison results produced by the data providers in your work (either using results to guide product selection or directly incorporating results)? (b) Q.60: For what purpose do you use validation and inter-comparison data? -- 93

Figure 6-35: Summary of responses to Q.61: What are the barriers preventing you from using validation and inter-comparison data? -- 94

Figure 6-36: Summary of responses to Q.62: What validation and inter-comparison information would be most useful for your primary application? (The 45% line is included to show the threshold for a soft requirement – see Section 4.) -- 95

Figure 6-37: Summary of responses to the following questions: (a) Q.63: Would you prefer a consistent approach to cloud-clearing across sensors, or a 'best for each sensor' approach, even if this means changes between sensors? (b) Q.64: Do you prefer LST data to be pre-screened for cloud-contaminated pixels, or would you prefer to apply a bitmask or probability screening yourself? (c) Q.65: Would you prefer a pre-defined binary cloud mask or clear-sky probabilities to enable you to define your own cloud mask (or both)?-- 96

Figure 6-38: Responses to Q.63 (a) and Q.64 (b) partitioned by user spatial domain. Q.63: Would you prefer a consistent approach to cloud-clearing across sensors, or a 'best for each sensor' approach, even if this means changes between sensors? Q.64: Do you prefer LST data to be pre-screened for cloud-contaminated pixels, or would you prefer to apply a bitmask or probability screening yourself? --------- 97

Figure 6-39: Summary of responses to Q.66: If you were provided with clear-sky probabilities, how would you use this data to cloud clear LST data?-- 97

Figure 6-40: Summary of responses to Q.67: If you were to choose a clear-sky probability threshold to define a cloud-contamination mask for your primary application, what value do you feel might be appropriate? -- 98

List of Tables

Table 1-1: Summary of all requirements, optional requirements and advice notes relating to the LST_cci project. Optional requirements are highlighted in light grey and advice notes are highlighted in light blue in the table below. ---------- 2

Table 3-1: GCOS requirements for LST data at threshold and target levels (WMO, 2016). ---------- 15

Table 3-2: Datasets to be provided within the LST_cci project (CCI+ Phase 1 - New ECVs: Land Surface Temperature - Technical Proposal, 2017). ---------- 17

Table 3-3: Summary of LST user requirements classified according to product scale, adapted from the paper for LST needs (Hook, 2006). Reproduced from (Bulgin & Merchant, 2016). ---------- 18

Table 3-4: Applications and associated LST spatial and temporal target resolutions. Reproduced from the NCDC Workshop Report (Bosilovich, et al., 2008). ---------- 18

Table 3-5: Key strengths, limitations and desired developments for LST datasets from the LST user exploitation document (Ghent, 2011). ---------- 19

Table 3-6: Key common areas for development of LST products from the LST user exploitation document (Ghent, 2011). ---------- 20

Table 3-7: Summary of user requirements for LST data from GlobTemperature (Bulgin & Merchant, 2016). ---------- 21

Table 3-8: Summary of LST user requirements for climate from GlobTemperature (Bulgin & Merchant, 2016). ---------- 23

Table 4-1: Summary of requirement types, definitions and when they are applicable (Bulgin and Merchant, 2016). ---------- 25

Table 4-2: Definitions of threshold, breakthrough and objective level requirements (Rayner, 2017). ---------- 25

Table 4-3: Definitions of data quality terms: accuracy, precision and stability. ---------- 26

Table 5-1: Summary of responses to Q1: Do you currently use satellite derived Land Surface Temperature (LST) for climate applications, or intend to in the next 5 years? ---------- 31

Table 5-2: Responses from Q2 - total number of participants working on each climate application, listed in decreasing number of user selections. ---------- 31

Table 5-3: Summary of responses to Q.3: If you use satellite LST, please explain the main challenges you experience in using the data. If you do not currently use LST data, please explain any concerns about using it, or the reason you have not yet used, or considered using LST. ---------- 32

Table 5-4: Summary of responses to Q4: If you use/might use LST, which is more important to your climate application (select one)? ---------- 33

Table 5-5: Summary of responses to Q.5: If you use/might use LST, which is more important to your climate application (select one)? ---------- 33

Table 5-6: Summary of responses to Q6: If you use/might use LST, which would be more useful for your climate application (select one)? ---------- 33

Table 5-7: Summary of responses to Q7: Merging InfraRed (IR) data products from Low Earth Orbiting (LEO) and Geostationary Earth Orbiting (GEO) satellites can help to resolve the diurnal cycle and improve data coverage. If you use/might use LST, would you choose a merged product like this over single sensor products? ---------- 34

Table 5-8: Summary of responses to Q8: If you use/might use LST, are you concerned about cloud effects in infrared LST datasets for climate applications? (Select as many as are appropriate). -------------------- 34

Table 5-9: Summary of responses to Q9: Many data come with uncertainty information, what would you most likely use? (Select as many as are appropriate, even if you have no interest in using LST). ---------- 35

Table 5-10: Summary of responses to Q.10: If you use/might use LST, what would you want in an ideal satellite LST dataset? ---------- 35

Table 6-1: Summary of LST processing levels and their definitions. ---------- 39

Table 6-2: Description of random, locally systematic, and large-scale systematic uncertainty components. ---------- 40

Table 6-3: Summary of responses to the following questions: Q.2: What is the name of the institution you work at?; Q.3: In which countries do you currently work? ---------- 63

Table 6-4: Summary of concerns ranked in Q.16 (see Figure 6-12) ordered using a points system in which a rank of #1 receives 3 points, rank #2 receives 2 points and #1 receives 1 point. ---------- 74

Table 6-5: Summary of additional detail provided by some participants in the comments for Q.17: Over what spatial domain do you require LST data for your primary application? ---------- 75

Table 6-6: Summary of required observation time pattern, regarding responses to Q.18 (responses shown in Figure 6-14). Q.18: At what time of day do you require LST observations? ---------- 76

Table 6-7: Summary of all comments provided by respondents at the end of the survey Q.69: Do you have any further comments on LST data requirements for climate before exiting and submitting your responses to the survey? ---------- 99

Table 6-8: Summary of threshold, breakthrough and objective requirements relating to questions 20-25 shown in Figure 6-15 to Figure 6-20. ---------- 101

Table 7-1: Overview of discussion topics covered in Climate Research Group (CRG) interviews. ---------- 104

Table 8-1: Zoom live session attendance ("Approx. Number") & views and downloads of the live session recordings ("Zoom Rec.). Note that the number of views and downloads is the total number for all four sessions on each day. Although each individual session was recorded separately, statistics for each individual session on each day are not available from Zoom. ---------- 117

Table 10-1: List of specific recommendations resulting from the LST_cci 2022 User Workshop. The recommendations are explained and numbered in Section 4 of the UWR and are indicated in the 'Notes' column of this table, e.g., LST-UWR2022-REC-01 refers to Recommendation #01 [AD-01]. ---------- 134

Table 11-1: Summary of requirements from the GlobTemperature project relating to data format and accessibility, which are also relevant to LST_cci (Bulgin & Merchant, 2016). ---------- 141

Table 11-2: Summary of requirements relating to data format and accessibility. ---------- 141

Table 11-3: Summary of advice notes issued relating to data format and accessibility. ---------- 142

Table 11-4: Summary of requirements relating to product type. ---------- 145

Table 11-5: Summary of advice issued in relation to product types. ---------- 146

Table 11-6: Summary of requirements relating to data specification. ---------- 148

Table 11-7: Summary of advice notes relating to data specification. ---------- 148

Table 11-8: Summary of requirements relating to data quality specification. ---------- 149

Table 11-9: Summary of advice relating to data quality specification. ---------- 149

Table 11-10: Summary of requirements relating to dataset priorities. -- 150

Table 11-11: Summary of advice issued in relation to dataset priorities.--------------------------------------- 151

Table 11-12: Summary of requirements regarding quality control information. ---------------------------- 152

Table 11-13: Summary of advice issued in relation to quality control information. ------------------------- 152

Table 11-14: Summary of requirements from the GlobTemperature project relating to error and uncertainty, which are also applicable here (Bulgin & Merchant, 2016).--------------------------------------- 153

Table 11-15: Summary of requirements relating to error and uncertainty.------------------------------------ 153

Table 11-16: Summary of advice issued regarding error and uncertainty data. ----------------------------- 154

Table 11-17: Summary of requirements relating to validation and inter-comparison results. ------------ 155

Table 11-18: Summary of advice issued relating to validation and inter-comparison results. ------------ 156

Table 11-19: Summary of requirements from the GlobTemperature project relating to clouds, which are also applicable here (Bulgin & Merchant, 2016). --- 156

Table 11-20: Summary of requirements relating to clouds.-- 157

Table 11-21: Summary of advice issued regarding provision of cloud information. ------------------------- 157

Table 11-22: Summary of advice issued for other requirements. -- 158

Table 11-23: Summary of all requirements, optional requirements and advice notes relating to the LST_cci project. Optional requirements are highlighted in light grey and advice notes are highlighted in light blue in the table below.-- 160

Table 0-1: Full responses to Q.3 of the Joint Land Workshop: “If you use satellite LST, please explain the main challenges you experience in using the data. If you do not currently use LST data, please explain any concerns about using it, or the reason you have not yet used, or considered using LST.” ----------------- 172

Table 0-2: Full responses to Q.10 of the Join Land Workshop Questionnaire: “If you use/might use LST, what would you want in an ideal satellite LST dataset?” --- 173

Table 0-3: Summary of all information collected during the interview with CRG members from the Met Office Hadley Centre. --- 174

Table 0-4: Summary of all information collected during the interview with CRG members from DMI.-- 175

Table 0-5: Summary of all information collected during the interview with CRG member from U. Hamburg. --- 177

Table 0-6: Summary of all information collected during the interview with CRG members from MPI. -- 180

Table 0-7: Summary of all information collected during the interview with CRG member from MeteoRomania. -- 182

Table 0-8: Summary of all information collected during the interview with CRG member from LIST. --- 183

Table 0-9: Summary of all information collected during the interview with CRG member from MeteoSwiss. --- 185

Table 0-10: Summary of all information collected during the interview with CRG/CMUG members from the Met Office Hadley Centre.-- 187

List of Acronyms

(A)ATSR	(Advanced) Across Track Scanning Radiometer
ABI	Advanced Baseline Imager
AHI	Advanced Himawari Imager
AIRS	Atmospheric IR Sounder
AMSR(-E)	Advanced Microwave Scanning Radiometer (- Earth Observing System)
API	Application Programming Interface
ARD	Analysis Ready Dataset
ASTER	Advanced Space borne Thermal Emission and Reflection Radiometer
ATBD	Algorithm Theoretical Basis Document
AUX	Auxiliary
AVHRR	Advanced Very High Resolution Radiometer
BAMS	Bulletin of the American Meteorological Society
BR	Breakthrough
BT	Brightness Temperature
C3S	Copernicus Climate Change Service
CAR	Climate Assessment Report
CCI	Climate Change Initiative
CDR	Climate Data Record
CEOS	Committee on Earth Observation Satellites
CEST	Central European Summer Time
CF	Climate and Forecast
CMG	Climate Model Grid
CM-SAF	Satellite Application Facility of Climate Monitoring
CMUG	Climate Modelling User Group
CORINE	Co-ordinated Information on the Environment
CRG	Climate Research Group
CrIS	Cross-track Infrared Sounder
CRUTEM	Climatic Research Unit Temperature
CSWG	Climate Science Working Group
DA	Data Assimilation
deg	Degrees
DMI	Danish Meteorological Institute
DMSP	Defence Meteorological Satellite Program
DUE	Data User Element
EASE	Equal-Area Scalable Earth
ECOSTRESS	ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station
ECV	Essential Climate Variable
ERS	European Remote-Sensing Satellite
ESA	European Space Agency
ESIP	Earth Science Information Partners
ET	Evapotranspiration
EU	European Union
EURO4M	European Reanalysis and Observations for Monitoring
EUSTACE	EU Surface Temperature for All Corners of Earth

FRAC	Full Resolution Area Coverage
GAC	Global Area Coverage
GCOS	Global Climate Observing System
GDPR	General Data Protection Regulations
GEM	Greenland Ecosystem Monitoring
GEO	Geostationary Earth Orbit
GIS	Geographic Information System
GOES	Geostationary Operational Environmental Satellite
HDF	Hierarchical Data Format
IASI	Infrared Atmospheric Sounding Interferometer
ILSTE	International Land Surface Temperature and Emissivity
IPCC	Intergovernmental Panel on Climate Change
IPMA	Instituto Português do Mar e da Atmosfera
IR	InfraRed
IST	Ice Surface Temperature
ISWG	International Surface Working Group
JAMI	Japanese Advanced Meteorological Imager
JULES	Joint UK Land Environment Simulator
LAI	Leaf Area Index
LEO	Low Earth Orbit
LIST	Luxembourg Institute of Science and Technology
LPV	Land Product Validation
LSA-SAF	Satellite Application Facility on Land Surface Analysis
LSAT	Land Surface Air Temperature
LST	Land Surface Temperature
MODIS	Moderate Resolution Imaging Spectroradiometer
MOHC	Met Office Hadley Centre
MPI	Max Plank Institute
MSG	Meteosat Second Generation
MTSAT	Multifunction Transport Satellite
MVIRI	Meteosat Visible and InfraRed Imager
MW	MicroWave
N/A	Not Applicable
NASA	National Aeronautics and Space Administration
NATT	North Australian Tropical Transect
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Centre
NDVI	Normalised Difference Vegetation Index
NetCDF	Network Common Data Form
NOAA	National Oceanic and Atmospheric Administration
NRT	Near Real Time
NWP	Numerical Weather Prediction
PUG	Product User Guide
QC	Quality Control
RBD	Requirements Baseline Document
RCM	Regional Climate Model
RetMIP	Retention Model Inter-comparison Project
RMSE	Root Mean Square Error

SEB	Surface Energy Balance
SEVIRI	Spinning Enhanced Visible and InfraRed Imager
SHP	Shapefile shape format
SLSTR	Sea and Land Surface Temperature Radiometer
SSM/I	Special Sensor Microwave Imager
SST	Sea Surface Temperature
SOTC	State of the Climate
SUHI	Surface Urban Heat Island
SUHII	Surface Urban Heat Island Intensity
T2m	2m Air Temperature
TCI	Thermal Comfort Index
TOA	Top Of Atmosphere
TR	Threshold
UCM	User Consultation Meeting
UCS	User Case Study
UHI	Urban Heat Island
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
URD	User Requirements Document
USA	United States of America
UTC	Coordinated Universal Time
UWR	User Workshop Report
VHI	Vegetation Health Index
VIIRS	Visible InfraRed Imaging Radiometer Suite
WATCH	Water and Global Change
WMO	World Meteorological Organisation

1. Executive Summary

This document summarises the Land Surface Temperature (LST) user requirements for climate science collected within the framework of the European Space Agency's LST Climate Change Initiative (CCI; http://cci.esa.int/lst). The approach builds on the work carried out within the LST_cci precursor project, Data User Element (DUE) GlobTemperature (http://www.globtemperature.info/). User requirements for LST_cci have been obtained through two surveys, which were open to both current and potential users of LST for climate applications. Firstly, a short paper survey with ten questions was issued at the Joint International Surface Working Group (ISWG) / LSA-SAF (Satellite Application Facility on Land Surface Analysis) Workshop held in Lisbon in 2018 (http://cimss.ssec.wisc.edu/iswg/meetings/2018/). The workshop was attended by scientists working with both land models and observations and included a dedicated session to gather requirements for LST_cci. A total of 22 responses were obtained from a range of climate applications. While the results of the survey enabled quantitative analysis of some user requirements, it also provided useful information and guidance for creating the second survey, which was a longer online questionnaire. The online survey, which comprised of 69 questions, was launched on 17 July 2018 and remained open until 16 September 2018. The survey was circulated widely within the scientific community, both by email and Twitter, in order to obtain responses from all key user groups (e.g. the modelling community through the Climate Modelling User Group (CMUG), observational scientists and modellers through the International Surface Working Group (ISWG)). Questions focused on gathering information about user applications, current data use, user concerns surrounding satellite LST products, dataset specification (e.g. temporal and spatial resolution, stability, accuracy, etc.), data format, quality and uncertainty information, requirements for validation and inter-comparison information, and issues concerning clouds. A total of 76 responses to the online survey were received. In addition, eight interviews with the LST_cci Climate Research Group (CRG) were conducted in parallel with the survey, to gain an in-depth understanding of their user requirements and to provide context for the information gathered through the two surveys. Finally, additional requirements were defined through interaction with early and potential LST_cci data users during the project, in particular at the virtual LST_cci User Workshops that took place in 2020 and 2022.

The information obtained through the surveys, interviews and interactions with users has been synthesised and used to define LST user requirements for climate applications. This includes an evaluation of requirements for the parameters specified by the Global Climate Observing System (GCOS): LST spatial and temporal resolution, data set length, accuracy, precision and stability. In line with the GCOS requirements, the requirements for LST_cci are also assessed at the 'threshold' and 'target' levels. (Threshold **-** a minimum requirement that has to be met to ensure that data are useful. Below this minimum, the benefit derived does not compensate for the additional cost in using the observation. Target - a maximum requirement. An ideal value, above which, further improvement of the observation would not cause any significant improvement in performance for the application in question. In LST_cci, the term 'objective' level is used in place of the term 'target' used by GCOS for consistency with GlobTemperature.) In defining user requirements for LST_cci, all three strands of information gathering (paper survey, online survey, interviews and user interactions) were considered equally. Where possible, requirements have been defined using a quantitative approach, for example, a requirement for accuracy or spatial resolution that satisfies a certain proportion of the survey respondents. Where this has not been possible, for example where information has been gathered through the CRG interviews or free-text boxes in the surveys, an 'advice note' has been issued to make a recommendation that meets the needs of users. These requirements and advice notes are summarised in Table 1-1, using the following naming convention:

LST-URD-<*type*>-<*number*>-<*source*>

Where:

- LST-URD indicates that the requirement or advice note has originated from this LST_cci User Requirements Document (URD)
- <*type*> can be one of three options:
  - "REQ": A requirement that must be addressed by the project.
  - "OPT": An optional requirement that should be met where possible.
  - "ADV": An advisory requirement that should be considered where feasible. These are used where requirements cannot be analysed quantitatively, for example the CRG interviews or free text questions provided in the Lisbon and Online questionnaires.
- <*number*> is a two-digit counter
- <*source*> identifies where the requirement originated, in this case it can be one or more of four options:
  - 'L': Joint Land Workshop held in Lisbon [Section 5]
  - 'O': Online questionnaire [Section 6]
  - 'I': Interviews with members of the CRG [Section 7]
  - 'U': User interactions, e.g. workshop, other feedback [Section 8 and 9]

The source of the requirement, indicated by a 'L', 'O', 'I' or 'U', therefore also indicates where requirements originate from more than one source. For example, requirement 'LST-URD-REQ-05-LO' is based on information obtained through both the survey issued at the Joint Land Workshop held in Lisbon, and the online survey. The exception here is the source, 'U', which has been added for v2 and v3 of this URD (it was not present in URD v1). In this case, the 'U' source has not been added to the ID for requirements that were defined in v1 to preserve traceability for documents citing requirements that were defined before v2 of this URD was produced.

The LST_cci project should address all the 'REQ' requirements listed in Table 1-1. The 'OPT' requirements are more stringent versions of the six 'REQ' requirements concerning spatial and temporal resolution, and accuracy, stability and precision, and should be addressed by the project where possible. The 'ADV' requirements should be considered where feasible and are essentially recommendations identified through user engagement. It is recognised that some of the OPT and ADV requirements will not be achieved during Phase I or even Phase II of LST_cci but through later phases or follow-on projects. Many of the ADV requirements in particular are ambitious and require additional work that is beyond the scope of the first two phases of the project. For example, the provision of LST data for additional sensors or in near real time. Therefore, the ADV requirements should also be used to inform the design of future LST_cci project phases as they provide information on what is most important to current and potential LST data users.

Table 1-1: Summary of all requirements, optional requirements and advice notes relating to the LST_cci project. Optional requirements are highlighted in light grey and advice notes are highlighted in light blue in the table below.

ID	Requirement	Notes
	Data Format and Accessibility	
LST-URD-REQ-01-O	Provide LST products in NetCDF format	90% of respondents were able to use NetCDF data
LST-URD-ADV-01-O	CCI standard format is recommended for LST_cci products	52 participants currently use CCI products, 32 use these in conjunction with LST data
LST-URD-ADV-02-OI	Disseminate clear information on what LST data represents, potential	Aim to improve understanding of what LST data represents, including linking to model parameters.

ID	Requirement	Notes
	applications and how the data may be used	
LST-URD-ADV-03-I	Provide documentation detailing assumptions made during the retrieval process or product construction, including detailed information on any techniques used for merging	Aim to make it as easy as possible to understand the data
LST-URD-ADV-04-LI	Ensure long term, easy access to data	CCI Open Data Portal will be used (note that the GlobTemperature portal suggested as a good model)
LST-URD-ADV-05-O	Provide a summary of the availability and characteristics of different LST products	
LST-URD-ADV-06-LI	Consistency should be maintained between different LST products within LST_cci	Users often require data from multiple sensors
LST-URD-ADV-07-OI	Consistency between LST_cci and other CCI products should be maintained	32 participants use CCI ECV products in conjunction with LST data
LST-URD-ADV-08-OI	Provide information on how comparable LST_cci products are with other CCI datasets, for example, spatial and temporal averaging, uncertainties, changes likely to impact LST (e.g. vegetation fractional cover)	
LST-URD-ADV-35-U	Provide guidance to users on which LST products should be used for different applications	Users can be overwhelmed by the choice of LST products, e.g. many single-sensor products.
LST-URD-ADV-40-U	Regularly consult with users on appropriateness of data format, accessibility and usability.	Good examples provided by NOAA and NASA through ESIP.
LST-URD-ADV-41-U	Provide hands-on experience for users at dedicated workshops	Hold demonstrations, provide Jupyter notebooks, example code, etc.
LST-URD-ADV-42-U	Provide LST use examples (with code) in a dedicated document. Include information on what can be achieved with the data (e.g. limitations).	
LST-URD-ADV-47-U	Ensure all LST_cci documentation is readily and easily available to users.	Links to documentation and info about data storage structure needs to be added to data portal, including public area on Jasmin for Beta products.
LST-URD-ADV-51-U	Provide information on LST trends	Calculated trends for multi-decadal LST products could be provided within user documentation. This could include information on known trends in the underlying raw satellite data.

ID	Requirement	Notes
LST-URD-ADV-54-U	Provide tools to enable users to select the data they want themselves.	E.g. for specific regions, with specific QC or other screening applied, etc.
LST-URD-ADV-59-U	Provide LST_cci data sets in real time, ideally with near-daily updates.	11 of 12 respondents require data within 48 hours of acquisition. Some applications require less-frequent updates, e.g. monthly. Provision of real-time anomalies could also be considered.
LST-URD-ADV-61-U	Highlight in LST_cci documentation that most GIS packages can use netCDF data.	
LST-URD-ADV-62-U	Improve delivery of data via data portals – enable users to visualise and use data within the portal.	
LST-URD-ADV-63-U	Raise awareness of satellite LST and its benefits through improved publicity.	E.g. a white paper could be produced.
LST-URD-ADV-64-U	Provide information and/or tools to convert LST_cci data into different formats.	
LST-URD-ADV-65-U	Establish a non-specialist user group to consult for data provision to non-specialist users.	
LST-URD-ADV-66-U	Provide a range of documentation targetted at different user levels/details.	Consider unified/standardised documentation, e.g. https://lpdaacsvc.cr.usgs/gov/appeears/
LST-URD-ADV-67-U	Provide information to users in a variety of ways, e.g. traditional documentation, videos, podcasts, etc.	In addition to holding workshops [LST-URD-ADV-41-U]
LST-URD-ADV-68-U	Make LST_cci data available in ARD and/or data cube formats.	
LST_URD_ADV-82-U	Provide reprocessed LST_cci datasets at least annually	
LST_URD_ADV-83-U	Provide LST data on a Polar EASE grid	Low priority – only 2-3 users identified with this need.
LST_URD_ADV-84-U	Ensure LST_cci ARDs are provided with good documentation, in easy-to-access formats with simple quality flags.	Low priority – only a few users have identified a need for ARD so far.
LST_URD_ADV-85-U	Provide fill values in files for missing data products and an inventory of files with missing data.	Some users would prefer to have e.g. days of missing data with 100% fill values, rather than having a missing data file.
LST_URD_ADV-86-U	Extend LST_cci Regridding Tool to produce temporal means (e.g. weekly, pentads, etc).	
LST_URD_ADV-87-U	Develop a wrapper for the LST_cci Regridding Tool to process multiple files.	

ID	Requirement	Notes
LST_URD_ADV-88-U	Maintain a webpage/blog as a permanent resource that can be accessed for historical issues.	High priority action.
LST_URD_ADV-89-U	Provide users with the option to be sent email notifications when new issues are discovered and added to the issues list.	High priority action.
LST_URD_ADV-90-U	Provide information on data gaps, e.g. due to sensor outages or satellite manoeuvres.	High priority action.
	Product Types	
LST-URD-REQ-02-O	Provide LST from IR LEO satellites	68% of respondents are interested in these data
LST-URD-REQ-03-O	Provide LST from IR GEO satellites	66% of respondents are interested in these data
LST-URD-REQ-04-O	Provide products which merge LST from multiple IR LEO satellite datasets to create a long running, near-global CDR	54% of respondents are interested in these data
LST-URD-REQ-05-LO	Provide products produced by merging LEO and GEO datasets	90% (Lisbon) / 63% (Online) of participants were interested in merged products
LST-URD-REQ-06-O	Provide LST data products at level 2	47% of respondents selected Level 2 data
LST-URD-REQ-07-O	Provide LST data products at level 3C	55% of respondents selected Level 3C data
LST-URD-REQ-08-O	Data from MODIS instruments should be given high priority	75% of respondents currently use MODIS LST data for climate applications
LST-URD-ADV-09-LI	Provide multi-decadal, homogenised datasets, free from non-climatic discontinuities	Long term, consistent datasets are required for climate science. Links to LST-URD-REQ-13-O and LST-URD-OPT-13-0
LST-URD-ADV-10-OI	Provision of MW LST products	43% of respondents were interested in MW products
LST-URD-ADV-11-LOI	Provision of all-sky LST datasets	Some members of the CRG are gap-filling IR LST data sets already; a standard option would be useful. Not clear whether users want gap-filled LSTs to represent clear-sky or all-sky. 38% of respondents to the online survey are interested in a merged IR and MW product
LST-URD-ADV-12-O	Provision of Meteosat data	Meteosat was the second most popular instrument out of respondents currently use LST data for climate applications
LST-URD-ADV-13-O	Provision of Landsat data	Landsat was the third most popular instrument out of respondents who currently use LST data for climate applications

ID	Requirement	Notes
LST-URD-ADV-14-O	Provision of AVHRR data	To extent data record length
LST-URD-ADV-58-U	Improve consistency between MW and IR LST_cci data sets.	Currently the QC flags are not the same.
LST-URD-ADV-76-U	Provide a dedicated Ice Surface Temperature retrieval.	
LST-URD-ADV-79-U	Provide downscaled SEVIRI data (e.g. using MODIS).	
LST-URD-ADV-81-U	Provide LST products for VIIRS.	
LST_URD_ADV-91-U	Provide LST_cci data as 10-day means.	Low priority: At least 3 users requested this.
LST_URD_ADV-92-U	Provide LST climatologies.	Low priority: At least one user requested this.
LST_URD_ADV-93-U	Provide selected properties derived from LST, for example, anomalies, daily minimum and maximum LST, annual means and LST- 2m air temperature differences.	Low priority: Each list item was requested by at least one user.
Data Specification		
LST-URD-REQ-09-O	Provide global coverage of LST data	47% of respondents require global data
LST-URD-REQ-10-O	Provide observations at all hours of the day	52% of respondents requested observations at all hours of the day
LST-URD-REQ-11-O	Provide minimum dataset length of 10 years	Satisfies 82% of respondents at the threshold level
LST-URD-OPT-11-O	Provide minimum dataset length of 30 years	Satisfies 87% of respondents at the breakthrough level
LST-URD-REQ-12-O	Provide datasets with a spatial resolution of 1 km	Satisfies 83% of respondents at the threshold level
LST-URD-OPT-12-O	Provide datasets with a spatial resolution finer than 1 km	Satisfies 100% of respondents at the breakthrough level
LST-URD-REQ-13-O	Provide data with temporal resolution of 6 hours	Satisfies 75% of respondents at the threshold level
LST-URD-OPT-13-O	Provide data with a temporal resolution of 1 hour	Satisfies 94% of respondents at the breakthrough level
LST-URD-ADV-15-OI	Provision of LST observations close to solar noon / early afternoon should be prioritised	31% of respondents who did not request observations at all times of day selected 12 noon: this option received the highest number of selections
LST-URD-ADV-34-U	Provide high-resolution LST ≤300 m	Needs for both 30-50 m and 300 m data were noted.
LST-URD-ADV-39-U	Provide data at the highest resolution possible	Links with LST-URD-ADV-38-U: Highest resolution data stored, user re-grids and sub-sets as required.
LST-URD-ADV-50-U	Provide LST ‘normalised’ to a specific time, e.g. solar noon	Requires use of a diurnal model for LST

ID	Requirement	Notes
LST-URD-ADV-56-U	Improve provision of 0.01° data, e.g. using georeferenced tile-based system.	
LST_URD_ADV-94-U	Provide LST_cci products on UTC grids.	Low priority: Requested by 1 of 9 respondents. Provide time-consistent fields with time stamp 00:00, 01:00….23:00 UTC e.g. to match model output.
Data Quality Priorities		
LST-URD-REQ-14-O	Provision of data with accuracy of 1 K	Satisfies 84% of respondents at the threshold level
LST-URD-OPT-14-O	Provision of data with accuracy of 0.5 K	Satisfies 87% of respondents at the breakthrough level
LST-URD-REQ-15-O	Provision of data with precision of 1 K	Satisfies 80% of respondents at the threshold level
LST-URD-OPT-15-O	Provision of data with precision of 0.5 K	Satisfies 85% of respondents at the breakthrough level
LST-URD-REQ-16-O	Provision of data with stability of 0.3 K	Satisfies 85% of respondents at the threshold level
LST-URD-OPT-16-O	Provision of data with stability of 0.2 K	Satisfies 88% of respondents at the breakthrough level
LST-URD-ADV-16-I	Improve accuracy of LST retrievals for urban and arid biomes	Current LST products often perform poorly for these land cover types
LST-URD-ADV-70-U	Improve emissivity data used in the IR LST retrievals.	This issue has only been identified for MODIS so far, but may also be relevant to other IR LST data sets.
Data Specification Priorities		
LST-URD-REQ-17-L	Product accuracy should be prioritised over long term stability and global spatially complete fields	62% of participants agreed with this statement
LST-URD-REQ-18-O	High data quality should be prioritised over spatially complete fields	67% of participants agreed with this statement
LST-URD-ADV-17-O	Datasets intended for global studies should prioritise high temporal resolution and long datasets	Of those requiring data globally: 56% prioritised high temporal resolution over spatial 63% prioritised long datasets over high resolution
LST-URD-ADV-18-O	Datasets intended for local studies should prioritise high spatial resolution	Of those requiring data for local studies: 75% prioritised high spatial resolution over temporal 88% prioritised high resolution over long datasets
LST-URD-ADV-19-O	Datasets intended for global studies should prioritise using a consistent approach to cloud clearing and provide a pre-screened dataset	Of those requiring data globally: 58% preferred a consistent approach to cloud clearing 56% preferred pre-screened data
LST-URD-ADV-20-O	Datasets intended for regional or local studies should prioritise using the best	Of those requiring data for regional or local studies:

ID	Requirement	Notes
	cloud clearing algorithm for each sensor, and allow the user to apply the cloud mask themselves	62% preferred a best for each sensor approach 61% preferred to apply a cloud mask themselves
LST-URD-ADV-21-LOI	Improvements in LST spatial resolution should be prioritised	
LST-URD-ADV-69-U	LST observations over sparsely-observed regions should be prioritised (e.g. Arctic, deserts)	
LST_URD_ADV-95-U	Prioritise dealing with cloud cover in IR data sets.	This is clearly a very high priority for many users.
Quality Control		
LST-URD-REQ-19-L	Provide LST data with quality flags	64% of participants would use quality flags
LST-URD-REQ-20-O	Provide the following QC flags (in order of preference): ❖ Day / night ❖ Summary cloud ❖ Summary confidence ❖ Land ❖ Aerosol	Participants were asked to order the importance of these QC flags
LST-URD-REQ-21-O	Provide the following QC flags in addition to the above: ❖ Water body ❖ Snow / ice	75% of participants requested a water body flag 66% of participants requested a snow / ice flag
LST-URD-REQ-22-O	Provide LST data with QC level data on a pixel level	93% of participants requested these data
LST-URD-REQ-23-O	Provide LST data with QC level data on a file level	69% of participants requested these data
LST-URD-ADV-53-U	Provide worked examples to show how to decode bit-encoded QC information.	Examples, e.g. in PUG, using common programming languages would be useful.
Error and Uncertainty		
LST-URD-REQ-24-LO	Provide per pixel total uncertainty values	73% requested this data
LST-URD-REQ-25-O	Provide uncertainty data partitioned into components according to correlation properties	72% of respondents required more than just a total uncertainty Interviewees also expressed interest in these data 27% of Lisbon survey respondents requested this information
LST-URD-REQ-26-O	Uncertainty information should be provided with clear documentation including descriptions of how to use the data and worked examples	93% of participants requested descriptions of how to use uncertainty data 64% of participants requested worked examples

ID	Requirement	Notes
LST-URD-ADV-22-I	Provide detailed information on how uncertainties are calculated	
LST-URD-ADV-23-OI	Provide information on what the uncertainties represent and why they are useful	
LST-URD-ADV-24-O	Provide information about spatial and temporal structure of the uncertainty components	Comment left by a participant
LST-URD-ADV-25-LOI	Include cloud effects in uncertainty data	
LST-URD-ADV-38-U	Provide tools to re-grid data and propagate uncertainties	Example code, Jupyter notebooks, online gridding facility delivered via the cloud, etc
LST-URD-ADV-43-U	Use ILSTE-WG to establish community standards for uncertainty information.	
LST-URD-ADV-44-U	Provide more detailed information on uncertainties in the LST_cci PUG.	
LST-URD-ADV-45-U	Investigate providing further breakdown of surface uncertainty components	Provide further breakdown into different sources, e.g. uncertainty in emissivity/biome due to geolocation, uncertainty in emissivity/biome, shadowing, etc.
LST-URD-ADV-46-U	Provide specific, easy-to-follow examples of how to propagate uncertainties (downscaling and upscaling), guidelines for threshold-based use.	
LST-URD-ADV-48-U	Consider using ensembles to represent uncertainty, especially where retrieval complexity is significant.	Likely a trade-off here with processing time and memory. Not always necessary to take this approach.
LST-URD-ADV-49-U	Consider errors in geolocation in uncertainty budget	
Validation and Inter-comparison		
LST-URD-REQ-27-OI	Provide comparisons of satellite LST data with in-situ measurements as part of the validation and inter-comparison results	82% of respondents requested this information
LST-URD-REQ-28-O	Provide inter-comparisons between LST products as part of the validation and inter-comparison results	75% of respondents requested this information
LST-URD-REQ-29-LO	Provide a summary of accuracy and precision per product as part of the validation and inter-comparison results	67% of respondents requested this information 59% of respondents to Lisbon questionnaire Q.9 also requested this information
LST-URD-REQ-30-O	Provide an overview of the best performing products in different	51% of respondents requested this information

ID	Requirement	Notes
	scenarios as part of the validation and inter-comparison results	
LST-URD-ADV-26-O	Provide results from time series analysis	44% of respondents require this information
LST-URD-ADV-27-O	Consider including validation of uncertainty components	Comment left by participant
LST-URD-ADV-28-O	Consider including validation of clear-sky probabilities	Comment left by participant
LST-URD-ADV-29-O	Where possible provide advice on how validation and inter-comparison results can benefit users, and how the results can be incorporated into their work	
	Clouds	
LST-URD-REQ-31-O	Provide a binary cloud mask	52% of participants requested both binary cloud mask and clear-sky probability
LST-URD-REQ-32-O	Provide clear-sky probabilities	52% of participants requested both binary cloud mask and clear-sky probability
LST-URD-REQ-33-O	Where clear-sky probabilities are provided, include descriptions of how to use these data and worked examples	89% requested descriptions 57% requested worked examples
LST-URD-ADV-30-I	Provide a description of what is represented by clear-sky probabilities and how they are calculated	
LST-URD-ADV-31-O	Provide a recommended starting value to be used by users for cloud clearing, ideally for a set of different applications	Comment left by participant
LST-URD-ADV-32-LI	Investigate and provide information to users concerning clear-sky bias in IR LST data	
LST-URD-ADV-33-LOI	Reduce errors due to cloud contamination in IR LST data sets	73% were concerned about cloud contamination errors (Lisbon) Cloud contamination errors were the second highest concern in the online survey
LST-URD-ADV-37-U	Improve cloud screening over ice and snow	
LST_URD_ADV-96-U	Provide detailed information on IR cloud screening processes.	
	Other	
LST-URD-ADV-36-U	Provide information on LST vs T2m data	Highlight advantages and disadvantages of LST vs T2m, expected differences, etc.
LST-URD-ADV-52-U	Provide L3 data where data have not been averaged over multiple overpasses.	Some users cannot use data that have been averaged over multiple overpasses.

ID	Requirement	Notes
LST-URD-ADV-55-U	Provide information and worked examples on how to convert pixel overpass times to other date-time formats.	
LST-URD-ADV-57-U	Provide local solar time in the LST_cci data files.	Users can calculate this, but it requires additional effort.
LST-URD-ADV-60-U	Provide component LSTs in gridded data sets based on observations (no modelling).	Even basic vegetation vs non-vegetated would be useful.
LST-URD-ADV-71-U	Provide dynamic land cover class information in the LST_cci data files.	
LST-URD-ADV-72-U	Provide satellite view zenith angles with sign (i.e. '-' or '+') that indicates whether the view is towards the east or west.	
LST-URD-ADV-73-U	Correct global attributes "geospatial_lat_min", "geospatial_lat_max", "geospatial_lon_min", "geospatial_lon_max" by half a pixel	Currently these values correspond to the centre of the pixel, rather than a corner, which would indicate the true geo-bounding box, which is confusing for users.
LST-URD-ADV-74-U	Correct or provide user guidance regarding the change in spatial extent of the SEVIRI disk part-way through the record.	
LST-URD-ADV-75-U	Provide information regarding fields 'ncld' and 'variance' in the LST_cci MSG_SEVIRI_L3U, which have no meaning.	
LST-URD-ADV-77-U	Extend SEVIRI data record beyond 2008-2010.	
LST-URD-ADV-78-U	Provide nadir-equivalent LST retrievals (implement geometrical correction).	
LST-URD-ADV-80-U	Provide instantaneous LSTs in L3 products as an extra fields in the LST_cci products (e.g. averaged LSTs over each orbit separately)	Partly addressed through LST-URD-ADV-52-U.
LST_URD_ADV-97-U	Provide observation time, view angles, total uncertainty and land cover classification in LST_cci ARD products.	Combined response from 4 respondents.
LST_URD_ADV-98-U	Provide observation operators to convert LST to T2m and potentially other variables.	Based on information provided by 9 respondents. For example, to soil moisture, below- and within-canopy temperatures and temperatures associated with different PFTs.

ID	Requirement	Notes
LST_URD_ADV-99-U	Include additional variables in LST_cci products where possible to support climate services using LST.	Based on feedback from 10 respondents, include T2m and land cover classification (both high priority); other variables such as surface humidity, modelled surface 'skin' temperature, emissivity, NDVI, fractional vegetation and total column water vapour could also be considered (low priority).

2. Purpose and Scope

The European Space Agency's (ESA's) Climate Change Initiative (CCI) project aims to provide a comprehensive and timely response to the challenging requirements set by the Global Climate Observing System (GCOS) and the Committee on Earth Observation Satellites (CEOS) for highly stable, long-term, satellite-based products for climate research (ESA's Climate Change Initiative).

Space observations provide unique information that cannot be obtained from traditional ground stations – they can provide better spatial coverage and resolution, and records are now approaching the time periods required for climate research. As part of the CCI project, a total of 22 Essential Climate Variables (ECVs) have been targeted. Fourteen of these ECVs were included in the first phase of ESA's CCI project. A further eight have been selected for the second phase of the project (European Space Agency, 2016a). Land Surface Temperature (LST) is included in this second phase, and this document provides baseline user requirements for this ECV.

While other initiatives, such as ESA's DUE GlobTemperature project (European Space Agency, 2016b), have gathered comprehensive user requirements for all applications of satellite LST, the LST_cci is the first project where a detailed assessment of user requirements has been performed solely for climate LST applications. LST requirements for climate science applications differ from other applications, as they typically require accurate datasets that are very stable in time, free from non-climatic discontinuities; ensuring a reliable long-term record.

LST provides a valuable set of observations for characterising land surface states and land-atmosphere exchange. It is increasingly recognised as an essential parameter for diagnosing Earth System behaviour and evaluating Earth System Models (WMO, 2016) because it provides:

- a globally consistent record from satellite of radiative temperatures of the Earth's surface
- a crucial constraint on surface energy balances, particularly in moisture-limited states
- a metric of surface state when combined with vegetation parameters and soil moisture, and is related to the driving of vegetation phenology (Karnieli, et al., 2010)

Direct measurements of near-surface air temperature (T2m) are often not available on the spatial scale and density needed to meet the evolving needs of climate science and services. LST and T2m are typically well coupled (Good, 2016; Good et al., 2017; Lian et al., 2017), and this relationship can been exploited in order to create improved fields of T2m, such as those being produced in the EUSTACE project (EU Surface Temperature for All corners of Earth: https://www.eustaceproject.eu/) and other studies (Good, 2015; Janatian, et al., 2016; Kilibarda, et al., 2014). Therefore, LST can be an important source of information for deriving T2m in regions with sparse measurement stations, such as parts of Africa and the Antarctic. Such studies typically use existing LST products, for example the MODIS LST products available from NASA, although the MODIS LST products used to derive T2m in EUSTACE were produced through a EUSTACE/GlobTemperature collaboration to provide the specialised uncertainty information required for the EUSTACE analysis.

A long, stable record of LST is particularly useful for model evaluation in regions where few in situ measurements of surface air temperature exist. In these regions, uncertainty due to station data sparsity can be as large as the differences seen between naturally- and historically-forced climate model simulations (King et al., 2013; van Oldenborgh et al., 2018). Current attribution studies in station-data sparse regions frequently rely on reanalysis T2m (Christidis, et al., 2012; Christidis & Stott, 2014), but LST provides a viable alternative as a surface 'skin' temperature can be included in climate model outputs and compared with satellite LST observations (Fraser Lott, Met Office, personal communication).

ESA's LST CCI project strives to provide a range of products from multiple sensors, using consistent retrieval algorithms with provision of uncertainty estimates where possible. Recent developments in techniques for producing uncertainty estimates partitioned by correlation length scale, as performed in SST CCI, GlobTemperature and EUSTACE (Bulgin et al., 2016) will be applied to satellite LST products in this project. The LST_cci products will include information on cloud, using a consistent approach for all sensors used within each product, and where it is feasible, clear-sky probabilities will also be derived. Due to the need for long term, consistent datasets for climate research, two dedicated Climate Data Records (CDRs) will be produced from InfraRed (IR) satellites. One will be based on the ATSR/SLSTR sensors, using MODIS to fill the gap between (A)ATSR and SLSTR. The other will merge data from Low Earth Orbiting (LEO) and Geostationary Earth Orbiting (GEO) satellites to provide a consistent global, sub-daily data set. Acknowledging the need for all-sky data, the LST CCI project will also provide a muti-decadal MicroWave (MW) LST data set, and produce an experimental one year product merging data from IR and MW sensors.

Requirements provided by previous projects – including those from the GlobTemperature project that assess the use of satellite LST data in the general scientific community, and climate specific requirements from GCOS – form the foundation of the LST requirements assessment performed in LST_cci. Known user requirements are developed and explored further through two user questionnaires and interviews with members of the LST_cci Climate Research Group (CRG).

This document aims to provide a comprehensive assessment of the requirements of LST data within the climate science community. Firstly existing user requirements for satellite LST data are summarised in Section 3. Particular attention is given to the requirements obtained through the GlobTemperature project, which is the pre-cursor to the LST_cci project. Where appropriate, the GlobTemperature requirements are also included in the requirements output from this study, allowing the focus of LST_cci to be on obtaining further information or detail that is relevant to climate science. In Section 4, the methods used to specify requirements are defined and these are applied throughout the analysis described in this document. User requirements gathered at the Joint Land Workshop, held in Lisbon, 2018, are detailed in Section 5. Section 6 describes the online user requirements questionnaire, which provides the basis for most of the LST_cci requirements defined in this document. The interviews conducted with members of the Climate Research Group (CRG) are summarised in Section 7; full details of the information gathered during these interviews are provided in Appendix A. Sections 8 and 10 summarise the feedback gathered during the 2020 and 2022 LST_cci User Workshops, and Section 9 other feedback from users of the LST_cci beta products released after version 1 of the URD was produced. Finally, Section 11 summarises the requirements and advice notes issued based on the results provided in previous sections.

3. Existing User Requirements for Satellite LST Products

Land Surface Temperature (LST) has recently been identified as an Essential Climate Variable (ECV) with threshold and target requirements defined within the Global Climate Observing System implementation plan (WMO, 2016). LST is defined by GCOS as the 'aggregated radiometric surface temperature of the ensemble of components within the sensor field of view' (WMO, 2016) and is recognised as a key variable for understanding heat and energy exchange at the land surface. It also complements information provided by in-situ two metre air temperature measurements, enhancing understanding of near-surface processes. In this section an overview of the current status of general user requirements for LST as the platform for assessing LST requirements for climate is provided.

3.1. Establishing LST as an Essential Climate Variable

3.1.1. GCOS Requirements

LST provides an independent, spatially continuous, temperature dataset for quantifying climate change, complementary to the near surface air temperature ECV, which is based in in-situ measurements and reanalysis. It is important for the evaluation of land surface and land-atmosphere exchange processes, the constraint of surface energy budgets and flux variation, and global and regional observations of surface temperature variations. Key requirements are outlined in the GCOS 2016 Implementation Plan (WMO, 2016). Dataset specification requirements are detailed Table 3-1 at a threshold and target level, where threshold and target have the following definitions (WMO, 2011):

- **Threshold:** A minimum requirement that has to be met to ensure that data are useful. Below this minimum, the benefit derived does not compensate for the additional cost in using the observation
- **Target**: A maximum requirement. An ideal value, above which, further improvement of the observation would not cause any significant improvement in performance for the application in question

Table 3-1: GCOS requirements for LST data at threshold and target levels (WMO, 2016).

Requirement Type	Requirement Level	Specification
Spatial resolution	Threshold	0.05°
Temporal resolution	Threshold	Day-night
	Target	≤ 3-hourly
Dataset length	Threshold	20 years
	Target	>30 years
Accuracy	Threshold	<1 K
Precision	Threshold	<1 K
Stability	Threshold	<0.3 K per decade
	Target	<0.1 K per decade

The GCOS implementation plan includes four actions (T42, T43, T44 and T46) that are relevant to this project. These actions are, in general, addressed by this URD, and will be taken into account in the provision of data within the LST Climate Change Initiative (CCI) project and are regularly reviewed by the International Land Surface Temperature and Emissivity (ILSTE) working group.

Action T42: Land Surface Temperature: In-situ Protocols

- Promote standardised data protocols for in situ LST and support the Committee on Earth Observation Satellites - Land Product Validation (CEOS-LPV) group in development of a consistent approach to data validation, taking its LST Validation Protocol as a baseline
- LST data sets would be more accessible to users encouraging user uptake of more than one LST data set. This will lead to better characterisation of uncertainties and inter-data set variability

Action T43: Production of Land Surface Temperature Datasets

- Continue the production of global LST datasets, ensuring consistency between products produced from different sensors and by different groups
- Make available long time series of LST datasets in consistent formats, enabling more widespread use of LST for climate applications

Action T44: Reprocessing Land Surface Temperature (LST)

- Reprocess existing datasets of LST to generate a consistent long-term time series of global LST. In particular, reprocess archives of LEO and GEO LST observations in a consistent manner and to community agreed data formats
- Make available long time-series

T46: Land Surface Temperature Radiometric Calibration

- Radiometric Calibration inter-comparisons and uncertainties for LST sensors
- LST datasets better calibrated and over all land surface types for different satellite sensors. Independent calibration providing credibility and traceability of data and uncertainties, preferably referenced to a common framework

3.1.2. LST Climate Change Initiative

The objective of the LST CCI project is to provide a global LST data record spanning the last 20-25 years from a variety of satellite datasets, meeting the requirements set out by GCOS. More specifically the project outcomes include the following (ESA, 2018):

- A strong validation component providing globally representative and consistent in-situ validation and inter-comparison of LST products over all the major land cover types, informing the climate community of the performance of the LST ECV products.
- Sustained support to the surface temperature community through dedicated effort into the well-established International LST and Emissivity Working Group (ILSTE), which is the principle forum of community expertise from data providers to users.
- Detailed climate user input into the specifications of the LST ECV products, and user assessment of these products to drive LST exploitation in climate science.
- Strong buy-in from the climate science community coordinated by the Climate Research Group, with key inputs from the Climate Modelling User Group (CMUG) and Climate Science Working Group (CSWG), and user interaction at two dedicated user workshops.
- A comprehensive suite of high quality IR LST ECV Products and MW LST ECV Products for geostationary (GEO) and low earth orbit (LEO) satellites covering a range of time periods from 1995 for the earliest sensor through to 2020 for many current and some future sensors.

- A first Merged IR CDR from input bias corrected Level-1 GEO and LEO data at 0.05° and 3-hourly. This system specification will confront the expected requirements for an operational LST climate service.
- A consistent long-term LST CDR of over 20 years from 1995 to 2020 for (A)ATSR-2 through to SLSTR by bridging and filling the gap between (A)ATSR and SLSTR.
- Demonstration of a coherent and open pre-operational End-to-End processing system for delivering the LST ECV Products to the climate user community.
- A strong validation component providing globally representative and consistent in-situ validation and inter-comparison of LST products over all the major land cover types, informing the climate community of the performance of the LST ECV products with respect to the GCOS requirements.
- Sustained support to the surface temperature community through dedicated effort into the well-established International LST and Emissivity Working Group (ILSTE), which is the principle forum of community expertise from data providers to users.

The datasets intended for generation within the project are listed in Table 3-2 and include both single sensor and merged satellite products.

Table 3-2: Datasets to be provided within the LST_cci project (CCI+ Phase 1 - New ECVs: Land Surface Temperature - Technical Proposal, 2017).

Instrument	Satellite(s)	Time Window	Comments
LEO			
AVHRR/3	NOAA 15-19	1998 – 2020	Global area coverage (GAC) (4km)
	Metop A-C	2007 – 2020	EUMETSAT L1B (1km)
(A)ATSR-2	ERS-2	1995 – 2003	
(A)ATSR	Envisat	2002 – 2012	
SLSTR	Sentinel 3A+B	2016 – 2020	
MODIS	Terra	2000 – 2020	
	Aqua	2002 – 2020	
GEO			
SEVIRI	MSG 1-4	2004 – 2020	
Imager	GOES 12-16	2004 – 2020	
JAMI	MTSAT-2	2009 – 2015	
SSM/I	DMSP F-8, 11, 13, 17	1998 – 2020	Microwave, near polar orbiting
Merged Products			
(A)ATSR-MODIS-SLSTR CDR	(A)ATSR-2, (A)ATSR, MODIS, SLSTR	1995 – 2020	(A)ATSR-2 to SLSTR
Merged IR CDR	GEO + LEO IR	2009 – 2020	3 hourly merged GEO + LEO
Experimental IR + MW	Select IR + MW	1 year (2010)	Global diurnal cycle, clear + cloudy

3.2. LST User Requirement Summary

The GlobTemperature Requirements Baseline Document (RBD) (Bulgin & Merchant, 2016) provides a very comprehensive review of LST user requirements for all LST applications from a number of surveys and workshops completed prior to the GlobTemperature project. These requirements have been gathered over a period of 10 years from 2006 to 2016. In this time, significant improvements in the provision of LST data have been made, and so any assumptions made from these requirements must be considered carefully. A brief summary of these results is presented here for completeness, using material provided within the GlobTemperature RBD.

3.2.1. NASA white paper on LST

LST user requirements from the NASA White Paper for LST needs (Hook, 2006) are summarised in Table 3-3 (as reported in Bulgin et al. (2016)). User requirements are defined according to the spatial scales on which the data are used, with global users of LST typically requiring coarser spatial resolution but finer temporal resolution than users of LST data on a local scale.

Table 3-3: Summary of LST user requirements classified according to product scale, adapted from the paper for LST needs (Hook, 2006). Reproduced from (Bulgin & Merchant, 2016).

Sub-product	Spatial Resolution	Temporal Resolution	Accuracy	Precision	Current Data Sources	Future Data Sources
Global	10-20 km	Hourly	0.5 K	0.1-0.3 K	AIRS GOES MSG	CrIS GOES MSG
Regional	1-5 km	2-4 times daily	0.5-1 K	0.1-0.3 K	(A)ATSR AVHRR MODIS	(A)ATSR AVHRR VIIRS
Local	30-100 m	Once every 8-16 days	0.5-1 K	0.1-0.3 K	ASTER Landsat	

3.2.2. NCDC workshop

Table 3-4 provides a summary of user requirements by application from the National Climatic data Centre (NCDC) international workshop (Bosilovich, et al., 2008) (as reported in Bulgin et al. (2016)). Focussing specifically on the 'climate change' application, the target spatial resolution was 5 km and the target temporal resolution was 1-3 hours. Users of LST data for this purpose also recognised the need for longer datasets with overlap between different satellite sensors.

Table 3-4: Applications and associated LST spatial and temporal target resolutions. Reproduced from the NCDC Workshop Report (Bosilovich, et al., 2008).

Application	Target Spatial Resolution (m)	Target Temporal Resolution	Specific Requirements
Climate change	5000	1-3 hours	Sensor overlap
Climate change – urban heat island	50	12 hours - 30 days	Diurnal range
Land/atmosphere feedbacks – soil moisture	50	12 hours – 7 days	Single observation near maximum temperature or diurnal range
Modelling studies – numerical weather prediction	1000	1-3 hours	
Land cover change – land use	50	12 hours – 30 days	Diurnal range
Crop management – agricultural yield and water use	50	1-7 days	Co-located vegetation cover
Water management – national drought assessment	1000	1 hour	Co-located vegetation cover
Water management – regional drought monitoring	50	1-7 days	Co-located vegetation cover

Application	Target Spatial Resolution (m)	Target Temporal Resolution	Specific Requirements
Water management – watersheds and ecological services	50	1-7 days	
Fire monitoring	50	12 hours – 7 days	Sensitivity to high temperatures
Geological applications – lithology and geological hazards	50	12 hours – 7 days	Sensitivity to high temperatures and diurnal range

3.2.3. LST User Exploitation Document

The LST user exploitation document (Ghent, 2011) provides a summary of user requirements from a survey of sixteen researchers. In Table 3-5, some of the key strengths, limitations and desired developments are condensed from the results section of the user exploitation document.

Table 3-5: Key strengths, limitations and desired developments for LST datasets from the LST user exploitation document (Ghent, 2011).

Strengths	Limitations	Desired Developments
• Temporal resolution • Spatial resolution • Accessibility • Global Coverage • Long term availability • Consistency • Quality • Cross comparison • Documentation • Product evolution	• Cloud contamination • Cloud misidentification • Cloud cover assumptions • Accuracy • Error information • Signal saturation • Insufficient validation • Spatial resolution • Temporal resolution • Accessibility • Emissivity information • Emissivity assumptions • Split window algorithms • View angle dependency	• Improved cloud screening • Error information • Uncertainty characterisation • Increased validation • Increased resolution • Emissivity information • Correction of view angle dependency • Common LST algorithms • Near real-time provision of LST • Improved data accessibility • Condensed products • L3 products • Additional channels • Bi-angular retrievals

Here the strengths of LST data are identified as their resolution (spatial and temporal), coverage and availability. Concerns are raised about potential cloud contamination and emissivity assumptions and suggested improvements include further development of cloud detection methods and uncertainty characterisation.

The document also includes a summary of the most widely cited limitations of LST datasets and the improvements required to overcome these limitations. These are presented in Table 3-6.

Table 3-6: Key common areas for development of LST products from the LST user exploitation document (Ghent, 2011).

Topic	Concerns	Improvements
Accuracy	Uncertainties associated with inadequate cloud screening, emissivity and land cover classifications. Regarding cloud screening, the lack of data caused by correct identification of cloud is also a problem, and MW retrievals offer too low spatial resolution to be a feasible alternative	Improved cloud screening algorithms and accounting for aerosols. Multiple observation angles and thermal channels to improve atmospheric correction. Provision of uncertainty estimates is important
Availability	Only a few operational LST products available, with no single source of information as to what products are offered. Data is provided in many formats, and varying ease of access. Often products are not provided over sufficient lengths of time. Time series may be sensor or algorithm specific	Data should be readily accessible with provision of slimmed down products. Increased provision of Level 3 gridded data at a variety of resolutions or tiled by biome. Processing of long time series. Good documentation and common file formats. Improved dialogue between the user community and the product development community
Resolution	Trade-off between spatial and temporal resolutions of satellite instruments tends to be application specific	Spatial resolution of 100m suggested for resolving urban features or agricultural fields, with temporal resolution of weekly, or less. Improved resolution of the diurnal cycle is required with constellation of instruments to reduce gaps between successive cloud free images. Possibility to combine LST products from LEO and GEO satellites to resolve the diurnal cycle of LST at a global scale
Validation	LST products remain insufficiently validated for many reasons, which leads to inconsistencies between datasets	Increased emphasis on validation, regarding both the undertaking of longer validation studies and increase in the number of inter-comparison studies

The four common areas for improvement identified across the sixteen questionnaires are those of accuracy, availability, resolution and validation. The limitations discussed include uncertainties associated with cloud screening, limitation of the availability of operational LST products, inconsistency in product format, trade-off between spatial and temporal resolution and insufficient validation.

3.2.4. Sentinel Convoy for Land Applications

The Sentinel Convoy for Land Applications workshop aimed to identify land surface science needs that could be addressed by sensors in the Sentinel series (Remedios & Humpage, 2012). The applications considered included carbon cycle and fire sensing, urban development, volcanoes, surface energy balance and monitoring biodiversity (Bulgin & Merchant, 2016). Many of the recommendations were focussed on high spatial resolution data with requests for frequent revisit times and good emissivity data.

3.3. LST User Requirements from ESA Data User Element GlobTemperature

3.3.1. ESA Data User Element GlobTemperature

The ESA Data User Element (DUE) GlobTemperature project was a precursor to the LST CCI. The aim of the GlobTemperature project was to generate a series of LST data products from satellite data for a range of LST applications. A prototype LST Climate Data Record (CDR) was developed using data from the Along Track Scanning Radiometer ((A)ATSR) instruments ((A)ATSR-2 and (A)ATSR only), in addition to other single sensor LST products from instruments on both lower earth orbiting (LEO) and geostationary (GEO) satellites. GlobTemperature also pioneered the production of merged LST products from different satellite instruments; both from GEO and LEO satellites independently, and then merging GEO and LEO observations in a single product. This novel approach maximised the spatial coverage of LST data globally whilst also retaining information on the diurnal temperature cycle.

Between November 2014 until January 2018, more than 25 million files were downloaded, representing a volume of ~30 TB.

Within the GlobTemperature project, an extensive survey of user requirements was undertaken along with a detailed synthesis of previous user requirement assessments (as mentioned above). The GlobTemperature user requirements were based on the outcomes of an online survey with eighty participants. Further questions were then asked at a series of user consultation meetings held annually throughout the duration of the project. These were tailored to address specific sub-topics or cover questions that arose within the project (Bulgin & Merchant, 2016).

The user requirements that arose from the GlobTemperature project are summarised in Table 3-7. The letters 'TR' and 'BR' are used to represent threshold and breakthrough requirements respectively. The definition of these terms in this context is as follows:

- **Threshold**: The limit, beyond which, the data is of no use for the given application
- **Breakthrough**: The level at which significant improvement in the given application would be achieved

Table 3-7: Summary of user requirements for LST data from GlobTemperature (Bulgin & Merchant, 2016).

Number	Requirement
REQ-1-TR	Provide LST data at a spatial resolution of 1 km or finer
REQ-2-TR	Provide LST data at a temporal resolution of day/night (12 hours) or less
REQ-3-TR	Provide a dataset of at least 30 years in length
REQ-4-TR	Provide an LST uncertainty budget split into a number of different components e.g. uncertainties from random and systematic effects
REQ-5-TR	Provide LST data with a maximum bias of 1 K
REQ-6-TR	Provide LST data with a precision of 1 K or better
REQ-7-TR	Provide LST data with a stability of 0.3 K per decade or better
REQ-8-TR	Provide cloud screening information with LST data
REQ-9-TR	Provide surface emissivity assumed in the LST retrieval as an ancillary data field
REQ-10-TR	Provide LST data with individual file sizes of 200 MB or less
REQ-11-TR	Provide access to LST data via FTP download
REQ-12a-TR	Provide LST NRT data with timeliness for new observations of 12 hours
REQ-12b-TR	Provide LST long-term data record updates with a timeliness of 1 month for new observations
REQ-13-TR	Provide the timeliness specified in REQ-12-TR for 99 % of observations

Number	Requirement
REQ-14-TR	Provide dataset updates for reprocessing and algorithm development not more than quarterly
REQ-15-TR	Provide LST users with email alerts about data availability and reprocessing
REQ-16-TR	Establish a single file specification covering all metadata requirements
REQ-17-TR	Provide spatially averaged GEO, LEO or combined products in merged data at a resolution of 0.05 degrees or less
REQ-18-TR	Provide temporally averaged GEO, LEO or combined products in merged data at a resolution of 3 hours or less
REQ-19-TR	Provide a detailed description of externally linked datasets within a data portal
REQ-20-TR	Provide links to product specification documents for LST products
REQ-21-TR	Provide LST data with and without gap filling
REQ-22-TR	Provide LST data in both swath and gridded format
REQ-23-TR	Provide gridded LST products with both regular latitude-longitude and equal area projections
REQ-24-TR	For averaged LST products timescales of day/night or 24 hours should be applied
REQ-25-TR	Provide LST data at 0000, 0600, 1200, 1400 and 1800 local time
REQ-26-TR	Provide LST data at an hourly resolution for UTC times
REQ-27-TR	Provide LST data globally
REQ-28-TR	Establish a common nomenclature for the expression of error and uncertainty terms and provide information on the definition of terms
REQ-29-TR	Provide uncertainty information as confidence intervals, estimated root mean square total error or estimated mean and standard deviation of total error
REQ-30-TR	Provide the 95 % confidence interval with confidence level information
REQ-31-TR	Provide detailed flags for quality checks and statistics of data comparison with reference to in-situ validation data
REQ-32-TR	Provide information on 2 m air temperature, aerosol affected pixels, the diurnal cycle, data adjustment, total column water vapour, wind speed and humidity
REQ-33-TR	Provide land cover type, fraction of vegetation cover, albedo assumed in the retrieval and NDVI with LST data
REQ-34-TR	Provide LST products in NetCDF format
REQ-35-TR	Validate uncertainty estimates in LST data
REQ-36-TR	Provide merged datasets globally
REQ-37-TR	Provide descriptions of dataset length and coverage and a link to the main provider web page for data accessed via a portal
REQ-38-TR	Provide dataset validation reports, detailed descriptions of file content and dissemination options and interactive map services for LST data
REQ-39-TR	Provide tools for: a) Data reading and sub-setting b) Data extraction on different grids c) Data compositing d) Generation of match-up datasets e) Data visualisation tools f) Data inter-comparison tools g) Data processing tools h) Data analysis tools i) Trend analysis j) Tools for visualisation and evaluation of data uncertainties and quality

Number	Requirement
	k) Time series extraction
REQ-40-TR	Provide LST data from single sensors, instrument series and merged products
REQ-41-TR	Provide merged data both with and without gap filling
REQ-42-TR	Explore ways of sharing data reading and visualisation tools within the LST community
REQ-43-TR	Provide a data download tool with the ability to screen data as a function of cloud cover prior to download
REQ-44-TR	Provide tiled data for L3, L4 and geostationary satellite products at 10 x 10 degree resolution
REQ-45-TR	Provide cloud flag information as the first bit in the quality control data
REQ-46-TR	For each L3 observation provide information on the percentage of clear-sky pixels
REQ-47-TR	Provide a tool to filter data by day/night at the point of data download
REQ-1-BR	Provide LST data at a spatial resolution of < 1 km
REQ-2-BR	Provide LST data at a temporal resolution of 3 hours or less
REQ-3-BR	Provide LST data with a maximum bias of 0.1 K
REQ-4-BR	Provide LST data with a precision of 0.1 K or better
REQ-5-BR	Provide LST data with a stability of 0.1 K per decade or better
REQ-6-BR	Provide LST NRT data with timeliness for new observations of 6 hours
REQ-7-BR	Provide LST long-term data record updates with a timeliness of 48 hours for new observations

Some of these requirements were addressed by the GlobTemperature project in terms of data formatting, accessibility etc. However, the key GCOS requirements covering the needs of the climate community were not met by GlobTemperature, and can only be addressed by the more robust approach that will be taken in LST CCI.

The LST CCI project will build on this comprehensive list of user requirements across many LST applications, with a particular focus on user requirements for climate applications. It will take a similar approach to gathering and defining requirements, and will include requirements gathered above where appropriate.

3.3.2. GlobTemperature User Requirements for Climate

LST was defined as an ECV within the lifetime of the GlobTemperature project and in order to set appropriate requirements within the GCOS implementation plan, an understanding of user requirements from a climate perspective was required. The fourth GlobTemperature User Consultation Meeting was identified as a good location to assess over-arching LST user requirements for climate in terms of spatial resolution, temporal resolution and dataset length. All participants of the user consultation meeting were asked to complete a short questionnaire from the perspective of LST data users for climate (although many attendees did not in practice use LST data for this purpose). The results of this survey are summarised in Table 3-8.

Table 3-8: Summary of LST user requirements for climate from GlobTemperature (Bulgin & Merchant, 2016).

Requirement Type	Spatial Domain	Requirement Level	Specification
Spatial Resolution	Global	Threshold	0.5°
		Breakthrough	0.05°
	Regional	Threshold	0.25 °
		Breakthrough	0.05 °

Requirement Type	Spatial Domain	Requirement Level	Specification
	Local	Threshold	1 km
		Breakthrough	1 km
Temporal Resolution	Global	Threshold	Monthly
		Breakthrough	Day / night
	Regional	Threshold	Day / night
		Breakthrough	3 hourly
	Local	Threshold	Day / night
		Breakthrough	3 hourly
Dataset Length	Global	Threshold	15 years
		Breakthrough	25 years
	Regional	Threshold	15 years
		Breakthrough	25 years
	Local	Threshold	10 years
		Breakthrough	30 years

It was found that the user requirements were largely dependent on the spatial scale at which the LST data were used and consequently Table 3-8 is divided into responses from data users at global, regional and local scales for each of the LST criteria. Threshold and breakthrough requirements only are reported here, but objective requirements are also available in the GlobTemperature Requirements Baseline Document (Bulgin & Merchant, 2016). For spatial resolution, the threshold requirements ranged between 0.5-0.25° for global and regional data users with a breakthrough resolution of 1 km. For local data users, 1km resolution data was seen also as the threshold level. The threshold level temporal resolution for global data users was monthly and for all others day/night with a breakthrough level of three hourly. For dataset length the threshold level was 10-15 years with 25-30 years as the breakthrough level.

4. Defining Requirements for LST_cci

This section describes the methods used to define LST user requirements for climate applications. Two types of requirements are used in this document: an 'official requirement', where a quantitative analysis is possible with the use of certain exceedance thresholds, and an 'advice note', where a quantitative analysis is not possible, but qualitative information from users indicates a certain need. Advice notes result from both the discussions with the CRG, from free-text comments provided by respondents to the two surveys issued as part of this study and from the 2020 User Workshop and beta product users.

The results from the two surveys conducted in this study are analysed quantitatively wherever possible. Survey questions are analysed according to their format, with a predetermined threshold for issuing a requirement. Questions that ask for a requirement from a scale, such as spatial resolution, are assessed against the 'hard requirement' definition (Table 4-1). In this case, a requirement is issued where 75% of respondents are satisfied. For questions that ask the respondent to select one option from a range of options, a majority requirement can be issued if more than 50% of respondents select one option. Where a question offers multiple options, and respondents can select more than one option, a soft requirement can be issued for any option selected by at least 45% of respondents. These definitions are summarised in Table 4-1, and are chosen to be consistent with methods used in the GlobTemperature Requirements Baseline Document (RBD) (Bulgin & Merchant, 2016).

Table 4-1: Summary of requirement types, definitions and when they are applicable (Bulgin and Merchant, 2016).

Requirement type	Application	Definition
Hard requirement	Questions where the specification is selected from a scale	Requirement must satisfy at least 75% of respondents
Majority requirement	Questions where one option must be selected from a range of options	Requirement must satisfy at least 50% of respondents
Soft requirement	Question where multiple options can be selected from a range of options	Any requirement satisfying at least 45% of respondents

In some cases, questions ask respondents to provide a requirement at the threshold, breakthrough and objective level, following protocol laid out in SST CCI (Rayner, 2017) and used in the GlobTemperature RBD (Bulgin & Merchant, 2016). Definitions of these terms are found in Table 4-2.

Table 4-2: Definitions of threshold, breakthrough and objective level requirements (Rayner, 2017).

Requirement Level	Definition
Threshold	The limit, beyond which, the data is of no use for the given application
Breakthrough	The level at which significant improvement in the given application would be achieved
Objective	The level beyond which, no further improvement would be of value for the given application

At this stage of the project, and for consistency with the GlobTemperature RBD, requirements are only issued for threshold and breakthrough levels, as these are already quite ambitious targets for LST products.

Some of the user needs presented in this document cannot be analysed quantitatively, for example the interviews with the CRG or comments provided in the free text boxes in both the Lisbon and online questionnaires. In these circumstances, the criteria given in Table 4-1 to define a requirement cannot be used and the user need is provided as an advice note.

Requirements issued in this document have the following naming convention:

LST-URD-<*type*>-<*number*>-<*source*>

Where:

- LST-URD indicates that the requirement or advice note has originated from this LST_cci User Requirements Document (URD)
- <*type*> can be one of three options:
  - "REQ": A requirement that must be addressed. When questions are asked in terms of a threshold, breakthrough or objective requirement, the threshold requirement is used here.
  - "OPT": An optional requirement that should be met where possible. This aligns with the breakthrough requirement definition.
  - "ADV": An advisory requirement that should be considered where feasible. These are used where requirements cannot be analysed quantitatively, for example the CRG interviews or free text questions provided in the Lisbon and Online questionnaires.
- <*number*> is a two-digit counter
- <*source*> identifies where the requirement originated from, in this case it can be one or more of four options:
  - 'L': Joint Land Workshop held in Lisbon [Section 5]
  - 'O': Online questionnaire [Section 6]
  - 'I': Interviews with members of the CRG [Section 7]
  - 'U': User interactions, e.g. workshop, other feedback [Section 8 and 9]

The source of the requirement, indicated by a 'L', 'O', 'I' or 'U', therefore also indicates where requirements originate from more than one source. For example, requirement 'LST-URD-REQ-05-LO' is based on information obtained through both the survey issued at the Joint Land Workshop held in Lisbon, and the online survey. The exception here is the source, 'U', which has been added for v2 of this URD (it was not present in URD v1). In this case, the 'U' source has not been added to the ID for requirements that were defined in v1 to preserve traceability for documents citing requirements that were defined before v2 of this URD was produced.

The requirements and advice notes derived in this document are discussed in detail in Section 11 of this document. However, results or statements linked to each requirement or advice note are cited through the analysis sections in square brackets, e.g. [LST-URD-REQ-09-O], to enable traceability in each case.

Throughout this document data quality specifications are discussed in terms of accuracy, precision and stability. The definition of these terms are shown in Table 4-3.

Table 4-3: Definitions of data quality terms: accuracy, precision and stability.

Term	Definition
Accuracy	The degree of conformity of the measurement to the accepted 'true' value. This is theoretical, as the true value cannot be known due to measurement error.
Precision	The closeness of agreement between independent measurements of a quantity under the same conditions.
Stability	The consistency of LST measurements from a given satellite product over time (including a product comprised of multiple satellite instruments)

5. Joint Land Workshop

In June 2018, the International Surface Working Group (ISWG) and Land Surface Analysis Satellite Application Facility (LSA-SAF) jointly held a workshop on Remote Sensing and Modelling of Surface Properties. The meeting was attended by a number of the LST CCI project team and an oral presentation was given on the project. The opportunity was used to gather early user requirements for the project through a short questionnaire for which a dedicated slot was provided to describe the survey. Scientists from a variety of backgrounds attended the meeting and presented work on a range of land-related research. Due to the varied nature of the meeting, not all participants were familiar with satellite derived LST data, or specifically working on climate research. For this reason, a short questionnaire was designed aimed at gathering general concerns and opinions regarding the use of LST datasets irrespective of current or intended use of LST data. As the workshop was small, the responses obtained could be analysed individually, and the results used to guide choice of questions for the more detailed online questionnaire, described in Section 6.

5.1. Satellite LST for Climate Applications Questionnaire

The questionnaire was presented to workshop attendants as a two-sided A4 questionnaire as part of the welcome pack, to be filled in by hand and returned before the workshop closed. The free-hand nature of the questionnaire allowed detail to be provided where necessary, enabling assessment of how well the questions were received and understood, as well as providing context to the responses. The questionnaire as provided to participants is presented below.

5.1.1. Introduction

This questionnaire relates to the **climate requirements** for satellite derived Land Surface Temperature (LST) datasets, as part of the **ESA LST Climate Change Initiative (CCI) project**. We are interested in your answers to this questionnaire whether you have used satellite LST or not. We would like to explore the challenges you experience in using LST, or the reasons why you have not yet used LST, and what might help to improve climate LST user experience.

The option to leave name and contact email address was also given should the participant be willing to be further contacted about the questionnaire.

5.1.2. Current Data Use

The first question was to establish if the participant is a current user of LST:

1. Do you currently use satellite derived Land Surface Temperature (LST) for **climate** applications, or intend to in the next 5 years?
    - Yes, I currently use LST
    - No, but I intend to in the next 5 years
    - No, but I might be interested in using LST if I could find a dataset that meets my needs
    - No, and I have no need to use LST for a climate application at present

5.1.3. LST Applications

Participants were asked to identify one primary climate application for which they either currently use LST, or may consider using LST:

2. Please select a **climate** application on which to base your answers for the following questions. Please only select **one**.
   - If you currently use LST, please select your primary application for LST
   - If you intend to use LST in the future, please select this application
   - If you do not use LST, nor intend to at present, please select an application that you work on for which you can see the strongest link with LST
     - Climate modelling
     - Climate forecasting
     - Model evaluation
     - Model assimilation
     - Detection and attribution of climate change
     - Climate monitoring
     - Climate variability
     - Re-analysis
     - Dataset production
     - Validation / inter-comparison
     - Urban climate
     - Polar climate
     - Surface / atmosphere interactions
     - Evapotranspiration
     - Extreme events
     - Climate impacts
     - Climate services
     - Other (please specify):

5.1.4. Concerns Regarding LST

Participants were offered the opportunity to raise any concerns they have regarding LST data. The objective of this question was to identify key user concerns, and in particular, those that had not already been identified in previous user requirement gathering exercises (Section 3).

3. If you use satellite LST, please explain the main challenges you experience in using the data. If you do not currently use LST data, please explain any concerns about using it, or the reason you have not yet used, or considered using LST.

5.1.5. Requirement Priorities

Due to the physical and technical capabilities of observing LST remotely, requirements for improved datasets can be conflicting, for example having both high spatial and temporal resolution, or providing a product that is of high-quality, but with estimated LSTs where there are gaps due to cloud ('gap-filled'). For this reason, participants were asked prioritise certain requirements for their application.

4. If you use/might use LST, which is more important to your climate application (select **one**)?
    - Product accuracy
    - Long-term data stability
    - Global spatially-complete fields of lower quality
5. If you use/might use LST, which is more important to your climate application (select **one**)?
    - Long-term stable data records with observations at a specific time of day, e.g. 10 am/pm
    - Short-term diurnal information with e.g. hourly observations
6. If you use/might use LST, which would be more useful for your climate application (select **one**)?
    - Near-global daily moderate spatial resolution (e.g. 10 am/pm at 1-5 km)
    - Regional sub-daily coarser spatial resolution (e.g. hourly, 5-10 km)

5.1.6. Merged Products

A question was included to gauge user interest in the provision of merged products, which are part of the current LST CCI project plan.

7. Merging InfraRed (IR) data products from Low Earth Orbiting (LEO) and Geostationary Earth Orbiting (GEO) satellites can help to resolve the diurnal cycle and improve data coverage. If you use/might use LST, would you choose a merged product like this over single sensor products?
    - Yes
    - No

5.1.7. Clouds

A question was included on cloud-related issues, as this is known to be one of the main perceived challenges regarding the use of IR satellite derived LST data (Section 3).

8. If you use/might use LST, are you concerned about cloud effects in infrared LST datasets for climate applications? (select as many as are appropriate)
   - ☐ No
   - ☐ Cloud contamination errors (i.e. errors in LST retrievals due to missed cloud during the cloud-screening process)
   - ☐ Clear-sky bias (i.e. the lack of sampling under cloudy conditions)
   - ☐ Other (please specify):

5.1.8. Error and Uncertainty

Recent years have seen significant development in the provision of uncertainties, pioneered in other projects, such as SST CCI, GlobTemperature and EUSTACE. These projects have provided uncertainty components, where potential error sources have been partitioned according to their correlation properties. This allows users a greater control over the use of uncertainty information in their application, for example, the propagation of uncertainties when re-gridding data on to different spatial and temporal scales. However, not all (potential) users will have been exposed to this concept so question 9 aims to understand what uncertainty data is most likely to be used.

9. Many data come with uncertainty information, what would you most likely use? (select as many as are appropriate, even if you have no interest in using LST)
   - ☐ General statement on accuracy and precision e.g. from validation studies
   - ☐ Quality flags
   - ☐ Uncertainty values per pixel
   - ☐ Uncertainty breakdown into different components (e.g. with different error correlation properties) on a per pixel basis
   - ☐ I am not interested in uncertainty information
   - ☐ Other (please specify)

5.1.9. Ideal Dataset

The final question in the survey asked what users would consider to be the ideal dataset. Providing the opportunity to detail such a product requires participants not just to look at the problems, but how they would like to use the data, and what they would need to do this.

10. If you use/might use LST, what would you want in an ideal satellite LST dataset?

5.2. Results and Analysis

A total of 22 hand-written responses were collected, of these 10 provided a name and contact email address. The results are summarised below.

5.2.1. Current Data Use

Ten respondents to the questionnaire are current users of LST, whilst ten are potential users. Two respondents do not use LST at all (Table 5-1).

Table 5-1: Summary of responses to Q1: Do you currently use satellite derived Land Surface Temperature (LST) for climate applications, or intend to in the next 5 years?

	Total
Currently use LST	10
Intend to use LST in next 5 years	4
Might be interested if right dataset	6
No	2

5.2.2. LST Applications

Twenty-one respondents provided information on their primary climate application. However, despite this question being a single option response, many respondents selected more than one option. Whilst this does provide more information, it creates a greater challenge when attempting to analyse responses by application. Where respondents have selected more than application, this may be indicative overlap between application areas, e.g. evapotranspiration and vegetation/crop monitoring. A few also provided applications that were not listed, these are denoted with an '*' in Table 5-2. The most widespread applications are surface atmosphere interactions, validation and inter-comparison, evapotranspiration, model assimilation, and model evaluation (Table 5-2).

Table 5-2: Responses from Q2 - total number of participants working on each climate application, listed in decreasing number of user selections.

Application	Total
Surface / atmosphere interactions	10
Validation / inter-comparison	9
Evapotranspiration	7
Model assimilation	6
Model evaluation	5
Re-analysis	2

Application	Total
Climate monitoring	2
Vegetation / crop monitoring*	2
Climate modelling	2
Detection and attribution of climate change	1
Climate variability	1
Dataset production	1
Urban climate	1
Extreme events	1
Water cycle*	1
Polar climate	0
Climate impacts	0
Climate services	0
Climate forecasting	0

5.2.3. Concerns Regarding LST

A variety of concerns were raised in response to Q.3, most commonly that IR LST is clear-sky only, there can be discrepancies between sensors, algorithms and products [LST-URD-ADV-06-LI], data access and availability, large uncertainties and accuracy. Fifteen participants provided comments, which are summarised in Table 5-3, full responses can be found in Appendix A.

Table 5-3: Summary of responses to Q.3: If you use satellite LST, please explain the main challenges you experience in using the data. If you do not currently use LST data, please explain any concerns about using it, or the reason you have not yet used, or considered using LST.

Response summary	Number of responses
IR LST data is clear sky only which affects the usability of the data, including temporal consistency	4
There are discrepancies between sensors, algorithms and products	3
Data access and availability. Easy to use API which can query data by spatial and temporal intervals	2
LST data has large uncertainties, especially over certain regions such as arid or semi-arid ecosystems	2
Accuracy	2
Temporal resolution	1
Bias	1
Continuity	1
Regional stability	1
Data characterisation	1
Desire products which combine benefits of LEO and GEO datasets	1
Desire for products which contain LST and other ECVs	1
Desire direct use of radiances, rather than an LST product	1
An LST product which can be treated as an in-situ measurement	1

5.2.4. Requirement Priorities

Three questions were asked in order to gain an understanding of user priorities relating to LST dataset provision. The aim of these questions is to understand what is most important to users, and where the requirements may be technically or physically conflicting. This information can be used in order to focus effort in the LST CCI project to better meet the needs of the user community.

Table 5-4 shows that product accuracy was viewed as more important to participants than long-term stability and globally complete fields of lower quality [LST-URD-REQ-17-L].

Table 5-4: Summary of responses to Q4: If you use/might use LST, which is more important to your climate application (select one)?

Which is more important?	Total
Product accuracy	13
Long-term data stability	6
Global spatially-complete fields of lower quality	3

User need for long-term stable data records versus short-term diurnal information is reasonably balanced, with a slight preference for the latter. It is likely that this is linked to the type of study, and hence there is not one overall preference, but a requirement for both dataset types within the community. A summary of these results can be found in Table 5-5.

Table 5-5: Summary of responses to Q.5: If you use/might use LST, which is more important to your climate application (select one)?

Which is more important?	Total
Long-term stable data records with observations at a specific time of day, e.g. 10 am/pm	10
Short-term diurnal information with e.g. hourly observations	14

Respondents have a marginal priority for near-global moderate spatial resolution datasets compared with regional sub-daily coarser spatial resolution datasets (Table 5-6). As above, this may be dependent on the type of study.

Table 5-6: Summary of responses to Q6: If you use/might use LST, which would be more useful for your climate application (select one)?

Which is more important?	Total
Near-global moderate spatial resolution (e.g. 10 am/pm at 1-5 km)	13
Regional sub-daily coarser spatial resolution (e.g. hourly, 5-10 km)	8

The results in this section of the questionnaire (Table 5-4 to Table 5-6) suggest an overall priority for accurate data over other requirements. There is no clear preference between long-term datasets and short-term high-resolution datasets, or near-global moderate spatial resolution and regional sub-daily with lower spatial resolution datasets, indicating there is a requirement for all these types of data within the community surveyed.

5.2.5. Merged Products

The proposed merged LEO and GEO products are of interest to all but one respondent, to help resolve the diurnal cycle and improve data coverage [LST-URD-REQ-05-LO] (Table 5-7). However, one participant commented that they would only be of interest if the data were proven to be of high quality.

Table 5-7: Summary of responses to Q7: Merging InfraRed (IR) data products from Low Earth Orbiting (LEO) and Geostationary Earth Orbiting (GEO) satellites can help to resolve the diurnal cycle and improve data coverage. If you use/might use LST, would you choose a merged product like this over single sensor products?

	Total
Merged products are of interest	18
Merged products are not of interest	1

5.2.6. Clouds

Most respondents are concerned about cloud effects in infrared LST data products, both due to cloud contamination errors [LST-URD-ADV-33-LOI] and clear-sky bias [LST-URD-ADV-32-LI]. One respondent commented that cloud contamination impacts temporal consistency, which has implications for applications such as vegetation monitoring. A summary of responses to question 8 can be found in Table 5-8.

Table 5-8: Summary of responses to Q8: If you use/might use LST, are you concerned about cloud effects in infrared LST datasets for climate applications? (Select as many as are appropriate).

Are you concerned about cloud effects?	Total
No	2
Cloud contamination errors	16
Clear-sky bias	12
Other	a. Uncertainty due to undetected clouds is still not so well characterised b. Considering a blended LST by merging IR and microwave c. Temporal consistency in order to see day to day changes during the growing season

5.2.7. Error and Uncertainty

The majority of participants indicated interest in a general statement on accuracy and precision [LST-URD-REQ-29-LO], quality flags [LST-URD-REQ-19-L] and per pixel uncertainty values [LST-URD-REQ-24-L], while six respondents showed interest in per-pixel uncertainty breakdown by correlation properties. This is encouraging, given that the provision of uncertainty components partitioned by correlation properties is currently limited to a few public datasets. In general, the number of users interested in per-pixel total uncertainty values is also encouraging and suggests that such information will be useful to users. A summary of responses to question 9 is shown in Table 5-9.

Table 5-9: Summary of responses to Q9: Many data come with uncertainty information, what would you most likely use? (Select as many as are appropriate, even if you have no interest in using LST).

What are you likely to use?	Total
General statement on accuracy and precision	13
Quality flags	14
Per pixel uncertainty values	16
Per pixel uncertainty breakdown by correlation properties	6
Not interested	1
Other	a. Try to provide information about what information was used to provide value at given pixel (sat-based, station, extrapolation, etc.)

5.2.8. Ideal Dataset

When asked to consider an ideal LST product, participants mostly requested high temporal and spatial resolution data [LST-URD-ADV-21-LOI], with spatial resolution of 1 km or less, and well resolved diurnal cycle, although these were not always requested together. Data quality, in particular accuracy was also deemed important. Other common topics are easy, long-term data access [LST-URD-ADV-04-LI], long-term stability, and all-sky datasets [LST-URD-ADV-11-LOI]. A summary of responses to question 10 is given in Table 5-10, full responses can be found in Appendix A - .

Table 5-10: Summary of responses to Q.10: If you use/might use LST, what would you want in an ideal satellite LST dataset?

Response Summary	Number of responses
High temporal resolution, diurnal cycle well resolved	4
High spatial resolution (<1 km, 300 m)	4
High temporal (diurnal cycle resolved) **and** spatial resolution (<1 km)	3
Quality, specifically accuracy (≤0.5 K)	3
Easy, fast, long term data access	2
Long term stability	2
All sky dataset	2
Standard data format	1
Global harmonised LSTs	1
Provision of co-location variables (surface albedo, rough vegetation coverage etc.)	1
Product skilful in capturing human management impacts	1
Consistency with emissivity	1

5.3. Summary

Respondents are very clearly concerned about cloud effects in LST data, which is evident in the answers to questions regarding LST concerns and ideal products. Concerns relate to both **errors due to cloud contamination** [LST-URD-ADV-33-LOI], and **clear-sky bias** [LST-URD-ADV-32-LI]. When asked to prioritise requirements for LST data products, spatially complete datasets were less important than **product accuracy** [LST-URD-REQ-17-L] and stability. However, there is a clear requirement for **all-sky LST** products [LST-URD-ADV-11-LOI] as some respondents consider data gaps due to cloud to be an issue for their application.

The survey respondents were clearly concerned about product accuracy and large uncertainties associated with the LST retrievals. Product accuracy is also a priority over product stability and the provision of spatially complete datasets. The availability of **per-pixel uncertainties** is of interest to users [LST-URD-REQ-24-L] and there is a clear requirement for the provision of **quality flags [**LST-URD-REQ-19-L], and **general statement on accuracy and precision** [LST-URD-REQ-29-LO]. There was significant interest in the provision of uncertainty components partitioned according to correlation lengths scales.

Respondents were concerned about differences in the LST products available from different sensors and algorithms, and require **consistent datasets** [LST-URD-ADV-06-LI]. **Merged products** are clearly of interest [LST-URD-REQ-05-LO] and users generally want products with **higher spatial** [LST-URD-ADV-21-LOI] and temporal resolution compared with what is already available to them. Although less of a priority than accuracy, **long-term product stability** is noted to be important for several respondents [LST-URD-ADV-09-LI].

6. User Requirements Questionnaire

6.1. Context

A comprehensive assessment of LST user requirements was performed as part of the ESA DUE GlobTemperature project (Section 3.3). As part of this process, a survey was issued online with detailed questions enabling a quantitative analysis of a wide range of user requirements, covering all scientific applications of LST. A similar approach has been adopted for LST CCI, building on the requirements gathered in GlobTemperature, but with a focus on LST needs for climate applications.

Many of the questions in the LST CCI online survey build on the heritage of the GlobTemperature questionnaire, and include questions around accuracy, spatial and temporal coverage, provision of uncertainty and data quality information, and data format. A further objective of the survey is to understand how respondents currently use the data and what other types of information they require for their applications. The survey also aims to determine the main barriers and concerns of the respondents in using LST data for climate applications, so that these might be addressed in the LST CCI project as far as practicably possible. Members of the project team were consulted during the process to ensure the information they required from the URD could be obtained.

The survey is comprised of 69 questions, although not all were visible to all respondents as some questions are dependent on the results of other questions asked in the survey. The estimated time for most respondents to complete the survey was around 30 minutes, which was considered to be a reasonable upper limit of time for respondents to commit to the task. The survey was issued through Survey Monkey (www.surveymonkey.co.uk) and was available to users between 17 July and 16 September 2018. Considerable effort was made to publicise the online survey link as widely as possible, to maximise the number of respondents. The survey link was issued through the personal contacts of the project team, including all science staff at the Met Office, the 'Climlist' mailing list, the mailing lists of the CMUG, Satellite Application Facility of Climate Monitoring (CM-SAF) and ISWG. The link was also tweeted through several Twitter accounts, including 'MetOffice_Sci', 'esaclimate', 'sat_metman', and 'Hadobs' (the Hadley Centre observations datasets twitter account). Originally, it was also planned to circulate the survey link via a tailored 'LST' mailing list, which would have been compiled through an interrogation of a list of authors from the Web of Science who had published papers using satellite LST, combined with the complete existing mailing list from the GlobTemperature project. However, owing to the new General Data Protection Regulations (GDPR) that were issued in May 2018, this approach had to be abandoned as both methods were considered to be in breach of the new EU guidelines. Instead, under the guidance of ESA, a new LST_cci mailing list was initiated by contacting all 727 members of the GlobTemperature mailing list and asking if they would like to have their details transferred to the new LST_cci project mailing list. All 'consent' emails have been retained for traceability. Approximately 140 GlobTemperature mailing list members provided their consent to be part of the new LST_cci mailing list before the survey closing date; all these contacts were emailed the link to the online survey. In the survey invitation emails, recipients were also encouraged to forward the link to colleagues to maximise the number of respondents.

A total of 76 online survey responses were received. This is considered to be good response and compares well with 80 responses received for the GlobTemperature online survey. However, it should be noted that the GlobTemperature survey was aimed at all LST users, whereas the LST_cci survey was aimed only at climate users of LST. Responses were received from approximately 28 countries and 47 institutions (only approximate numbers are given here because two different respondents may have provided slightly different names for the same institution or country, e.g. Met Office, and Hadley Centre). Not all respondents completed the survey: 25% of respondents only partially completed the survey but their responses are included in the results reported in this document as they are still considered useful given that most of the questions are independent from others asked in the survey.

The survey was aimed at both current and potential users of LST data for climate applications and this was highlighted in the communications inviting users to complete the questionnaire. It is recognised that some users may not be confident on how to answer questions regarding their requirements, for example, their needs for accuracy and stability of observations. However, it is likely that the ensemble of responses is likely to provide useful information.

6.2. Questionnaire Overview

The online questionnaire is presented in sections for clarity and consistency. A brief description of each section is provided here. Question wording can be found in full in section 6.3 including details such as question logic, wording is also provided with the results in section 6.4.

6.2.1. Introduction

This provides a brief overview of the project and the motivation behind the questionnaire.

6.2.2. General Information

Information such as participants name, organisation and contact details are requested, although none are mandatory. The participant has the option to register for potential future contact relating to the questionnaire, LST CCI project and other related projects.

6.2.3. LST Applications

The climate applications for which the participant uses or may use LST data are determined. The respondent is asked to provide one primary climate application, and to consider only this primary application when responding to the survey. The respondent is also offered the opportunity to indicate other areas of climate research where they may use, or be interested in using LST. This approach enables further analysis of the results by application type, should this be required in future.

6.2.4. Current Data Use

This section asks about current use of data, in particular LST and other CCI ECV products. It is established whether the participant is a current user of LST, or intends to use LST in the future. If they are a current user of data, information is collected about the data they are currently using. The respondent is also asked about their current or planned use of other CCI ECV products.

6.2.5. Concerns Regarding LST

In order to understand the main concerns surrounding use of LST data, respondents are asked to rank their top three concerns from a list of options; there is also a free text box to add their own options. Current users are likely to know the data reasonably well, and whilst the data may be very useful to them, they may have issues they would like to be addressed in future products. Potential users may also have concerns about using LST data, and may be delaying use of LST because of these concerns. It is expected that this information may be helpful in guiding the direction of future work and developments surrounding LST datasets.

6.2.6. Data Specification

This section gathers the technical requirements for the LST data such as spatial coverage, spatial and temporal resolution, observation time, temporal stability, and accuracy. Several questions request threshold, breakthrough and objective requirements, based on the definitions described in Table 4-2.

For data quality, questions are based on the GCOS specification for accuracy, precision and stability.

These questions are followed by asking participants to prioritise different requirements that may be technically or physically incompatible, or difficult to achieve, such as providing a global hourly LST dataset with 1km spatial resolution. This generates a priority order of the requirements, which will help to target effort on dataset production in LST_cci that best meet the needs of users.

Finally, in this section respondents are asked about the level of data processing they require (Level 2, Level 3, etc.). They are also provided with a list of proposed LST_cci products and asked to select those of interest. Definitions of processing levels are shown in Table 6-1, and proposed LST_cci products are summarised in Table 3-2.

Table 6-1: Summary of LST processing levels and their definitions.

Level	Acronym	Description
Level 2	L2	LST on orbit swath at native resolution
Level 3U	L3U	LST mapped on uniform space grid scales from a single orbit
Level 3C	L3C	LST mapped on uniform space-time grid scales, collated over multiple observations
Level 4	L4	Further processed LST data such as model output or data derived from multiple datasets

6.2.7. Data Format and Metadata

This section begins by asking the respondent if they are able to use data in NetCDF format, and then more specifically whether they use, or could use, the GlobTemperature harmonised product format, or the standard CCI data format. The objective of these questions is to establish the most popular file format for climate LST users, and to understand the impacts of providing the LST_cci data in either a format that differs from other CCI products, or from existing GlobTemperature products.

6.2.8. Quality Control

This section asks questions about quality control of data: what information is useful, which quality flags are most important, and whether they would make use of quality level data at the pixel or file level.

6.2.9. Error and Uncertainty

Significant effort was undertaken in GlobTemperature to advance the provision and use of uncertainty information, and to improve user understanding of these data. The GlobTemperature questionnaire highlighted that there were significant discrepancies in the understanding of nomenclature surrounding the topic. Often users do not fully understand the data, or what it truly represents, and hence do not know how to use the data in an appropriate way.

A focus of the questions is on the provision of uncertainty information broken down into components, described in Table 6-2. The components are based on those previously established within the SST CCI and GlobTemperature projects (Bulgin, Embury, Corlett, & Merchant, 2016).

Table 6-2: Description of random, locally systematic, and large-scale systematic uncertainty components.

Uncertainty Component	Description
Random	Uncertainties arising from random effects, which are independent between measured values. These include error sources such as instrument noise and sampling uncertainty in gridded products.
Locally Correlated (/Locally Systematic)	Uncertainties arising from locally systematic effects correlated on local spatio-temporal scales. Examples of error sources include retrieving surface properties through the atmosphere (e.g. local changes in total column water vapour), and in specifying surface properties such as emissivity and land surface type.
Large-scale Systematic	Uncertainties arising from systematic effects correlated on large scales. Error sources include instrument calibration and harmonisation between sensors in a series.

The aim of the questions in this section of the survey is to understand how users currently make use of uncertainty data and whether they could, or be interested in, using uncertainty components. Questions are also asked about any barriers preventing the use of uncertainty information, and what information users require to make full use of these data.

6.2.10. Validation and Inter-comparison

This section asks whether users currently make use of validation information, how they use this information, and any barriers preventing use of validation information. Respondents were also asked what validation information they would like to use, irrespective of current use.

6.2.11. Clouds

Clouds are known to be one of the main concerns surrounding infrared LST data, and there has been significant effort in recent years to develop improved methods for cloud-clearing infrared LST data. The questions in this section seek to establish user preference for cloud identification methods, e.g. binary or probabilistic, and to understand how users might make use of clear-sky probabilities if this information is provided with infrared LST retrievals.

6.2.12. Comments

Participants were given the opportunity to leave any further comments relating to LST data requirements before submitting the survey.

6.3. Questionnaire

This section details the online questionnaire, including sections, question type and layout, and logic. Some notes on the survey are provided below:

- '*' Indicates a mandatory question
- Open-ended questions are offered with a free-text box
- For questions that require the respondent to select one option only, an 'other' option is provided should their required option not be provided. This is provided with a text box to allow clarification, but cannot be filled in if any other options are selected.
- When multiple options could require clarification, or a participant may want to select one or more provided options and provide additional information, an 'other' option is provided as a comment box. This can be filled in by anyone answering the question, regardless of their selections.
- ○ Denotes a multiple choice question, for which only one answer is allowed
- ☐ Denotes a checkbox question, for which as many options as desired can be selected
- Question logic is applied to certain parts of the survey to avoid participants being asked unnecessary questions. Answers that alter the question flow are denoted with a superscript number, with a note at the bottom of that question explaining where the participant would be taken next.
- Each text box represents a separate page of the survey

6.3.1. Introduction

The Land Surface Temperature (LST) CCI project is funded by the European Space Agency (ESA) as part of the Agency's Climate Change Initiative (CCI) Programme. It aims to deliver a significant improvement on the capability of current satellite LST data records to meet the challenging Global Climate Observing System (GCOS) requirements for climate applications and realise the full potential of long-term LST data for climate science.

Accurate knowledge of LST plays a key role in describing the physics of land-surface processes at regional and global scales as they combine information on both the surface-atmosphere interactions and energy fluxes within the Earth Climate System. LST provides a metric of surface state when combined with vegetation parameters and soil moisture, and is one of the drivers of vegetation phenology. Furthermore, LST is an independent temperature dataset for quantifying climate change complementary to the near-surface air temperature Essential Climate Variable (ECV) based on in situ measurements and reanalyses.

The team will use data from a variety of satellites to provide an accurate view of temperatures across land surfaces globally over the past 20 to 25 years. This will involve developing innovative techniques to merge data from different satellites into combined long-term satellite records for climate. These will all be evaluated by scientists working at leading climate centres.

If you would like to read more about ESA's Climate Change Initiative (CCI) you can find out more here: http://cci.esa.int/

This questionnaire aims to understand the requirements of your climate application for LST data, with a particular focus on what is required for ongoing developments in the next 5-10 years.

6.3.2. General Information

The information entered below will be stored by the core LST CCI project team in a password-protected document for the duration of the project. The information you provide us with may be shared with other members of the LST CCI project team and ESA where this is beneficial to the project. We will not share this information with anyone outside of the core LST CCI project team, or use the information you provide for any purpose, other than activities that are directly related to the LST CCI project, without asking your permission first. The information you have entered will be transferred to a new LST CCI core project team, should this change at any point during the lifetime of the project, or the core project team for any direct LST CCI follow-on project, with the aforementioned restrictions and storage requirements. The information will be deleted by the original project team following transfer unless you give your express permission for this information to be retained by the original project team. You may request that the information you have provided below be removed from the project team database at any time by emailing: crg.lst-cci@acri-st.fr

1. If you are happy for your responses to be attributed to you, please provide your full name:

2. What is the name of the institution you work at?

3. In which countries do you currently work?

4. Would you be interested in being contacted about any of the following?
   - ☐ Follow up on your survey responses
   - ☐ Follow up, short questionnaires to clarify requirements for this project
   - ☐ Workshop on LST user requirements held at the Met Office in the UK in 2020
   - ☐ New LST CCI data that you may wish to use (single sensor data products from Low Earth Orbiting and Geostationary Earth Orbiting satellites; climate data records from InfraRed (IR) and Microwave (MW) instruments; merged IR products to resolve the diurnal cycle; experimental IR + MW merged product)
   - ☐ Other aspects of this project
   - ☐ Related / future LST projects
   - ☐ Related CCI projects

5. If you are happy for us to make contact about your selections above by email, please confirm your email address:

6. If you are happy for us to follow up your survey responses by telephone, please supple a contact number:

6.3.3. LST Applications

7. Please select the ***primary*** climate application from the list for which you use or intend to use LST data. **This is the application we would like you to have in mind when you answer the rest of the survey.** Secondary applications / interests can be selected in the following question. You may also submit multiple responses for different primary applications if you wish.*
    - Climate modelling
    - Climate projections
    - Model evaluation
    - Model assimilation
    - Detection and attribution of climate change
    - Climate monitoring
    - Climate variability
    - Re-analysis
    - Dataset production
    - Validation / inter-comparison
    - Urban climate
    - Polar climate
    - Surface / atmosphere interactions
    - Evapotranspiration / vegetation or crop monitoring
    - Water cycle
    - Extreme events
    - Climate impacts
    - Climate services
    - Regional climate
    - Continental climate
    - Climate in a particular country
    - Local scale climate (such as city / cities, river basin, etc.)
    - Other (please specify):

8. Please indicate from the list below if you use LST data for any other applications. Multiple boxes can be checked, but **please have in mind the primary application selected above when completing the remainder of the survey.**
   - ☐ Climate modelling
   - ☐ Climate projections
   - ☐ Model evaluation
   - ☐ Model assimilation
   - ☐ Detection and attribution of climate change
   - ☐ Climate monitoring
   - ☐ Climate variability
   - ☐ Re-analysis
   - ☐ Dataset production
   - ☐ Validation / inter-comparison
   - ☐ Urban climate
   - ☐ Polar climate
   - ☐ Surface / atmosphere interactions
   - ☐ Evapotranspiration / vegetation or crop monitoring
   - ☐ Water cycle
   - ☐ Extreme events
   - ☐ Climate impacts
   - ☐ Climate services
   - ☐ Regional climate
   - ☐ Continental climate
   - ☐ Climate in a particular country
   - ☐ Local scale climate (such as city / cities, river basin, etc.)
   - ☐ Other (please specify):

6.3.4. Current Data Use

These questions are to understand the types of data you currently use for your primary application.

9. Do you currently use LST data for climate-based applications?*
   - ○ I am a current user
   - ○ I am not a current user, but expect to use LST data in the next 5 years[1]
   - ○ I have no plans to use LST at the moment, but might be interested in using LST at some point in the future[1]

[1] Go to Q.13

10. Which satellite LST datasets do you currently use for your primary application?
    - ☐ (A)ATSR
    - ☐ SLSTR
    - ☐ AVHRR
    - ☐ MODIS (Terra / Aqua)
    - ☐ VIIRS
    - ☐ LandSat
    - ☐ ASTER
    - ☐ Meteosat (MVIRI / SEVIRI)
    - ☐ GOES (Imager / ABI)
    - ☐ MTSAT / Himawari (JAMI / IMAGER / AHI)
    - ☐ AMSR(-E) / AMSR-2
    - ☐ SSM/I

11. What level of LST data do you use?
    - ☐ LST on orbit swath at native resolution (Level 2)
    - ☐ LST mapped on uniform space grid scales from a single orbit (Level 3U)
    - ☐ LST mapped on uniform space-time grid scales, collated over multiple observations (Level 3C)
    - ☐ Further processed LST data such as model output or data derived from multiple datasets (Level 4)

12. Do you use any of the **GlobTemperature** datasets for your primary application?
    - ☐ No
    - ☐ (A)ATSR-2 Level 2
    - ☐ (A)ATSR-2 Level 3
    - ☐ (A)ATSR Level 2
    - ☐ (A)ATSR Level 3
    - ☐ (A)ATSR CDR Level 3
    - ☐ MODIS (Terra + Aqua) Level 2
    - ☐ SLSTR Level 2
    - ☐ SLSTR Level 3
    - ☐ AMSR(-E) Level 2
    - ☐ SSM/I Level 2
    - ☐ MTSAT Level 2
    - ☐ SEVIRI Level 2
    - ☐ GOES Level 2
    - ☐ Himawari Level 2
    - ☐ Merged Geostationary Earth Orbit (GEO) Level 4
    - ☐ Merged Low Earth Orbit (LEO) Level 4
    - ☐ Merged GEO + LEO Level 4

13. Do you use any of the other CCI Essential Climate Variable (ECV) data products for your primary application?*
    - ☐ No[1]
    - ☐ Aerosol
    - ☐ Cloud
    - ☐ Fire
    - ☐ Greenhouse Gasses
    - ☐ Glaciers
    - ☐ Antarctic Ice Sheet
    - ☐ Ice Sheets Greenland
    - ☐ Land Cover
    - ☐ Ocean Colour
    - ☐ Ozone
    - ☐ Sea Ice
    - ☐ Sea Level
    - ☐ Soil Moisture
    - ☐ SST

[1] Go to Q.15

14. Do you use these in conjunction with LST data?
    - ○ Yes
    - ○ No

15. Do you intend to use any of the new CCI ECV datasets?
    - ☐ No
    - ☐ Sea Surface Salinity
    - ☐ Sea State
    - ☐ Lakes
    - ☐ Above Ground Biomass
    - ☐ Permafrost
    - ☐ Water Vapour
    - ☐ Snow

6.3.5. Concerns Regarding LST

16. Please rank the top 3 main concerns or barriers (if any) you experience using LST (with 1 being the most important, and 3 the least):

	1	**2**	**3**
It is not clear to me exactly what satellite LST represents / I cannot relate satellite LST with other surface temperature data that I am using	○	○	○
Dataset time series are not long enough	○	○	○
Spatial resolution is too low for my application	○	○	○
Temporal resolution is too low for my application	○	○	○
Stability is unknown / too poor for my application	○	○	○
There is a lack of appropriate or accurate uncertainty information	○	○	○
Satellite derived LST measurements are currently expected to be within 1-3 K of the 'true' LST, this is too large for my application	○	○	○
InfraRed datasets only include cloud-free LST's and are therefore spatially incomplete	○	○	○
InfraRed datasets only include cloud-free LST's and therefore my analysis of these data may be clear-sky biased	○	○	○
Retrieved LST's may be contaminated with cloud, and therefore contain large errors	○	○	○

Other (please specify):

6.3.6. Data Specification

These questions ask about your requirements of LST data for **climate** purposes in terms of coverage, resolution and quality.

Please think about what is required to enable developments in your work in the next 5 - 10 years.

17. Over what spatial domain do you require LST data for your primary application?
    - ○ Globally
    - ○ Equatorial
    - ○ Mid Latitudes
    - ○ Polar Regions
    - ○ Continent (please specify)
    - ○ Country (please specify)
    - ○ Local scale (such as a city or cities) (please specify)

    Other (please specify): ____________________

18. At what time of day do you require LST observations (tick as many time slots as are applicable)? In the following question, you can specify whether these times are UTC or local time.

☐ 00:00	☐ 09:00	☐ 18:00
☐ 01:00	☐ 10:00	☐ 19:00
☐ 02:00	☐ 11:00	☐ 20:00
☐ 03:00	☐ 12:00	☐ 21:00
☐ 04:00	☐ 13:00	☐ 22:00
☐ 05:00	☐ 14:00	☐ 23:00
☐ 06:00	☐ 15:00	☐ All
☐ 07:00	☐ 16:00	
☐ 08:00	☐ 17:00	

19. Are the times selected above UTC or local time?
    - ○ UTC
    - ○ Local Time

For the following questions, please indicate the threshold, breakthrough and objective levels specific to your primary application using the definitions below.

Please think about the fundamental requirements of your primary application, as opposed to any specific instruments or datasets you may have in mind, when answering these questions.

Threshold: The limit, beyond which, the data is of no use for the given application.

Breakthrough: The level at which significant improvement in the given application would be achieved.

Objective: The level beyond which, no further improvement would be of value for the given application.

20. What is the minimum length of dataset that you require?

	< 1 year	1 year	3 years	5 years	10 years	20 years	30 years	> 30 years
Threshold	○	○	○	○	○	○	○	○
Breakthrough	○	○	○	○	○	○	○	○
Objective	○	○	○	○	○	○	○	○

21. At what spatial resolution do you require LST data?

	< 1 km	1 km	4 km	0.05 °	0.1 °	0.25 °	0.5 °	1 °	> 1°
Threshold	○	○	○	○	○	○	○	○	○
Breakthrough	○	○	○	○	○	○	○	○	○
Objective	○	○	○	○	○	○	○	○	○

22. At what temporal resolution do you require LST data? (Note that day / night, 5 day, weekly and monthly resolutions would include one daytime and one nighttime LST acquisition, whilst a 24 hour product would only have one acquisition in that time period.)

	< 1 hour	1 hour	3 hours	6 hours	Day / Night	24 hours	5 days	Weekly	Monthly
Threshold	○	○	○	○	○	○	○	○	○
Breakthrough	○	○	○	○	○	○	○	○	○
Objective	○	○	○	○	○	○	○	○	○

Please indicate the threshold, breakthrough and objective levels specific to your primary application using the definitions below.

Threshold: The limit, beyond which, the data is of no use for the given application.

Breakthrough: The level at which significant improvement in the given application would be achieved.

Objective: The level beyond which, no further improvement would be of value for the given application.

23. What are your requirements for LST Accuracy – the degree of conformity of the measurement to the accepted 'true' value? (Note this is theoretical, as the true value cannot be known due to measurement error.)

	0.3 K	0.5 K	1 K	2 K	3 K	5 K
Threshold	○	○	○	○	○	○
Breakthrough	○	○	○	○	○	○
Objective	○	○	○	○	○	○

24. What are your requirements for LST Precision – closeness of agreement between independent measurements of a quantity under the same conditions?

	0.3 K	0.5 K	1 K	2 K	3 K	5 K
Threshold	○	○	○	○	○	○
Breakthrough	○	○	○	○	○	○
Objective	○	○	○	○	○	○

25. What are your requirements for LST Stability – consistency of LST measurements from a given satellite product over time (kelvin per decade)?

	0.1 K	0.2 K	0.3 K	0.5 K	1 K	2 K	3 K
Threshold	○	○	○	○	○	○	○
Breakthrough	○	○	○	○	○	○	○
Objective	○	○	○	○	○	○	○

26. Which is more important for your primary application?
    - ○ High temporal resolution
    - ○ High spatial resolution

27. Which is more important for your primary application?
    - ○ High quality data (accuracy, precision and stability)
    - ○ Spatially complete fields

28. Which is more important for your primary application?
    - ○ High data resolution
    - ○ Dataset length

29. What level of LST data do you require?
    - ☐ LST on orbit swath at native resolution (Level 2)
    - ☐ LST mapped on uniform space grid scales from a single orbit (Level 3U)
    - ☐ LST mapped on uniform space-time grid scales, collated over multiple observations (Level 3C)
    - ☐ Further processed LST data such as model output or data derived from multiple datasets (Level 4)

30. Please select any dataset types you might be interested in:
    - ☐ LST from InfraRed (IR) Low Earth Orbiting (LEO) satellites (Near-global, moderate spatial and temporal resolution)
    - ☐ LST from IR Geostationary Earth Orbiting (GEO) satellites (Regional, higher temporal resolution, lower spatial resolution)
    - ☐ LST from Microwave (MW) LEO satellites (LST provided in cloudy conditions, lower spatial resolution and quality)
    - ☐ Merged LST from multiple IR LEO satellite datasets to create a long running, near-global Climate Data Record (CDR)
    - ☐ Merged IR LEO and GEO datasets (Resolved diurnal cycle, improved data coverage)
    - ☐ Merged IR and MW (Provides all-weather spatially complete LST, with lower resolution and quality, for one year only)

6.3.7. Data Format and Metadata

In the GlobTemperature project, a harmonised data format was developed based on generic user requirements for LST data. The data were provided in CF-compliant NetCDF format in two files for each data acquisition. The primary 'LST' file contained the retrieved LST data, uncertainties and quality information, whilst an additional auxiliary 'AUX' file contained information on the surface property specification and atmospheric properties. The reasoning behind this was to enable users to avoid downloading significant additional auxiliary data where this was not required, reducing file sizes.

31. Data products within the LST CCI project will be provided in NetCDF format, would you be able to use these for your application right now?
    - ○ Yes[1]
    - ○ No

[1] Go to Q.34

32. What are the barriers preventing you using NetCDF data?
    - ☐ I've never used NetCDF format before
    - ☐ I don't have access to software which can read NetCDF
    - ☐ Other (please specify):

33. Are there ways in which the data providers could help you overcome these barriers?

The standard CCI data format is slightly different to the GlobTemperature harmonised format, and it is possible the LST CCI data will be provided in either of these formats. The differences relate to:

- The filename convention
- Specification of the global metadata – CCI specification includes more global metadata
- Naming and number of dimensions – GlobTemperature 'AUX' files have more dimensions
- Number of files and file sizes – CCI data is all contained within one file, whereas GlobTemperature format uses two separate 'LST' and 'AUX' files

We want to understand what the impact of using either format would be on you.

34. Do you currently use, or intend to use, data from the GlobTemperature project?*
    - ○ Yes
    - ○ No[1]
    - ○ Maybe

[1] Go to Q.37

Differences between GlobTemperature and CCI ECV data product formats relate to:

- The filename convention
- Specification of the global metadata – CCI specification includes more global metadata
- Naming and number of dimensions – GlobTemperature 'AUX' files have more dimensions
- Number of files and file sizes – CCI data is all contained within one file, whereas GlobTemperature format uses two separate 'LST' and 'AUX' files

35. As a current or future user of GlobTemperature data, what is the likely impact of incorporating a product that conforms to the CCI data standards, with the differences described above?
    - o None
    - o Very little – I'd have to change one or two lines of code or similar
    - o Reasonable – I'd have to make some changes to make use of the data
    - o Significant – I'd have to make major changes in order to incorporate this data
    - o Other (please specify):

36. Which one of the possible changes from the GlobTemperature harmonised format would have the largest impact?
    - o Change in filename convention
    - o Change in global metadata specification
    - o Naming and number of dimensions
    - o Number of files and file sizes

37. Do you currently use, or intend to use, data from the ESA CCI project (LST or otherwise)?*
    - o Yes
    - o No[1]
    - o Maybe

[1] Go to Q.40

Differences between GlobTemperature and CCI ECV data product formats relate to:

- The filename convention
- Specification of the global metadata – CCI specification includes more global metadata
- Naming and number of dimensions – GlobTemperature 'AUX' files have more dimensions
- Number of files and file sizes – CCI data is all contained within one file, whereas GlobTemperature format uses two separate 'LST' and 'AUX' files

38. As a current or future user of CCI ECV products, what is the likely impact of incorporating a product that conforms to the GlobTemperature harmonised format, with the differences described above?
    - None
    - Very little – I'd have to change one or two lines of code or similar
    - Reasonable – I'd have to make some changes to make use of the data
    - Significant – I'd have to make major changes in order to incorporate this data
    - Other (please specify):

39. Which one of the possible changes from the CCI standard format would have the largest impact?
    - Change in filename convention
    - Change in global metadata specification
    - Naming and number of dimensions
    - Number of files and file sizes

6.3.8. Quality Control

In the GlobTemperature harmonised format, basic quality control flags are provided with all data, which consist of:

- Day / night flag
- Summary cloud flag
- Summary confidence flag (indicates one or more possible issues with pixel e.g. pixel produced but calibration suspect, pixel saturation, etc.)
- Aerosol flag
- Land flag

40. Please rank the order of importance of these flags for your application (with 1 being the most important and 5 being the least important):

	1	2	3	4	5
Day / night flag	o	o	o	o	o
Summary cloud flag	o	o	o	o	o
Summary confidence flag	o	o	o	o	o
Aerosol flag	o	o	o	o	o
Land flag	o	o	o	o	o

41. Please select any additional flags that you would find useful:
    - ☐ Snow / ice
    - ☐ Water body present in part of pixel
    - ☐ Individual confidence flags (e.g. pixel saturation, calibration suspect, blanking pulse, etc.)
    - ☐ Other (please specify):

Quality Level data can also be provided as a numeric value representing the following options:

- No data
- Bad data
- Worst quality
- Low quality
- Acceptable quality
- Best quality

42. Would you make use of Quality Level data **on a pixel level** should it be provided?
    - o Yes
    - o No

43. Would you make use of Quality Level data **on a file level** should it be provided?
    - o Yes
    - o No

6.3.9. Error and Uncertainty

Any measurement made has an associated error i.e. the difference between the given measurement and the actual measurement. This error arises because no measurement is perfect, and errors can be the product of things such as instrument problems, human error or the measurement methodology. In the context of LST retrieval, sources of potential error occur both within the satellite measurement and the retrieval process.

In many cases, the error in a measurement is unknown (if we knew the error then we could correct for it). Therefore it is appropriate to provide some measure with the data that relates to the distribution of errors that might reasonably be attributed to the measurement. This measure is called the uncertainty – it characterises the spread of errors that could reasonably be attributed to the measurement.

Error and uncertainty should not be confused with dataset accuracy and precision. These are defined as follows:

- Accuracy is the closeness of agreement between a measured LST dataset and a true LST
- Precision is the closeness of agreement that would be obtained if multiple measurements of a single LST were made under identical conditions

In practice, accuracy is very difficult to determine as all measurements have some associated error (as discussed above), so we do not have a true LST.

In order to construct a complete uncertainty budget for a retrieved LST, each of the error sources in the measurement and retrieval process needs to be identified and the distribution characterised, so that the resulting uncertainty can be propagated through the retrieval process to provide an uncertainty estimate for each datum.

Sources of error can be grouped into three categories according to their correlation length scales:

- **Random** – uncertainties arising from random effects, which are independent between measured values. These include error sources such as instrument noise and sampling uncertainty in gridded products.
- **Locally systematic** – uncertainties arising from locally systematic effects correlated on local spatio-temporal scales. Examples of error sources include retrieving surface properties through the atmosphere (e.g. local changes in total column water vapour), and in specifying surface properties such as emissivity and land surface type.
- **Large-scale systematic** – uncertainties arising from systematic effects correlated on large scales. Error sources include instrument calibration and harmonisation between sensors in a series.

Projects such as Sea Surface Temperature (SST) CCI, EU Surface Temperature for All Corners of Earth (EUSTACE), and ESA DUE GlobTemperature have provided this uncertainty information in a common format, giving the total uncertainty budget, and a breakdown of the uncertainty components into the three categories specified above.

These questions are to understand your current use of uncertainty information.

44. Do you use uncertainty information?*
    - ○ Yes[1]
    - ○ No

[1] Go to Q.46

45. What are the barriers in preventing you from using it?[1]
    - ☐ I don't understand the uncertainty data
    - ☐ The documentation isn't clear on how to use these data
    - ☐ The data I require is not available (please specify in the 'other' box)
    - ☐ I don't think it's needed for my work

    Other (please specify):

[1] Go to Q.54

46. Have you used a dataset that is provided with uncertainty information broken down into different components: random, locally systematic, and large scale correlated uncertainties?*
    - ○ Yes
    - ○ No[1]

[1] Go to Q.50

47. Which components have you made use of in your work?*
    - ○ Total uncertainty only[1]
    - ○ Uncertainty components
    - ○ None[1]

[1] Go to Q.49

48. Which of the uncertainty components did you use?[1]
    - ○ Total uncertainty
    - ○ Uncertainty due to random errors
    - ○ Uncertainty due to locally systematic errors
    - ○ Uncertainty due to large scale systematic errors

[1] Go to Q.50

49. What were the barriers preventing you from using the uncertainty components?
    - ☐ I don't understand how to use the individual components
    - ☐ The documentation on how to use the uncertainty breakdown is unclear
    - ☐ I don't think these are needed for my work
    - ☐ Other (please specify):

50. Do you generate higher level products from the LST data provided, for example averaging over longer time periods or larger spatial scales?*
    - ○ Yes
    - ○ No[1]

[1] Go to Q.52

51. Do you propagate the relevant uncertainty information in this process?
    - ○ Yes
    - ○ No

52. Do you assimilate LST data into a model or other system?*
    - ○ Yes
    - ○ No[1]

[1] Go to Q.54

53. Do you propagate the relevant uncertainty information in this process?
    - ○ Yes
    - ○ No

These questions aim to understand what you would like to use uncertainty information for, irrespective of your current use, and what you would need to do this.

54. For what purposes would you like to use uncertainty data?
    - ☐ Selecting which data values to use
    - ☐ To explain scientific results
    - ☐ To propagate uncertainty when calculating average or other values from the data
    - ☐ To propagate uncertainty when combining data sources
    - ☐ Data assimilation
    - ☐ I do not wish to use uncertainty information
    - ☐ Other (please specify):

55. Would you like uncertainty estimates broken down into different components (random, locally systematic and large-scale systematic) in addition to a total uncertainty?*
    - ○ Yes[1]
    - ○ No

[1] Go to Q.57

56. Please comment on why you do not want uncertainty estimates broken down into components:[1]

[1] Go to Q.58

57. Which components would you need to use?
    - ○ Total uncertainty
    - ○ Uncertainty due to random errors
    - ○ Uncertainty due to locally systematic errors
    - ○ Uncertainty due to large scale systematic errors

58. What documentation would you require to make use of uncertainty data broken down into components?
    - ☐ Description
    - ☐ Worked examples

    Other (please specify):

6.3.10. Validation and Inter-comparison

As part of the CCI LST project, products will be independently validated against in-situ reference data and inter-compared with external LST datasets. The LST uncertainties will also be validated using established techniques.

59. Do you consider validation and inter-comparison results produced by the data providers in your work (either using results to guide product selection or directly incorporating results)?*
    - ○ Yes
    - ○ No[1]

[1] Go to Q.61

60. For what purpose do you use validation and inter-comparison data?[1]
    - ☐ To select which data products to use
    - ☐ To better understand the data
    - ☐ I incorporate the results into my work (e.g. accuracy and precision data)
    - ☐ Other (please specify):

[1] Go to Q.62

61. What are the barriers preventing you from using validation and inter-comparison data?
    - ☐ I don't know how to incorporate it into my work
    - ☐ I need more information to be able to incorporate it (please specify below)
    - ☐ I don't think it will benefit my work
    - ☐ Other (please specify):

62. What validation and inter-comparison information would be most useful for your primary application?
    - ☐ An overview of the best performing products in different scenarios
    - ☐ A summary of accuracy and precision per product
    - ☐ Inter-comparison between LST products
    - ☐ Comparison of satellite LST with in-situ measurements
    - ☐ Time series analysis
    - ☐ Other (please specify):

6.3.11. Clouds

Bayesian and probabilistic methods of identifying cloud use the Bayesian equation, or a 'naïve-Bayes' algorithm to calculate a clear-sky probability for each LST retrieval. The advantages of this approach are the possibility of consistent application to data from different sensors, and by providing a clear-sky probability, the potential to have application-specific cloud screening.

63. Would you prefer a consistent approach to cloud-clearing across sensors, or a 'best for each sensor' approach, even if this means changes between sensors?
    - Consistent approach
    - Best for each sensor

By providing a clear-sky probability for each pixel, the user can determine the best threshold to use for their specific application, as opposed to having a summary cloud mask.

64. Do you prefer LST data to be pre-screened for cloud-contaminated pixels, or would you prefer to apply a bitmask or probability screening yourself?
    - Pre-screened
    - Apply mask myself

65. Would you prefer a pre-defined binary cloud mask or clear-sky probabilities to enable you to define your own cloud mask (or both)?
    - Binary cloud mask
    - Clear-sky probability
    - Both

66. If you were provided with clear-sky probabilities, how would you use this data to cloud clear LST data?
    - I would pick a known threshold, or one from the literature – this would be the same for all applications
    - I would pick a threshold known to be appropriate for my application – this could vary between applications
    - I would find the most appropriate value myself keeping in mind the data and my application – this could vary between applications, case studies and datasets
    - I don't know
    - Other (please specify):

67. If you were to choose a clear-sky probability threshold to define a cloud-contamination mask for your primary application, what value do you feel might be appropriate?
    - 50 %
    - 60 %
    - 70 %
    - 80 %
    - 85 %
    - 90 %
    - 95 %
    - 99 %
    - Other (please specify):

68. If clear-sky probabilities were provided instead of a binary mask, what information would you need to be able to make use of them?
    - ☐ Descriptions
    - ☐ Worked examples
    - ☐ Other (please specify):

6.3.12. Comments

Thank you for your time, your responses will help us to understand the requirements for LST datasets for climate applications. These responses will feed directly into the LST CCI project to define the user requirements that feed into the specification of data products and formats.

69. Do you have any further comments of LST data requirements for climate before exiting and submitting your responses to the survey?

6.4. Results and Analysis

This section provides general information regarding the responses received from the online survey, and reports on the results of the questionnaire for each section of the survey.

6.4.1. General Information

The questionnaire was open for two months, gathering a total of 76 responses with a completion rate approximately 75%. Due to question logic applied to avoid asking unnecessary questions, not all participants saw all questions, but only those choosing to skip a question or leave the survey early affect the completion rate. All responses are retained and analysed regardless. Where a response is denoted with an '*', the response was not offered in the questionnaire and originates from a comment left by a participant.

Table 6-3 provides the affiliation of the survey respondents who were willing to provide this information and shows the global reach of the survey. The names of respondents to the survey are not provided in this document owing to GDPR.

Table 6-3: Summary of responses to the following questions: Q.2: What is the name of the institution you work at?; Q.3: In which countries do you currently work?

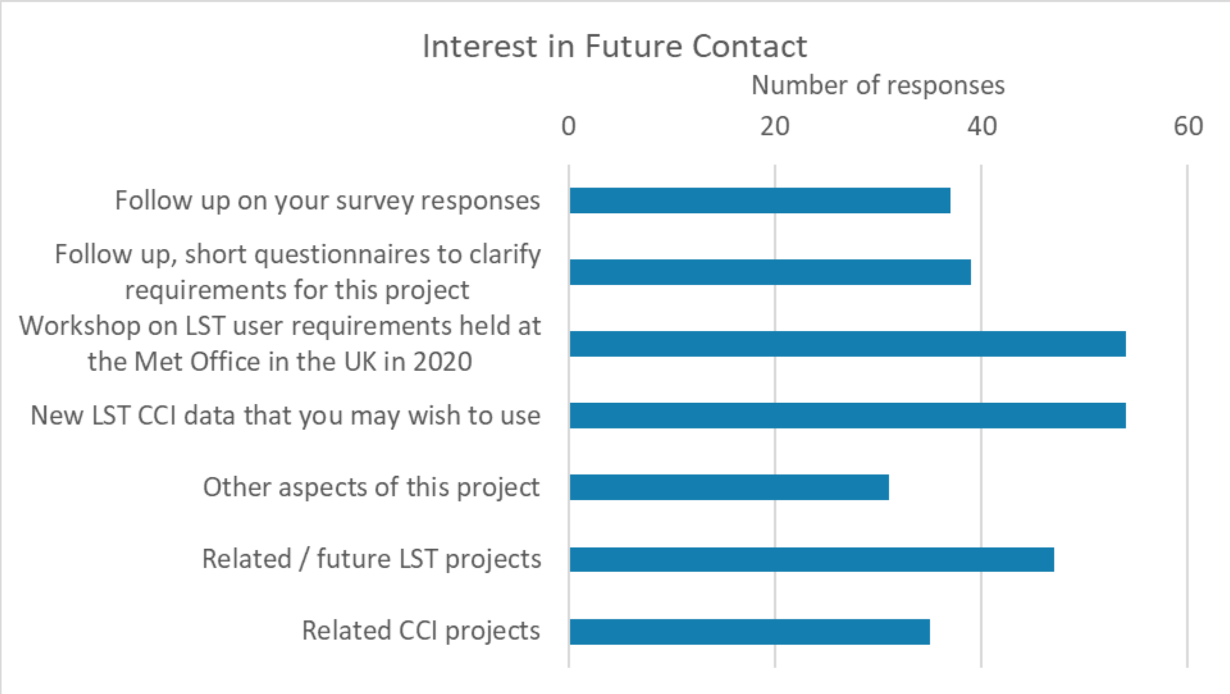
Institution	Country	Count
Forschungszentrum Jülich GmbH	Germany	2
Center for Remote Sensing of Land Surfaces (ZFL)	Germany	1
University of Bonn	Germany	1
Institute of Geodesy and Cartography	Poland	1

Institution	Country	Count
Sun Yat-sen University	China	1
University of York	Sweden, Norway	1
Met Office	UK, Brazil	12
Universitat de València	Spain	1
University of Bern	Switzerland	1
Politecnico di Milano	Italy	1
University of Reading	Developing countries (Africa and globally), Europe	1
Vlaamse Instelling voor Technolohisch Onderzoek (VITO) (Flemish Institute for Technological Research)	Belgium	1
Centre d'Etudes Spatiales de la Biosphere (CESBIO)	France, Tunisia, Morocco, India	3
University of Electronic Science and Technology of China	China	1
Univeristy of Ottawa	Canada	1
National Centre for Earth Observation (NCEO)	UK	1
State university of Rio de Janeiro	Brazil	1
Universiry of Cape Town	Southern Africa	1
Instituto Portugues do Mar e da Atmosfera (IPMA), LandSAF	Portugal	1
Max Plank Institute (MPI) Biogeochemistry	Germany	3
University College London (UCL)	UK	1
Danish Meteorological Institute	Denmark	1
Eidgenossische Technische Hochschule (ETH) (Federal Institute of Technology) Zürich	Switzerland	2
United Nations Office for the Coordination of Humanitarian Affairs (UN OCHA)	Senegal	1
Foundation for Research and Technology, Hellas	Globally	1
Institute of Tibetan Plateau Research	China	1
University of Maryland	USA	1
University of Waterloo	Canada	1
University of Leicester	UK	1
Environment and Climate Change	Canada	1
Open University of Cyprus	Greece, Cyprus	1
Instituto Superior Tecnico	Portugal	1
Copernicus support office	Italy	1
Sandholt ApS	Globally	1
National Observatory of Athens	Greece	1
University of Hamburg	Germany	1
University of Sussex	UK	1
Freelance scientist	Poland, Germany	1
University of Bucharest	Romania	2
Environmental Systems Research Institute (ESRI)	Romania	1
National Meteorological Administration	Romania	2
NASA Jet Propulsion Laboratory (JPL)	USA, Italy, Spain	1

Institution	Country	Count
Institute of Geography of the Romanian Academy	Romania	1
Ghent University	Belgium	1
University of Lisbon	Portugal	1
Meteorological Organization	Iran	1
Western Kentucky University	USA	1

Participants were provided with the opportunity to sign up for future contact regarding relevant topics. Figure 6-1 shows uptake for each option; at least 40% of participants were interested in all areas offered.

Figure 6-1: Summary of responses to Q.4: Would you be interested in being contacted about any of the following?



6.4.2. LST Applications

Participants were asked to select a primary climate application for which they currently use LST, or envisage using LST for in the future. Participants were asked to consider this application area in their answers to all other questions in the survey. An opportunity to provide information on other areas of interest was also provided. Responses to these two questions are shown in Figure 6-2 and Figure 6-3. The most frequently selected primary applications were model evaluation, evapotranspiration and vegetation or crop monitoring, and urban climate; however evapotranspiration and vegetation or crop monitoring, extreme events, validation and inter-comparison, surface / atmosphere interactions and regional climate received the most selections for secondary applications. Secondary applications may be related to the primary application of choice, or to entirely separate applications.

Figure 6-2: Summary of responses to Q.7: Please select the primary climate application from the list for which you use or intend to use LST data. This is the application we would like you to have in mind when you answer the rest of the survey. Secondary applications / interests can be selected in the following question. You may also submit multiple responses for different primary applications if you wish.

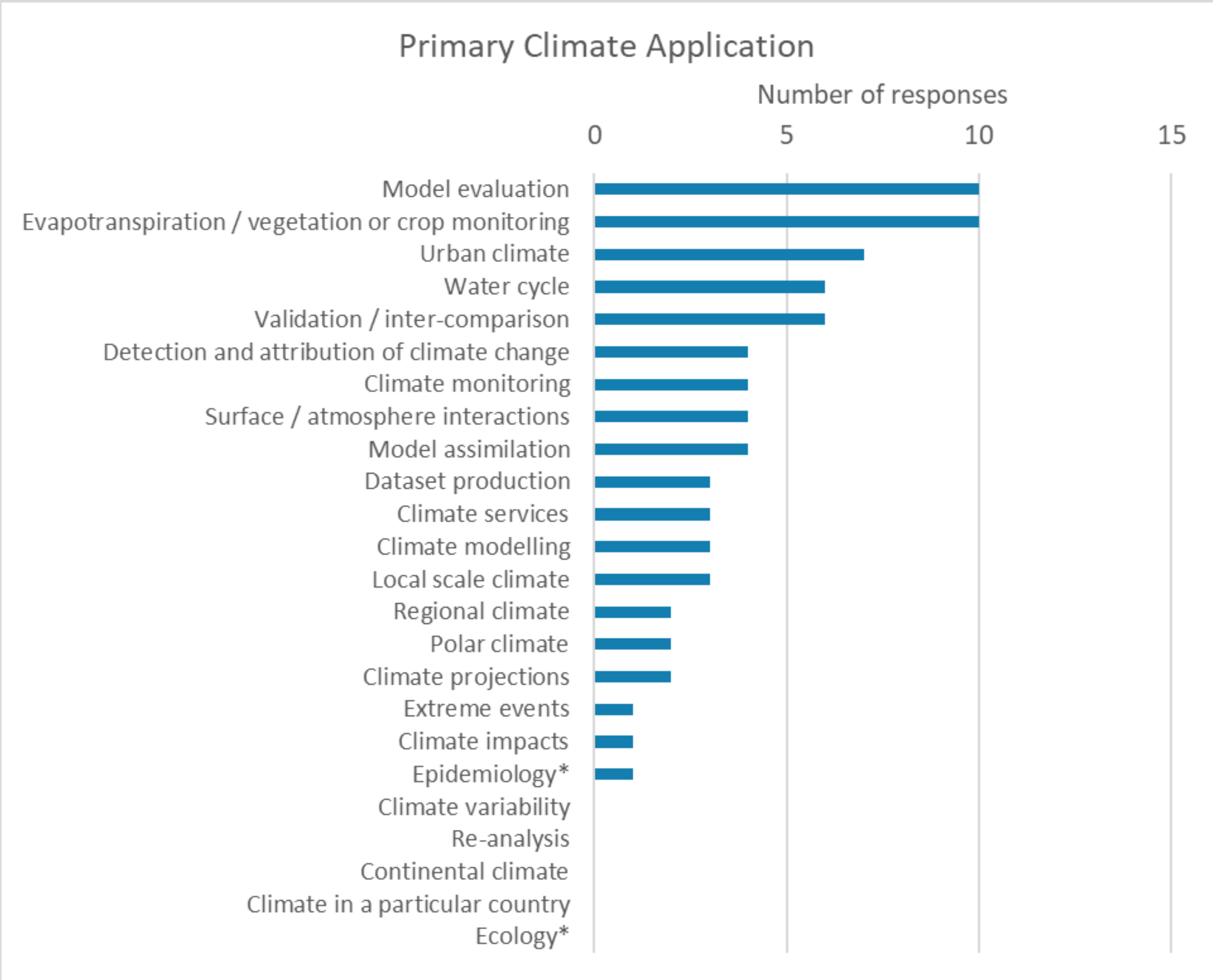
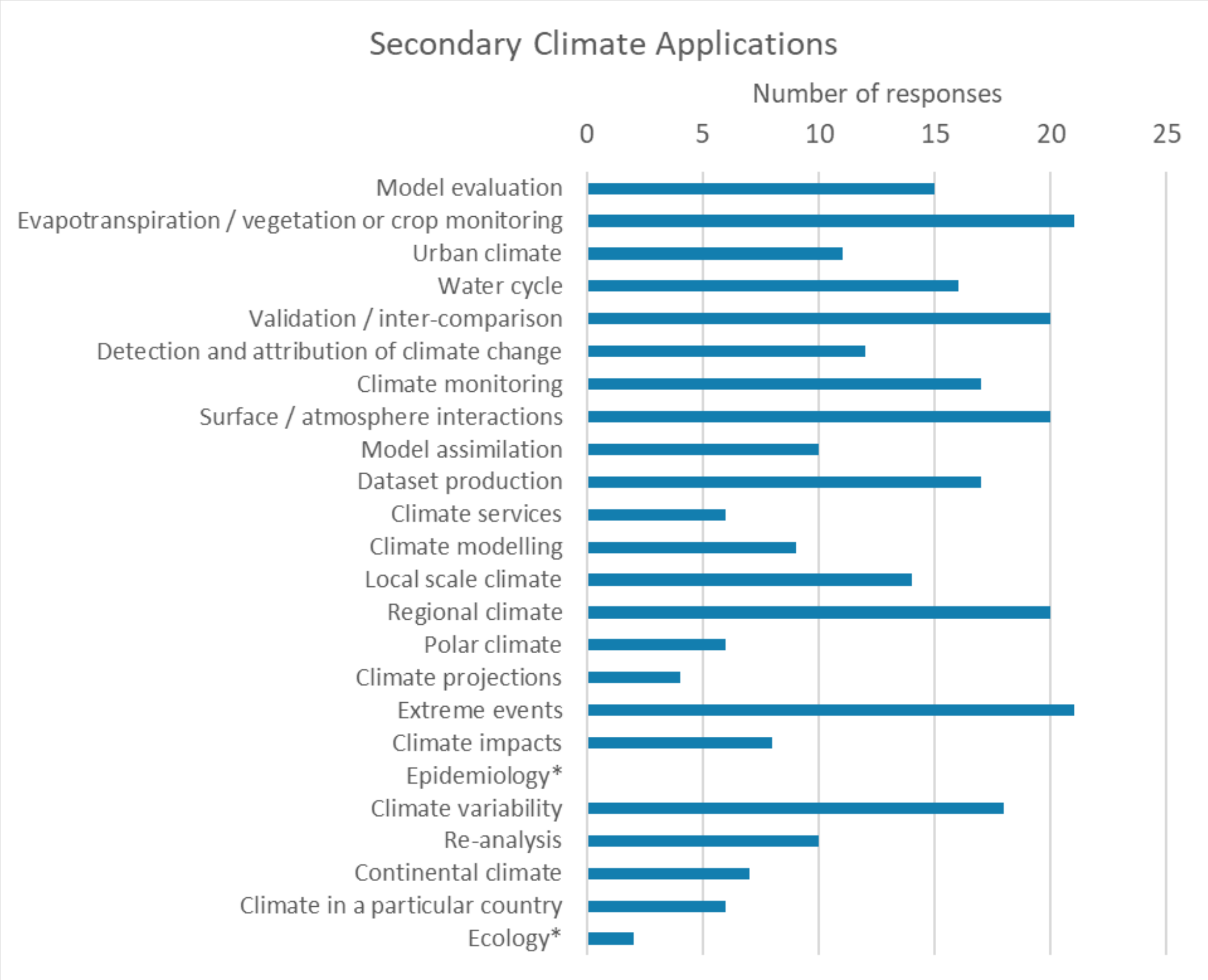


Figure 6-3: Summary of responses to Q.8: Please indicate from the list below if you use LST data for any other applications. Multiple boxes can be checked, but please have in mind the primary application selected above when completing the remainder of the survey.



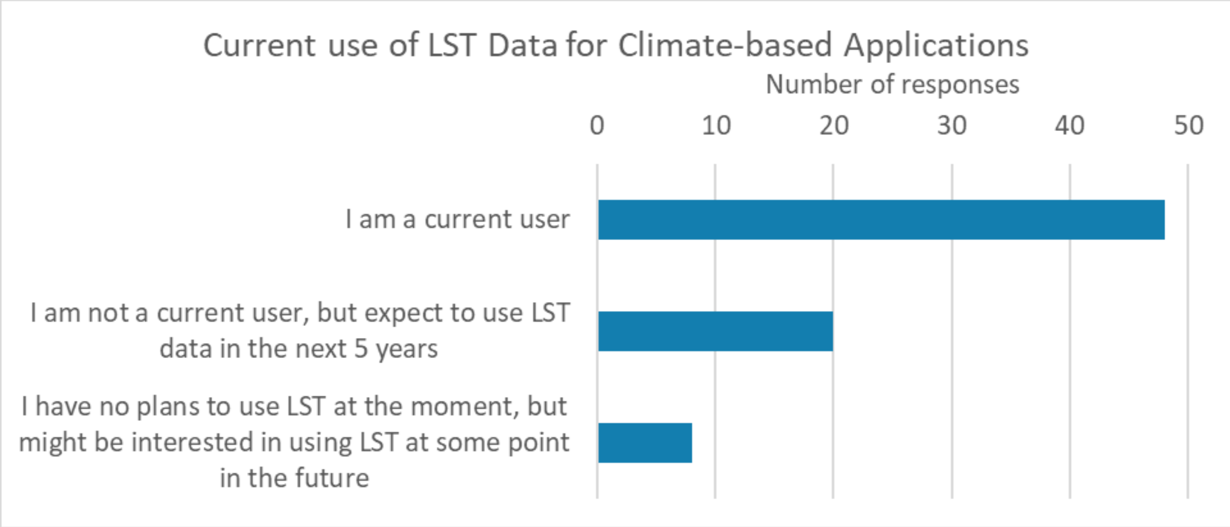
6.4.3. Data Use

Throughout the questionnaire, respondents are asked about their current or future use of both LST products and related CCI ECV products. This section provides an overview of those results.

6.4.3.1. Use of LST Data for Climate Applications

Firstly, participants' current use of LST for climate applications is established, with results summarised in Figure 6-4 – the majority of participants in the survey are current users of LST data, but there are also participants who intend to use the data in the future, or who may be interested in using the data should an appropriate product become available.

Figure 6-4: Summary of responses to Q.9: Do you currently use LST data for climate-based applications?



Participants who stated that they are current users of LST data were asked further questions regarding their data use. MODIS datasets are most frequently used [LST-URD-REQ-08-O], while Meteosat [LST-URD-ADV-12-O] and LandSat [LST-URD-ADV-13-O] are the second and third most popular datasets, respectively (Figure 6-5). It is worth noting that current data use may affect the requirements that users specify, and with such a high uptake in MODIS data, the existing characteristics and specifications of MODIS products may be reflected in the information gathered in this survey.

Figure 6-5: Summary of responses to Q.10: Which satellite LST datasets do you currently use for your primary application?

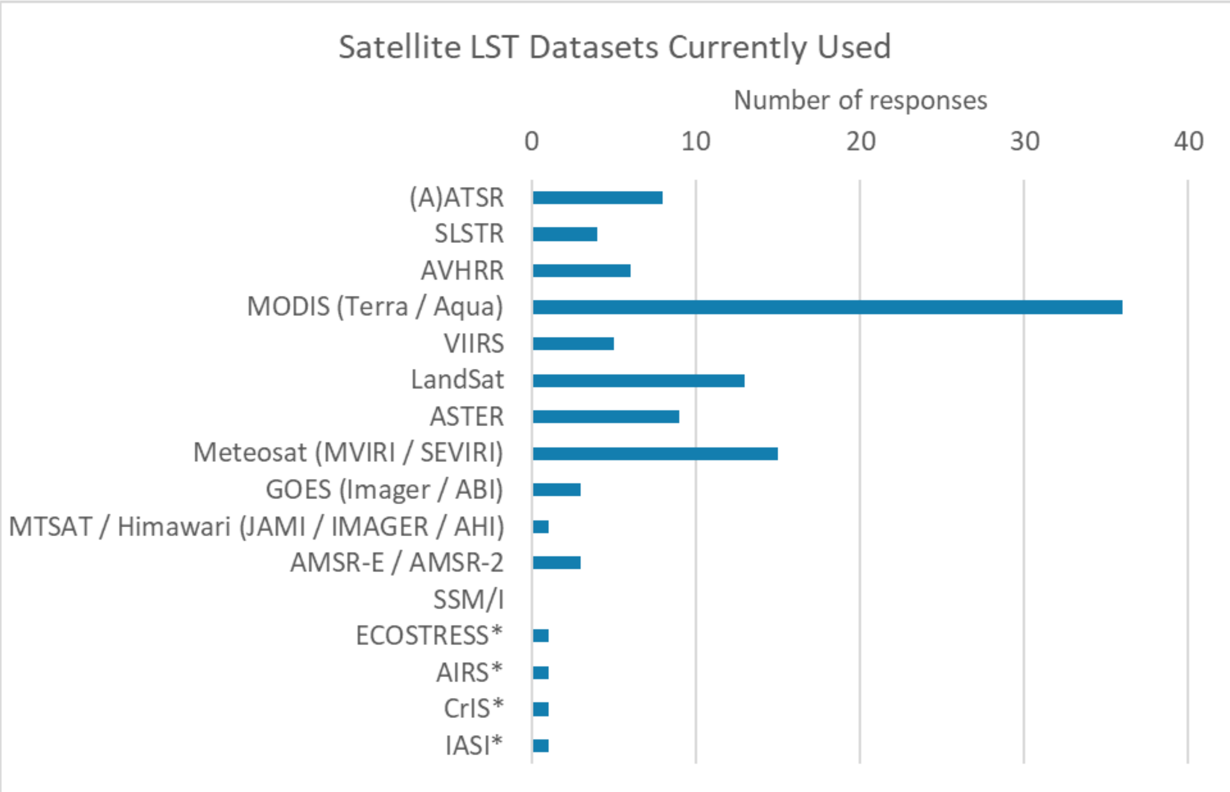
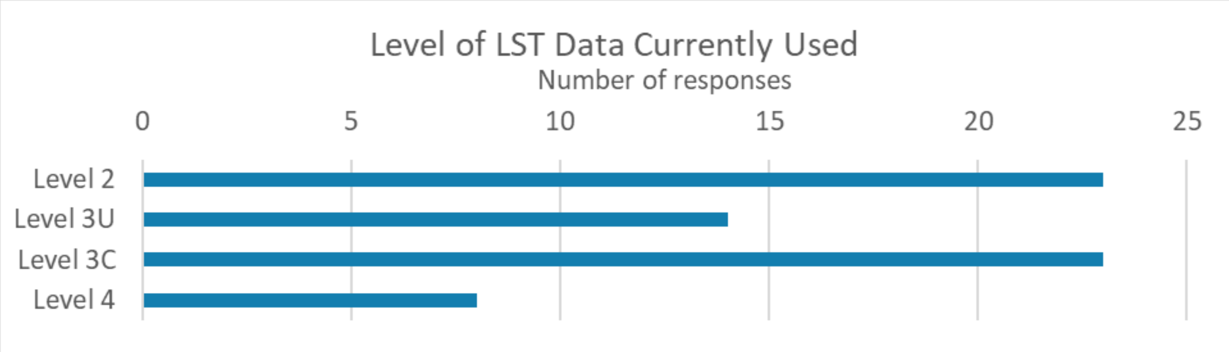


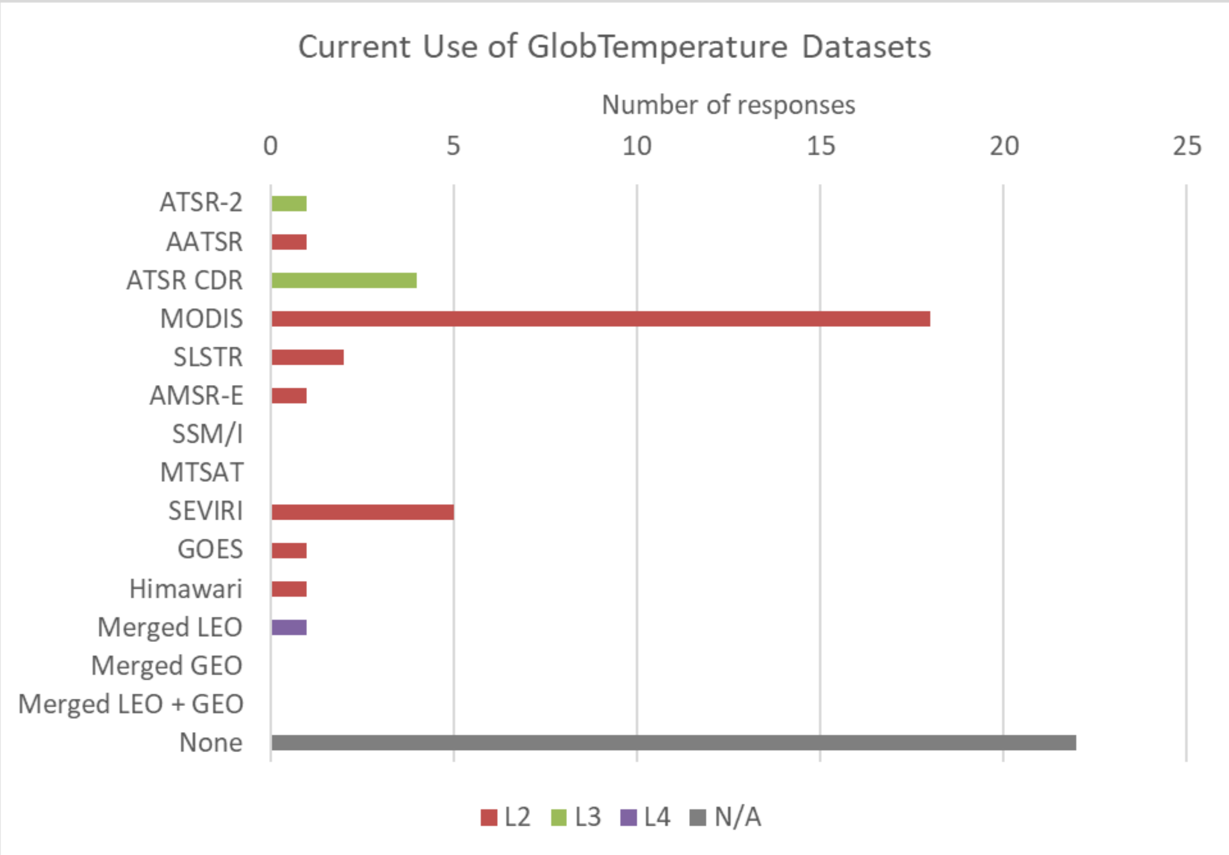
Figure 6-6 shows the current uptake of products at different levels. L2 (LST on orbit swath at native resolution) and L3C (LST mapped on uniform space-time grid scales, collated over multiple observations) (Table 6-1) datasets are used most frequently.

Figure 6-6: Summary of responses to Q.11: What level of LST data do you use?



The results of the survey indicate that 22 respondents currently use at least one of the GlobTemperature datasets, whilst some respondents use multiple GlobTemperature datasets. Usage of GlobTemperature data is shown in Figure 6-7. Again, as seen for Q.10, MODIS products are most frequently used, followed by SEVIRI/Meteosat. Landsat data, which were popular in Q.10, are not available through GlobTemperature. The (A)ATSR CDR is the third most popular GlobTemperature product. Only one respondent reports using the merged LEO product, while no respondents of the survey have used the merged GEO and LEO + GEO products.

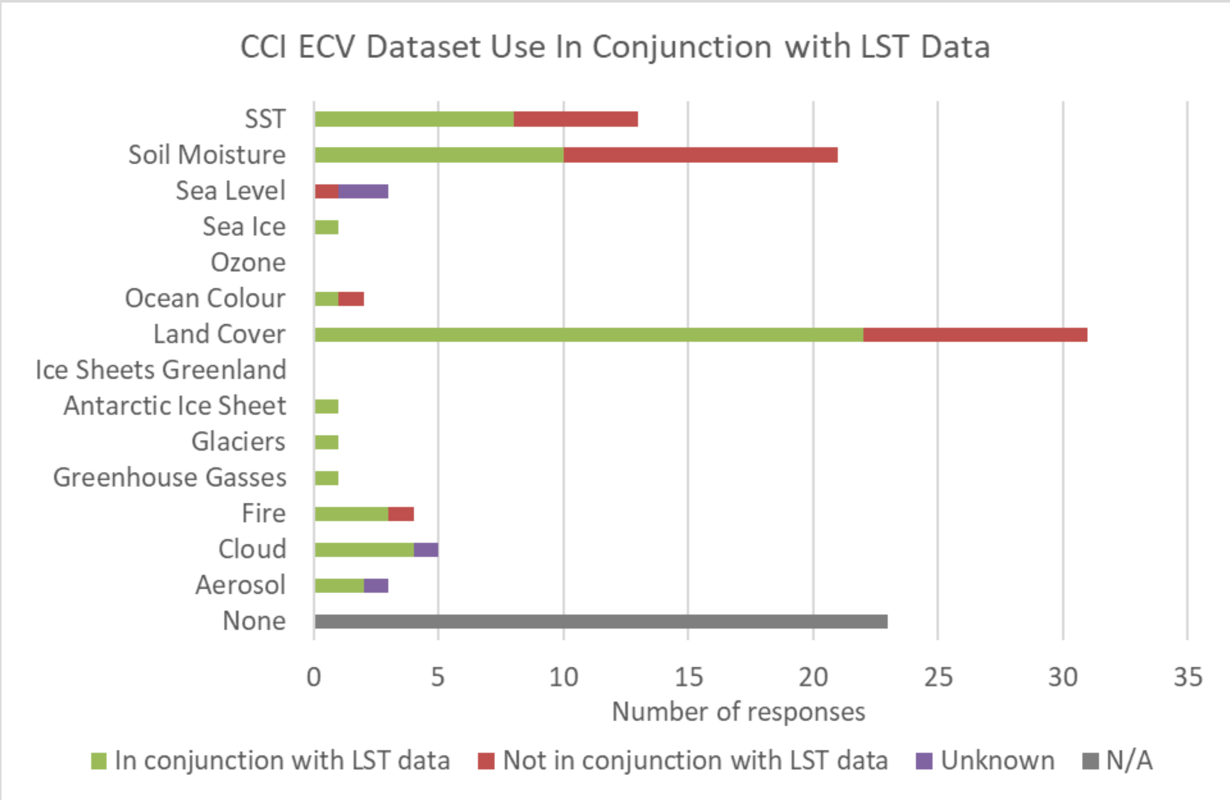
Figure 6-7: Summary of responses to Q.12: Do you use any of the GlobTemperature datasets for your primary application?



6.4.3.2. Use of CCI ECV Datasets for Climate Applications

CCI ECV datasets are popular among participants, with 52 indicating they use at least one of the existing CCI datasets. Of those who use CCI ECV products, 32 respondents use them in conjunction with LST data [LST-URD-ADV-01-O]; the most popular CCI products used are land cover, soil moisture and SST. A summary of responses can be found in Figure 6-8. In this figure, the green portion of the bars represent where the CCI ECV data set is used in conjunction with LST data, and the red portion where the CCI ECV data set are not used in conjunction with LST data. Purple indicates where it is not known whether the CC ECV data set is used in conjunction with LST data.

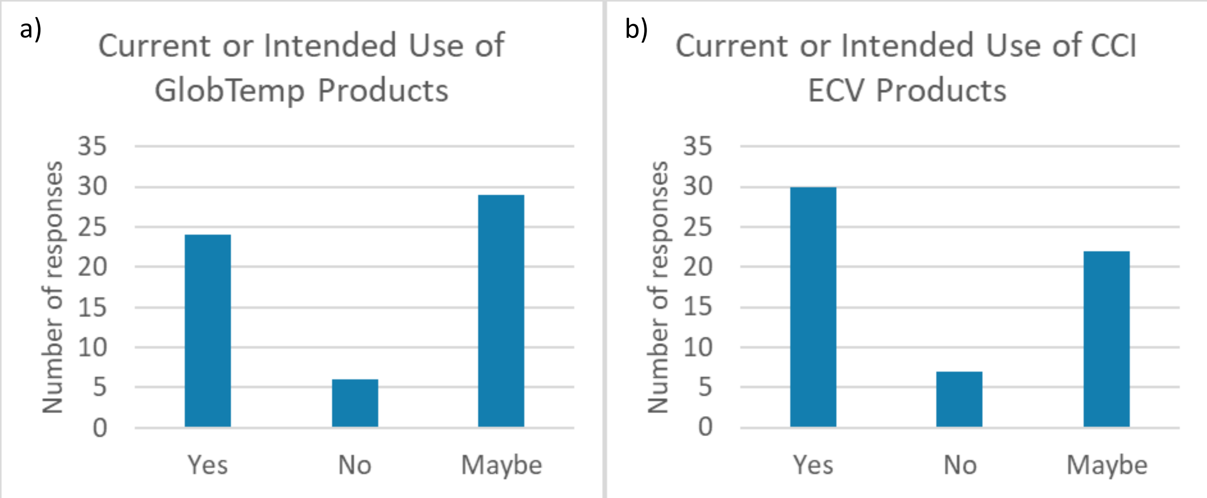
Figure 6-8: Summary of responses to the following questions: Q.13: Do you use any of the other CCI Essential Climate Variable (ECV) data products for your primary application?; Q.14: Do you use these in conjunction with LST data?



6.4.3.3. Intended Use of Data Products

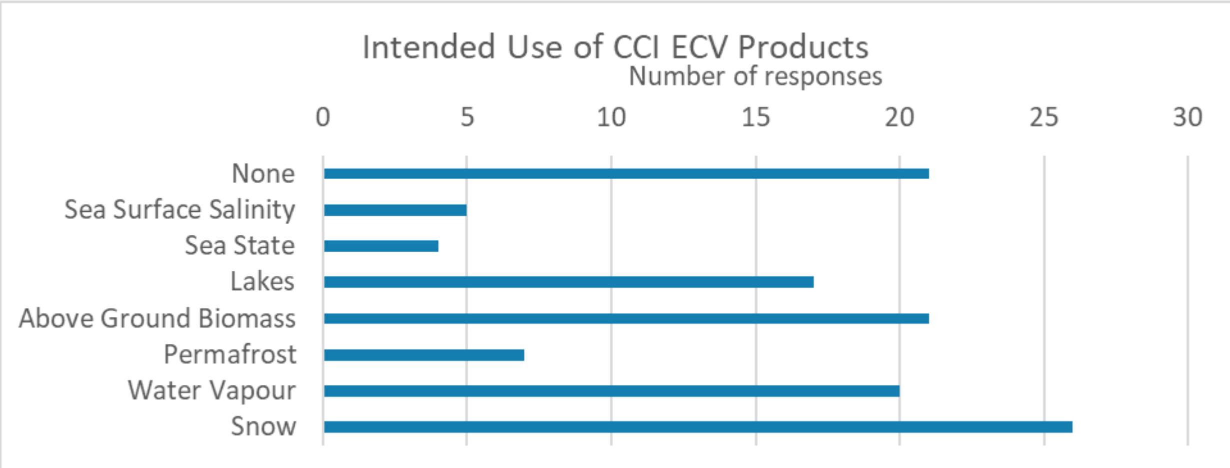
More than 50% of participants in the survey currently use GlobTemperature products or are interested in using these in the future. Similarly, more than 50% of participants use CCI ECV products, or are interested in using them in the future, as shown in Figure 6-9.

Figure 6-9: Summary of responses to a) Q.34 and b) Q.37: Q.34: Do you currently use, or intend to use, data from the GlobTemperature project?; Q.37: Do you currently use, or intend to use, data from the ESA CCI project (LST or otherwise)?



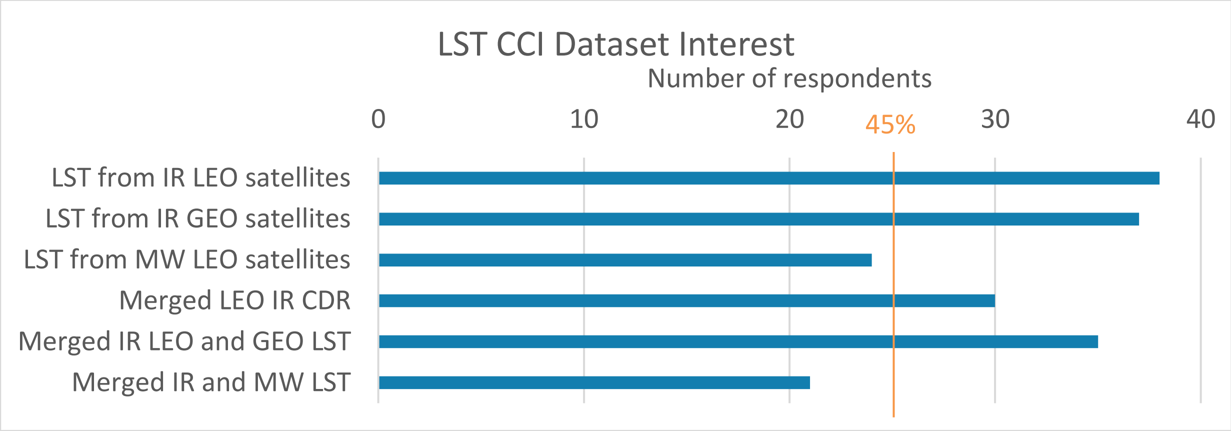
There is strong interest in other CCI ECV products currently under development, with 50 participants indicating intent to use at least one (note that respondents may select more than new ECV product).

Figure 6-10: Summary of responses to Q.15: Do you intend to use any of the new CCI ECV datasets?



Participants are interested in all products proposed as part of the LST CCI project, with 56 participants indicating intent to use at least one, as shown in Figure 6-11 [LST-URD-REQ-02-O, LST-URD-REQ-03-O, LST-URD-REQ-04-O, LST-URD-REQ-05-LO]. Products involving MW data are less popular, failing to meet a soft requirement (45%) [LST-URD-ADV-10-OI, LST-URD-ADV-11-LOI], but as there are currently no operational MW products available this could be due to lack of familiarity with these data.

Figure 6-11: Summary of responses to Q.30: Please select any dataset types you might be interested in.



6.4.4. Concerns Regarding LST

Question 16 required participants to rank their three greatest concerns regarding LST data from a range of options covering known problems, a summary of which can be found in Figure 6-12. Two comments were also provided by participants – one concerned with anisotropy, and one requesting that the actual LST observation time needs to be better integrated into LST products.

Figure 6-12: Summary of responses from Q.16: Please rank the top 3 main concerns or barriers (if any) you experience using LST (with 1 being the most important, and 3 the least). The key indicates the rank selected (#1, #2 or #3).

In order to prioritise user concerns, a points system is used, whereby an option ranked as #1 receives 3 points, #2 receives 2 points, and #3 receives 1 point, and a total is calculated for each option. The summary can be found in Table 6-4.

Analysing the data in this way indicates that users are most concerned – and by a notable margin of points – about low spatial resolution [LST-URD-ADV-21-LOI] and errors due to cloud contamination [LST-URD-ADV-33-LOI]. These issues are also the most frequent primary concern of the respondents (i.e. ranked #1 by respondents). Lack of understanding of exactly what satellite LST data represent [LST-URD-ADV-02-OI] and the temporal resolution of LST data being too low also scored highly in this points-based assessment. Interestingly, although dataset length is clearly a concern to many survey respondents, they are least concerned about dataset stability. This may be because most respondent applications do not require stability, or perhaps it is simply because this has not been an issue for users so far owing to the lack of long-term LST datasets currently available.

Table 6-4: Summary of concerns ranked in Q.16 (see Figure 6-12) ordered using a points system in which a rank of #1 receives 3 points, rank #2 receives 2 points and #1 receives 1 point.

Concern	Points
Spatial resolution is too low for my application	63
Retrieved LST's may be contaminated with cloud, and therefore contain large errors	59
It is not clear to me exactly what satellite LST represents / I cannot relate satellite LST with other surface temperature data that I am using	38
Temporal resolution is too low for my application	36
There is a lack of appropriate or accurate uncertainty information	32
Dataset time series are not long enough	31
Satellite derived LST measurements are currently expected to be within 1-3 K of the 'true' LST, this is too large for my application	27
InfraRed datasets only include cloud-free LST's and therefore my analysis of these data may be clear-sky biased	26
InfraRed datasets only include cloud-free LST's and are therefore spatially incomplete	21
Stability is unknown / too poor for my application	18

6.4.5. Data Specification

6.4.5.1. Spatial Domain

Most participants require LST data on a global scale [LST-URD-REQ-09-O], with some focusing on regional scales such as mid-latitudes, polar regions, continents or countries; a few are interested in data at local scales such as cities (Figure 6-13). Some participants provided further details regarding their area of study, for example the specific country or continent, and a summary of these can be found in Table 6-5.

Figure 6-13: Summary of responses (a) from Q.17: Over what spatial domain do you require LST data for your primary application? This is summarised on the right (b) as a percentage of responses for global, regional, and local scales, where regional includes equatorial, mid latitudes, Polar Regions, continental, and country.

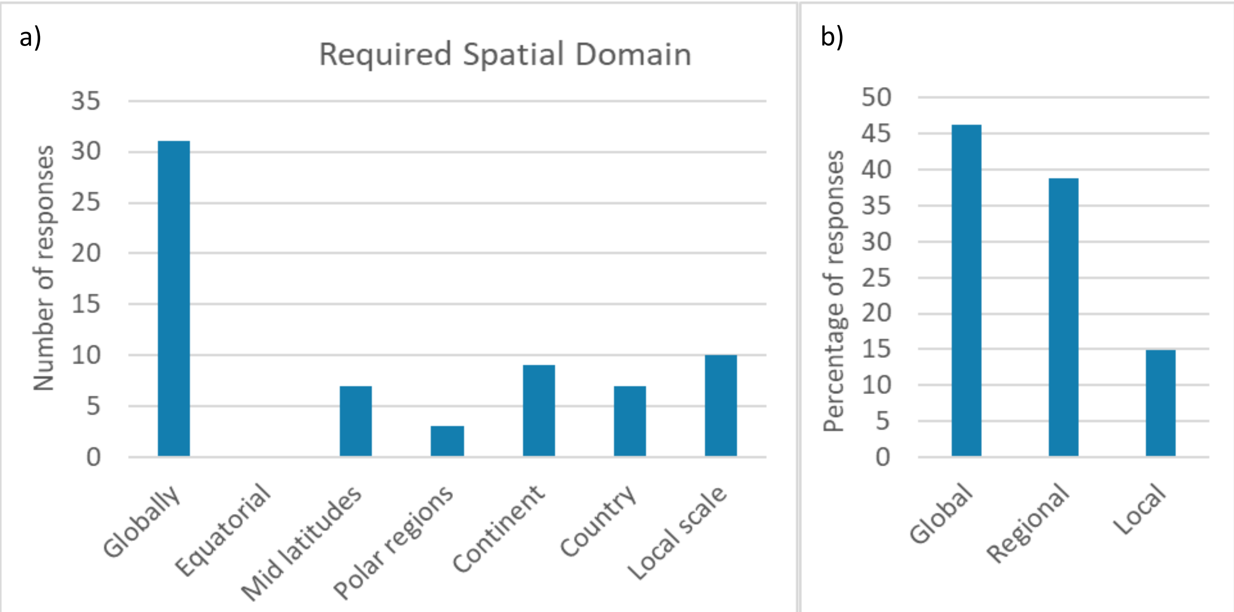


Table 6-5: Summary of additional detail provided by some participants in the comments for Q.17: Over what spatial domain do you require LST data for your primary application?

Spatial Domain	Detail	Frequency
Global	Special emphasis over North America	1
Polar regions	High latitude and high elevation	1
Continent	Southern Africa	1
	Europe	4
	Africa	1
Country	Brazil	1
	USA (California, Nevada, Arizona) Iran (Zagros Ranges)	1
	Romania	2
Local scale	Agricultural areas in Germany	1
	Footprint of eddy covariance towers (<= 1 km^2)	1
	Worldwide cities	1
	Local and regional scale, e.g. Mediterranean region	1
	Urban areas and hinterlands globally	1
	Cities in China	1

6.4.5.2. Time of Observation

Figure 6-14 provides a summary of requested LST observation times for UTC and local time. The results show that 48% of participants require observations at all times of day, surpassing the threshold for a soft requirement [LST-URD-REQ-10-O]. Besides this, four required observation time patterns can be identified by analysing the individual survey responses: short periods of the day covered by hourly observations, 3 hourly, 6 hourly, and specific observation times, which are detailed in Table 6-6. There is also a clear requirement for early-afternoon observations, close to the time of daily maximum LST and near-surface air temperature [LST-URD-ADV-15-OI].

Figure 6-14: Summary of responses to questions: Q.18: At what time of day do you require LST observations (tick as many time slots as are applicable)? And Q.19: Are the times selected above UTC or local time?

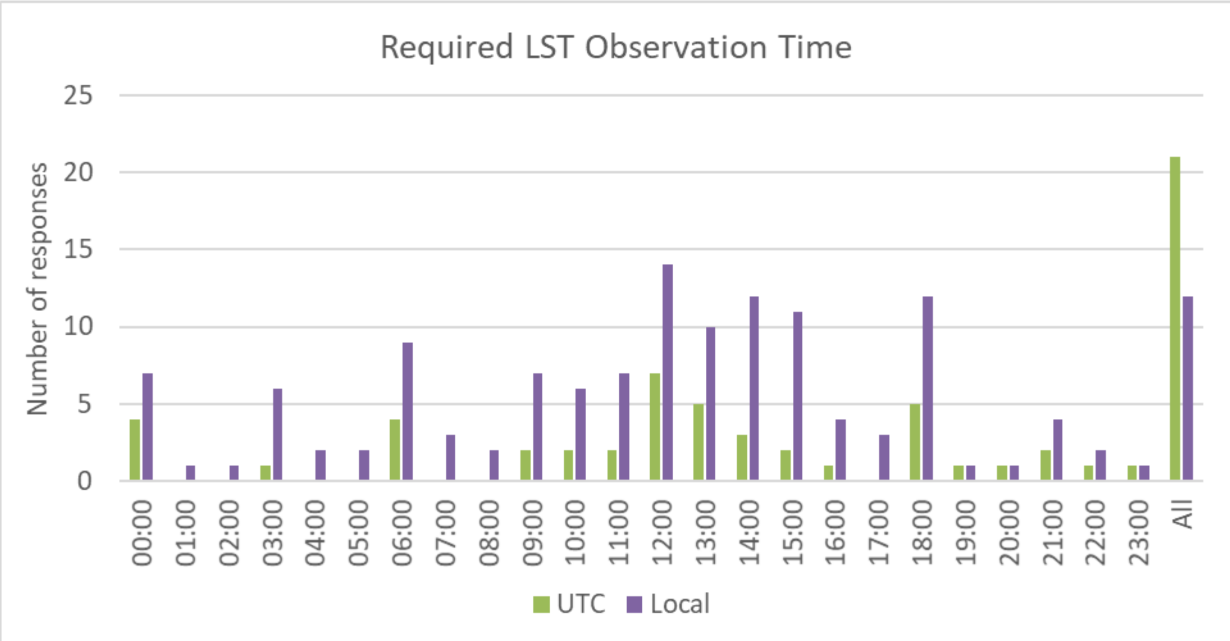


Table 6-6: Summary of required observation time pattern, regarding responses to Q.18 (responses shown in Figure 6-14). Q.18: At what time of day do you require LST observations?

Type	Notes	Percentage of responses
All	Observations at all times of day	53
Short periods covered by regular observations	One or more period(s) in the day spanning several hours, requiring hourly observations, with other periods requiring none	21
3 hourly	Observations every 3 hours, starting at midnight. One respondent did not want the midnight value	6
6 hourly	Observations every 6 hours, starting at midnight. One respondent did not want the midnight value	7
Specific	One or more specific observation times, e.g. 10 am	13

6.4.5.3. Dataset Length and Resolution

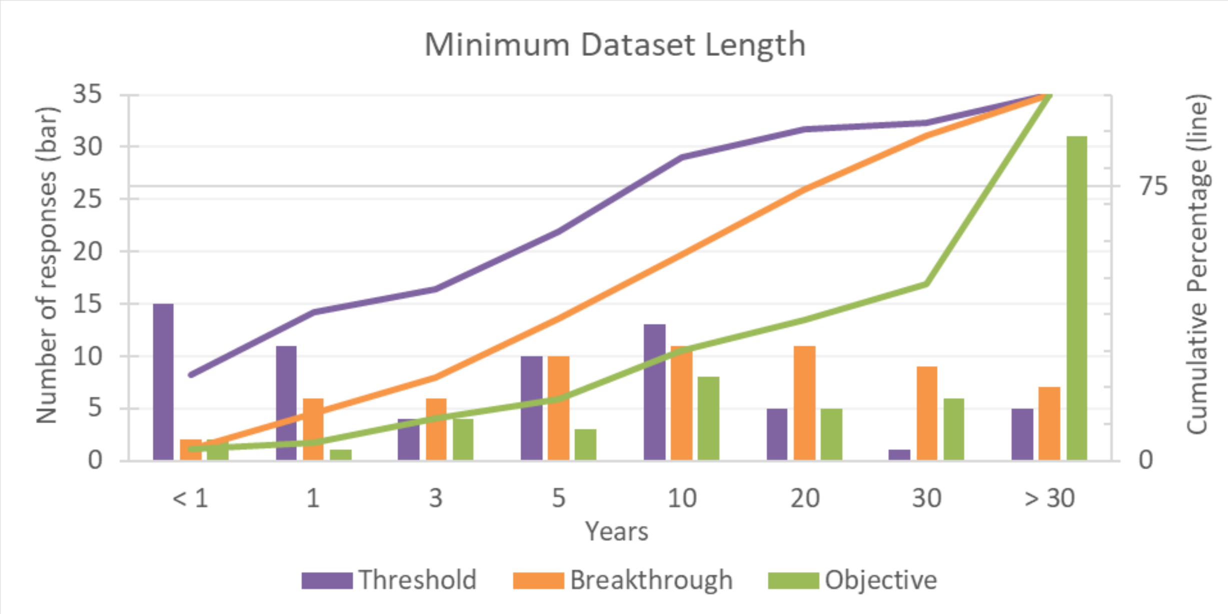
For the following questions, participants are asked to provide a threshold, breakthrough and objective level requirements (as defined in Table 4-2 previously) from a range of options on a scale. The requirement levels are defined as:

- **Threshold**: The limit, beyond which, the data is of no use for the given application
- **Breakthrough**: The level at which significant improvement in the given application would be achieved
- **Objective**: The level beyond which, no further improvement would be of value for the given application

The nature of these questions allows for hard requirements to be identified i.e. requirements that satisfy at least 75% of respondents. A summary of dataset length, resolution and quality requirements can be found in Table 6-8 in the summary section of this chapter.

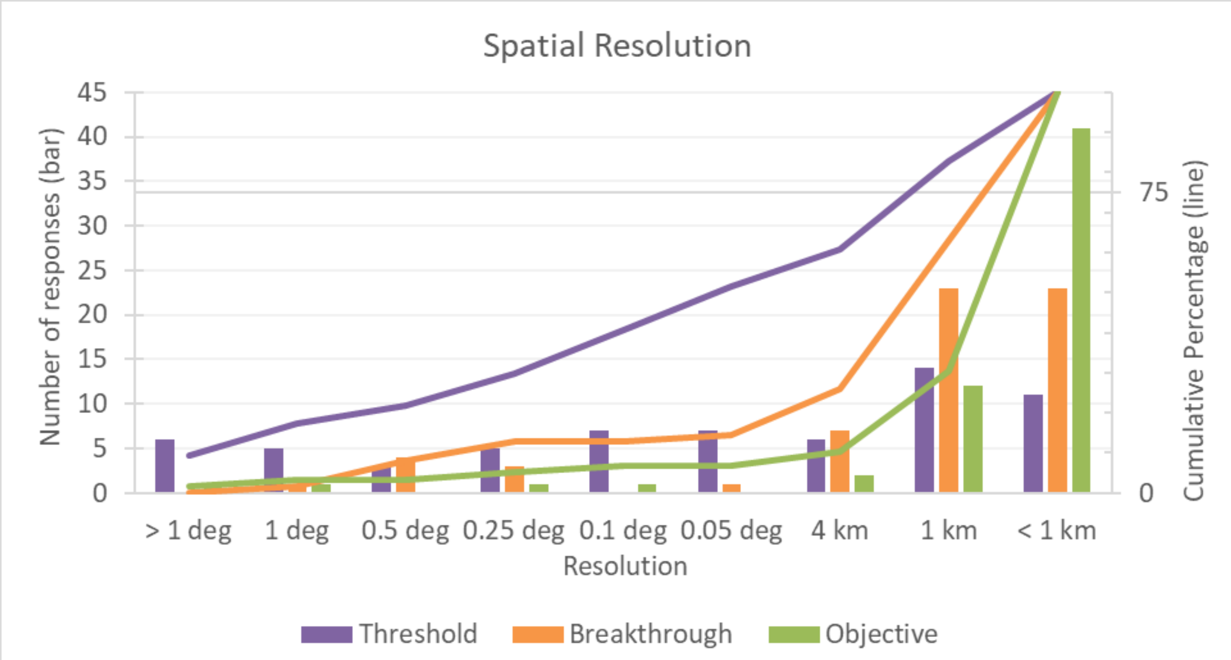
For dataset length (Figure 6-15), the threshold, breakthrough and objective requirements are 10, 20 and >30 years, respectively [LST-URD-REQ-11-O, LST-URD-OPT-11-O]. This is broadly in line with the results from the GlobTemperature survey, where the threshold and breakthrough requirements were found to be 10-15 years and 25-30 years, respectively (Table 3-8). Datasets of >30 years are the most popular choice for an objective requirement by a considerable margin; for climate research this fits with expectations as 30 years is typically used to create a climatological baseline period. Interestingly, 15 respondents would still find a dataset length of <1 year useful. This is encouraging as it suggests that there could be user uptake of the experimental datasets proposed in LST_cci (e.g. blended IR + MW), despite their very short length.

Figure 6-15: Summary of responses to Q.20: What is the minimum length of dataset that you require? Number of responses are shown as columns referencing the left axis, with the cumulative percentage overlaid as a line referencing the right axis. The cumulative percentage indicates the percentage of respondents who would be satisfied by each successive requirement.



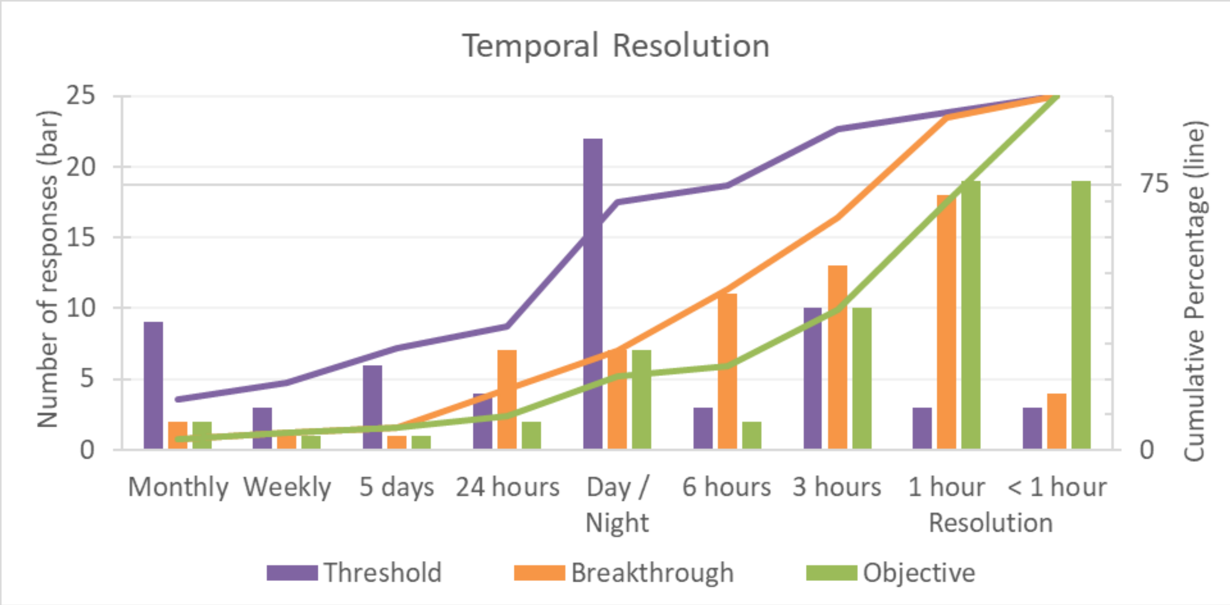
For dataset spatial resolution (Figure 6-16), the threshold requirement is 1 km [LST-URD-REQ-12-O], whereas both the breakthrough and objective spatial resolutions are <1 km [LST-URD-OPT-12-O]. These results differ from the GlobTemperature survey results for climate applications (Table 3-8), where most climate users were satisfied by data at a much coarser spatial resolution than 1 km (e.g. 0.05-0.5°). However, they are close to the requirements obtained at the NCDC workshop (Table 3-4), where the spatial resolution required for most applications is 1 km or better, and the NASA white paper on LST (Table 3-3), where the spatial resolution for regional and local applications is better than 5 km. The results of this survey may reflect the high proportion of respondents who use MODIS data (Figure 6-5), whose native resolution is ~ 1km, and L2 data (Figure 6-6), which is at the native resolution of a sensor (e.g. MODIS, (A)ATSR data are 1 km). The results may also reflect the primary application of the respondents (Figure 6-2): the three most popular primary applications are model evaluation, evapotranspiration/vegetation or crop monitoring and urban climate, all of which may quite feasibly require data with a spatial resolution of 1 km or better.

Figure 6-16: Summary of responses to Q.21: At what spatial resolution do you require LST data? Number of responses are shown as columns referencing the left axis, with the cumulative percentage overlaid as a line referencing the right axis. The cumulative percentage indicates the percentage of respondents who would be satisfied by each successive requirement.



For dataset temporal resolution (Figure 6-17), the threshold, breakthrough and objective requirements are calculated to be 6 hours [LST-URD-REQ-13-O], 1 hour [LST-URD-OPT-13-0], and <1 hour, respectively. However, it is worth noting that the threshold requirement is very nearly met by day/night temporal resolution, which would satisfy 70% of survey respondents. This is broadly in line with the findings of the NASA white paper (Table 3-3: 2-4 times daily for regional applications and hourly for global), but perhaps less so with the NCDC workshop, where most applications were found to require data with a frequency of between 12 hours and 7 days (Table 3-4). The GlobTemperature survey also suggested that users typically require a lower temporal resolution than found in this survey, with a threshold temporal resolution of between monthly and day/night, and the breakthrough values ranging between day/night and 3-hourly.

Figure 6-17: Summary of responses to Q.22: At what temporal resolution do you require LST data? Number of responses are shown as columns referencing the left axis, with the cumulative percentage overlaid as a line referencing the right axis. The cumulative percentage indicates the percentage of respondents who would be satisfied by each successive requirement.

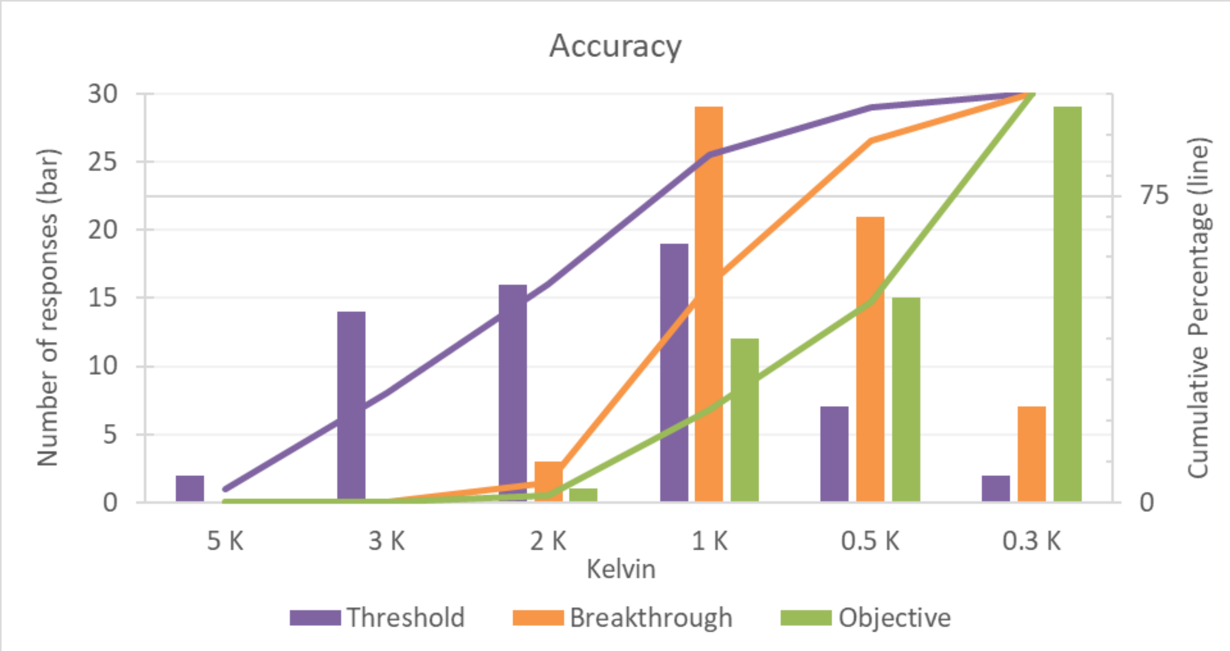


6.4.5.4. Data Quality

GCOS refers to data quality in terms of three measures: accuracy – the degree of conformity of the measurement to the accepted 'true' value; precision – the closeness of agreement between independent measurements of a quantity under the same conditions; and stability - consistency of LST measurements from a given satellite product over time.

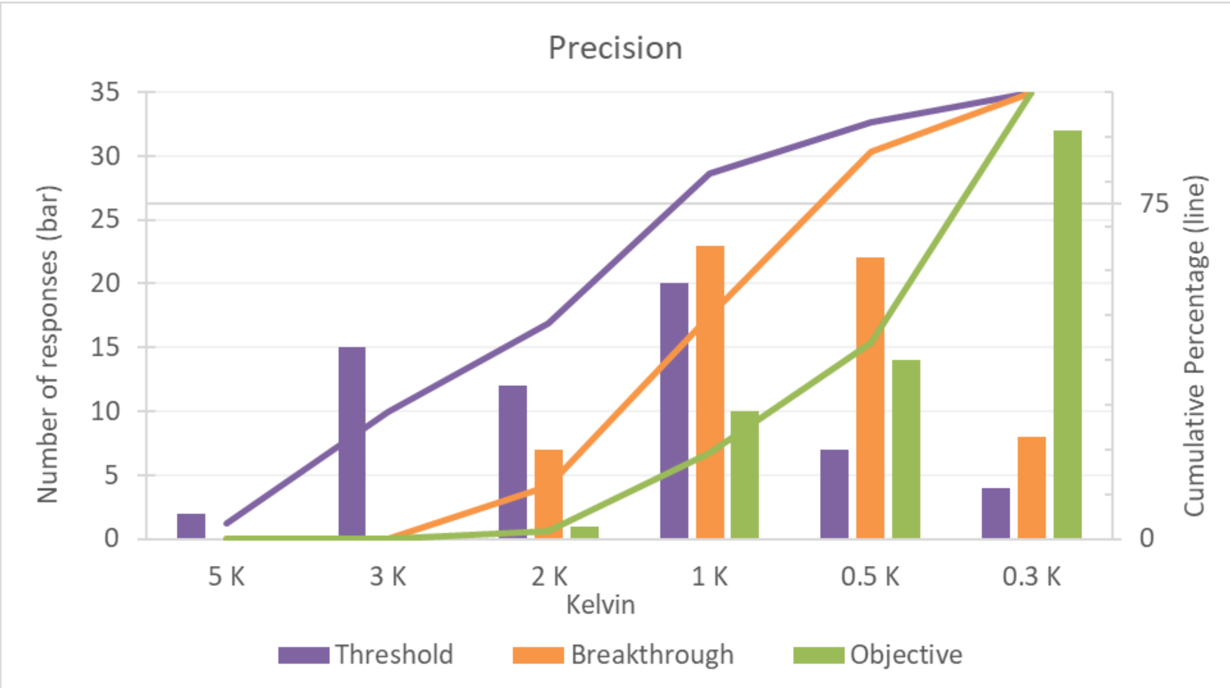
For dataset accuracy (Figure 6-18), the threshold, breakthrough and objective requirements are 1 K [LST-URD-REQ-14-O], 0.5 K [LST-URD-OPT-14-O], and 0.3 K, respectively. These findings are very close to those reported in the NASA white paper (Table 3-3: 0.5-1 K) and GlobTemperature (Table 3-7: maximum bias of 1 K). The threshold requirement obtained in this study is also consistent with the GCOS threshold requirement of <1 K for accuracy (Table 3-1: no breakthrough or objective requirement is provided by GCOS).

Figure 6-18: Summary of responses to Q.23: What are your requirements for LST Accuracy – the degree of conformity of the measurement to the accepted 'true' value? Number of responses are shown as columns referencing the left axis, with the cumulative percentage overlaid as a line referencing the right axis. The cumulative percentage indicates the percentage of respondents who would be satisfied by each successive requirement.



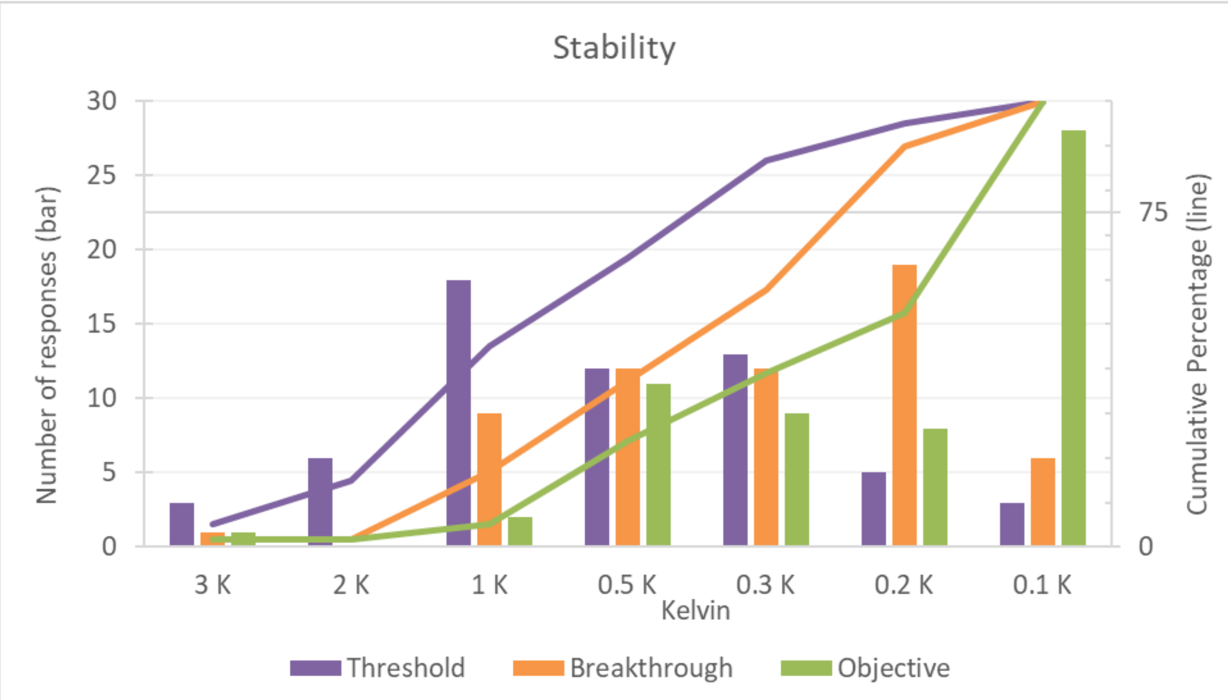
For dataset precision (Figure 6-19), the threshold, breakthrough and objective requirements are also 1 K [LST-URD-REQ-15-O], 0.5 K [LST-URD-OPT-15-O], and 0.3 K. The threshold requirement result obtained in this study is consistent with the GCOS threshold requirement of for precision of <1 K (Table 3-1: no breakthrough or objective requirement is provided by GCOS).

Figure 6-19: Summary of responses to Q.24: What are your requirements for LST Precision – closeness of agreement between independent measurements of a quantity under the same conditions? Number of responses are shown as columns referencing the left axis, with the cumulative percentage overlaid as a line referencing the right axis. The cumulative percentage indicates the percentage of respondents who would be satisfied by each successive requirement.



For LST dataset stability (Figure 6-20), the threshold, breakthrough and objective requirements are calculated to be 0.3 K/decade [LST-URD-REQ-16-O], 0.2 K/decade [LST-URD-OPT-16-O], and 0.1 K/decade, respectively These findings are consistent with the GCOS requirements (Table 3-1: threshold: <0.3 K/decade, objective: <0.1 K/decade) and those obtained for the GlobTemperature project (Table 3-7: threshold: <0.3 K/decade).

Figure 6-20: Summary of responses to Q.25: What are your requirements for LST Stability – consistency of LST measurements from a given satellite product over time (kelvin per decade)? Number of responses are shown as columns with regards to the left axis, with the cumulative percentage overlaid as a line with regards to the right axis. The cumulative percentage indicates the percentage of respondents who would be satisfied by each successive requirement.



6.4.5.5. Specification Priorities

As with the Joint Land Workshop questionnaire, respondents to the online survey were asked to prioritise between certain requirements that may be technically conflicting using conventional LST datasets, for example, providing a dataset with both high spatial (e.g. 1 km) and temporal resolution (e.g. hourly).

From the results shown in Figure 6-21, it is only clear that data quality is more important than spatially complete fields for most participants [LST-URD-REQ-18-O]. For the two other questions in this category, the responses received were well balanced between the conflicting options provided. However, when the results are separated by application spatial domain, i.e. global, regional and local, there does appear to be some preference (Figure 6-22). It is found that those working on global scales prioritise high temporal resolution and dataset length [LST-URD-ADV-17-O], whilst those working with local domains prioritise high spatial resolution over high temporal resolution, and prioritise high-resolution data in general over dataset length [LST-URD-ADV-18-O]. Results for those working with regional domains remain quite balanced.

Figure 6-21: Summary of responses to Q.26, Q.27 and Q.28: Which is more important for your primary application?

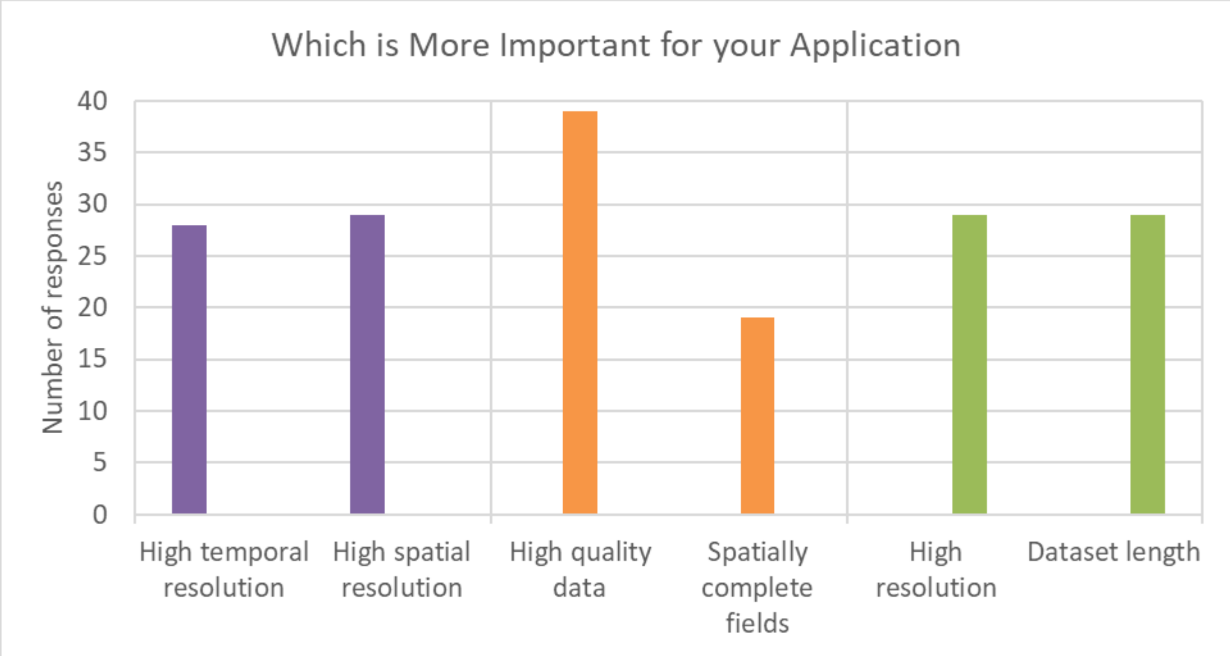
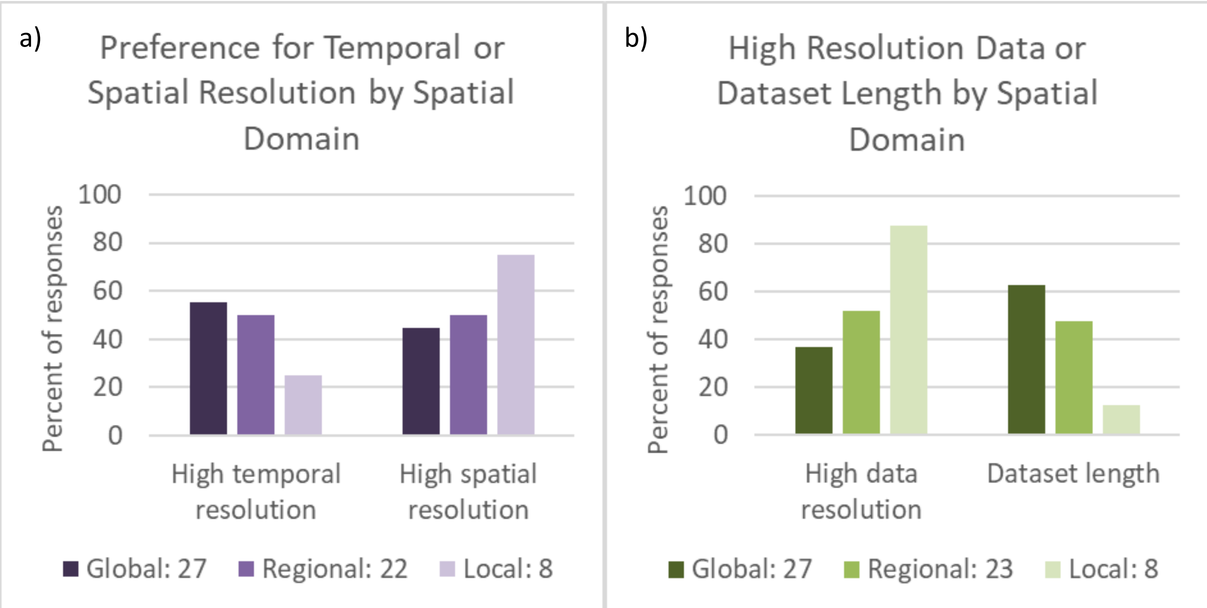


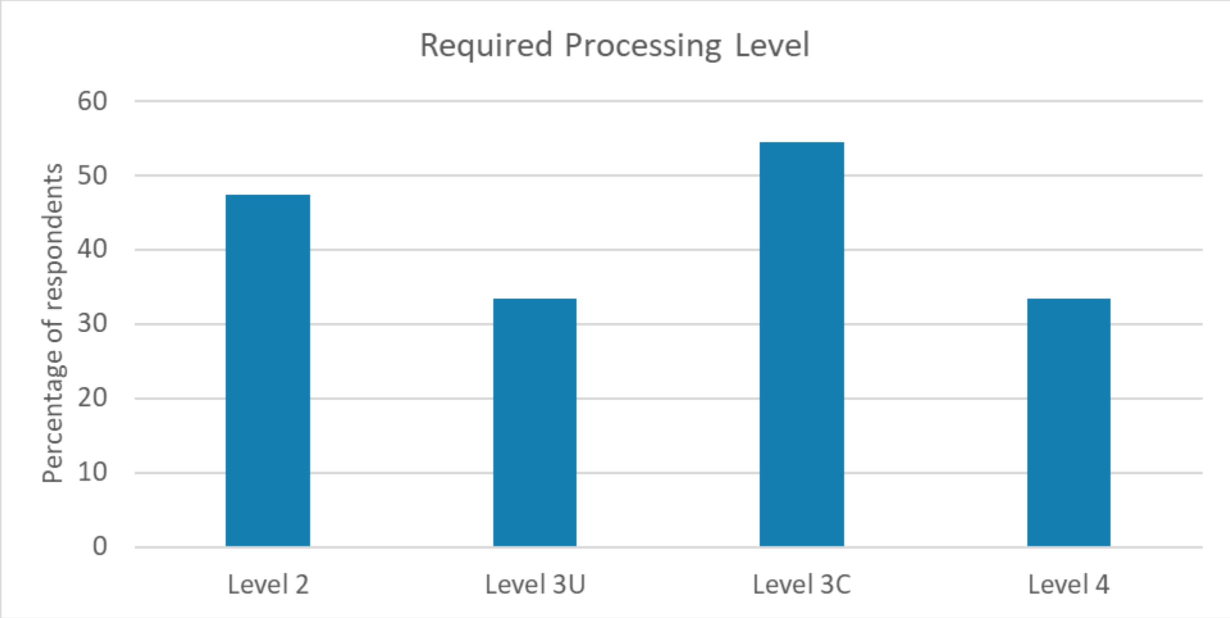
Figure 6-22: Responses to Q.26 (a) and Q.28 (b) regarding priorities, broken down by required spatial domain, see Figure 6-13b.



6.4.5.6. Data Processing Level

Satellite data are provided to users with different levels of processing. In this survey, users were asked what level of LST data they required from a choice of Level 2 (LST on orbit swath at native resolution), Level 3U (LST mapped on uniform space grid scales from a single orbit), Level 3c (LST mapped on uniform space grid scales from a single orbit, and Level 4 (Further processed LST data such as model output or data derived from multiple datasets). A total of 57 respondents answered this question suggesting that users require data are at all processing levels, but L2 [LST-URD-REQ-06-O] and L3C [LST-URD-REQ-07-O] are the most popular, both passing the 45% threshold for a soft requirement (Figure 6-23).

Figure 6-23: Summary of responses to Q.29: What level of LST data do you require? This question was answered by 57 respondents.

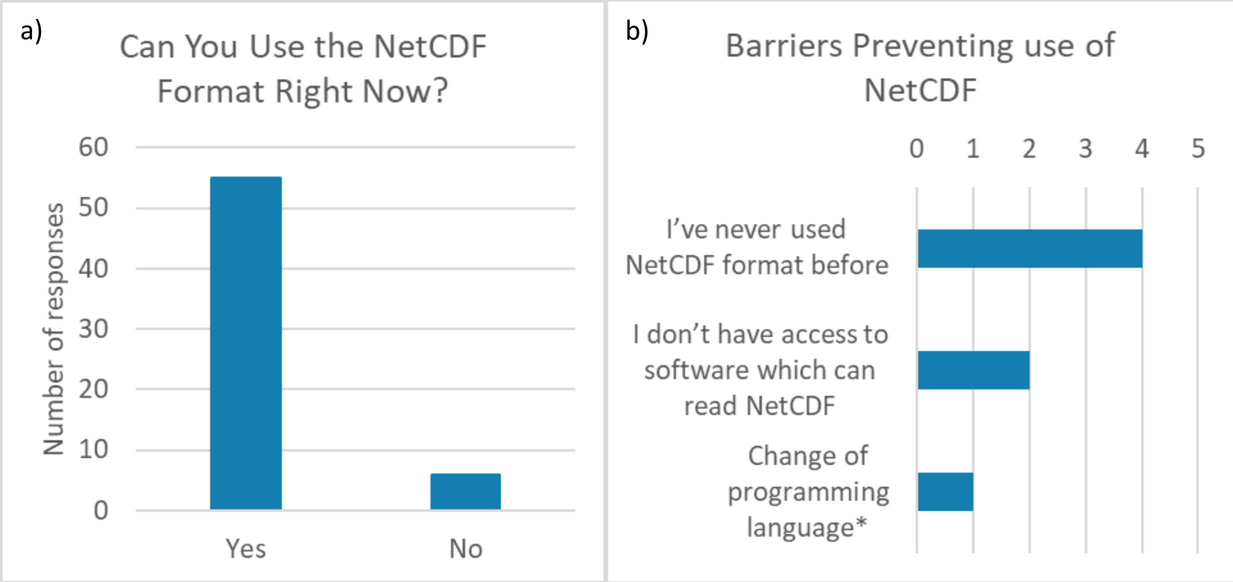


6.4.6. Data Format and Metadata

It is planned to release the LST_cci products in NetCDF format, which is widely used in the scientific community. Thus the first question in this section seeks to establish whether respondents can use NetCDF; a significant number of negative responses to this question would suggest that provision of a data converter could be considered.

Only seven of the 57 respondents are currently not capable of using NetCDF (Figure 6-24a) [LST-URD-REQ-01-O]. Figure 6-24b indicates that four of these respondents have not used NetCDF before, while two do not have access to NetCDF-reading software. One participant noted that they would have to change programming language in order to read the data. These participants were asked if there is anything that data providers could offer to help overcome these barriers: one respondent requested the provision of a python module with relevant tools, and one requested data in HDF or SHP format. Under these circumstances it may be advisable to consider a data converter.

Figure 6-24: Summary of responses to Q.31 (a) regarding ability to use NetCDF format and Q.32 (b) covering barriers preventing use of the data. Q.31: Data products within the LST_cci project will be provided in NetCDF format, would you be able to use these for your application right now? Q.32: What are the barriers preventing you using NetCDF data?



The data format for the LST_cci project is likely to be either the GlobTemperature harmonized format, or the CCI standard format (European Space Agency Climate Office, 2018), which is used for other ECVs within the CCI programme. The two formats both use netCDF and the differences relate mainly to the specification of data dimensions and metadata. This section of the questionnaire seeks to understand the impact of changing data file format on users who already use one of these formats. Participants who currently use, or may use GlobTemperature products and CCI products are asked about the impact of using an alternative format with changes relating to the following topics:

- The filename convention
- Specification of the global metadata – CCI specification includes more global metadata
- Naming and number of dimensions – GlobTemperature 'AUX' files have more dimensions
- Number of files and file sizes – CCI data is contained within one file, whereas GlobTemperature format uses two separate 'LST' and 'AUX' files

Results are summarised in Figure 6-25 (current or future users of GlobTemperature data), and Figure 6-26 (current or future users of CCI data). From the respondents of the survey, 23 are existing GlobTemperature data users, with 53 stating they either currently use the data or may be interested in future, and 53 are current CCI ECV users. The majority of participants in both categories deemed the likely impact of changing format to be very little to none. The impact of changing format for GlobTemperature users is slightly higher (Figure 6-25a: 63% state very little or no impact) than for LST_cci users (Figure 6-26a: 71% state very little or no impact). In both cases the file naming convention was only a problem for one participant, whilst changes in metadata specification, naming and number of dimensions, and the number of files and file sizes were of greater concern. On the basis that more respondents currently use CCI ECV products and the impacts of the changes described above are deemed to be little or none, the standard CCI format is advised for LST_cci products [LST-URD-ADV-01-O].

Figure 6-25: Summary of responses to Q.35: (a) shows the number of responses for each impact category as a bar chart (left axis), with the cumulative percentage of responses shown as a line (right axis); and Q.36 (b) indicating the file format changes likely to have the greatest impact on current GlobeTemperature data users. Q.35: As a current or future user of GlobTemperature data, what is the likely impact of incorporating a product that conforms to the CCI data standards, with the differences described above? Q.36: Which one of the possible changes from the GlobTemperature harmonised format would have the largest impact?

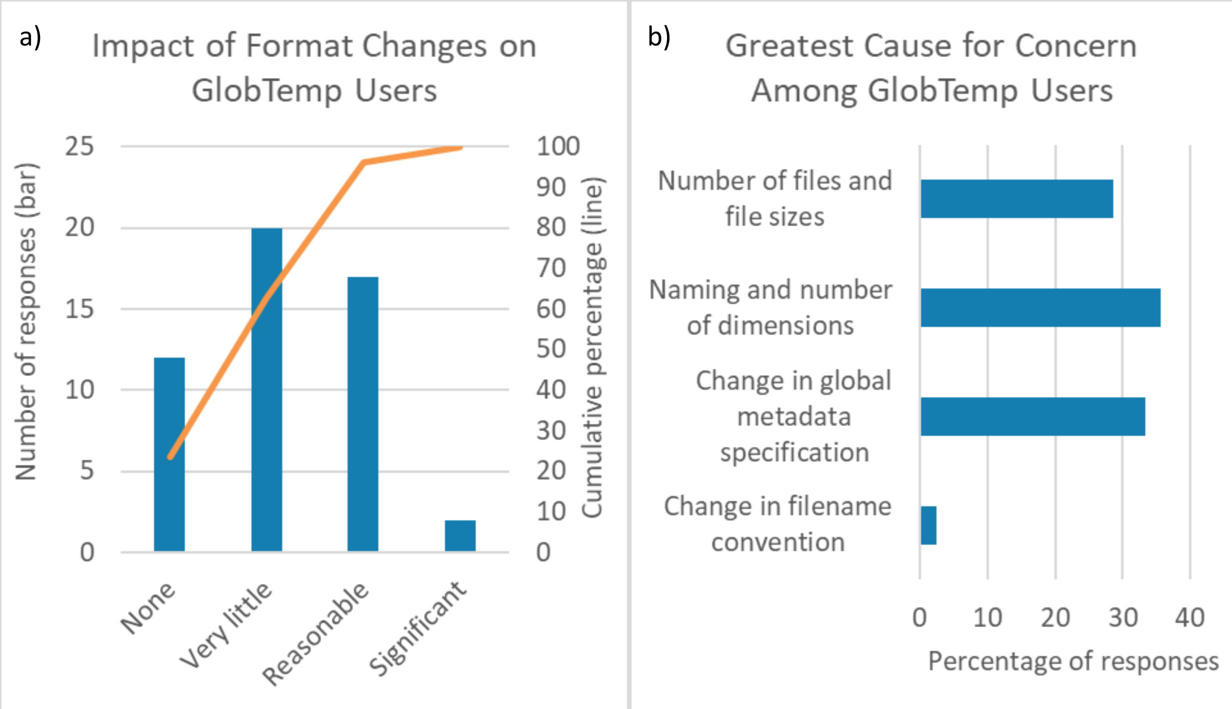
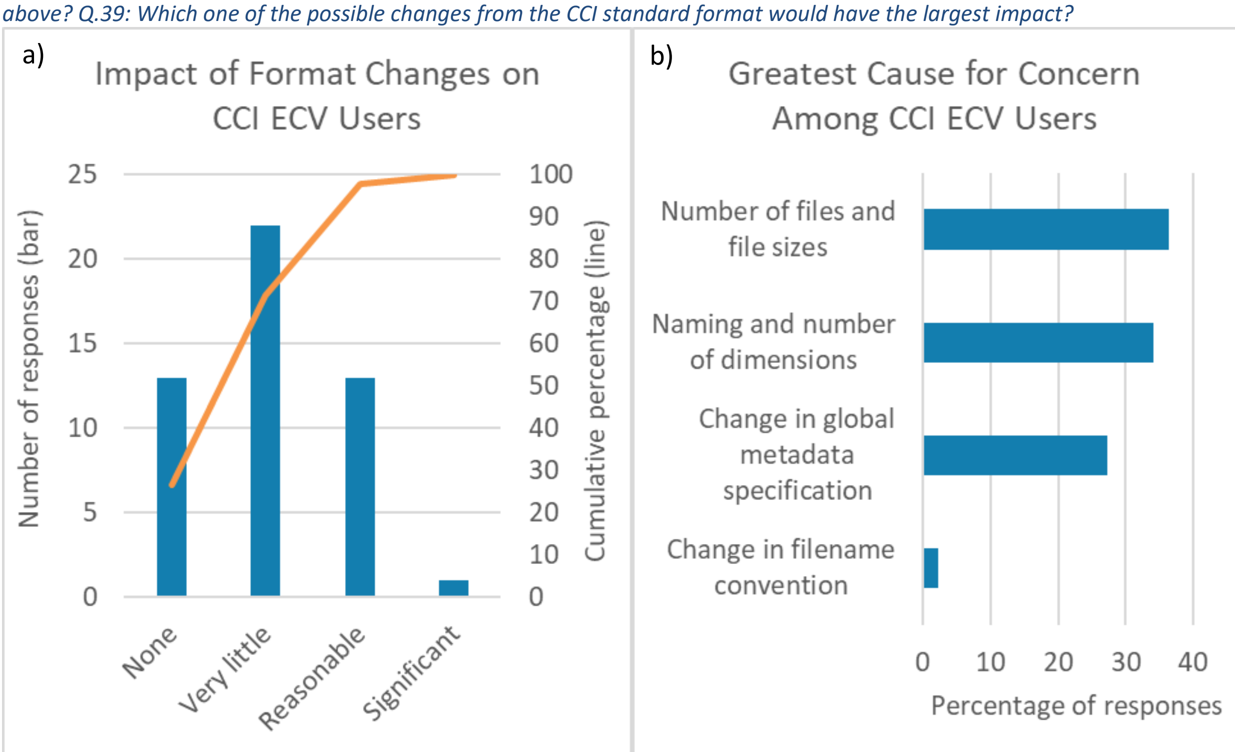


Figure 6-26: Summary of responses to Q.38 (a) shows the number of responses for each impact category as a bar chart (left axis), with the cumulative percentage of responses shown as a line (right axis); and Q.39 (b) indicating the file format changes likely to have the greatest impact on current CCI ECV data users. Q.38: As a current or future user of CCI ECV products, what is the likely impact of incorporating a product that conforms to the GlobTemperature harmonised format, with the differences described above? Q.39: Which one of the possible changes from the CCI standard format would have the largest impact?



6.4.7. Quality Control

Participants were asked to select, in the order of importance, some quality control flags that might be included with the data (Figure 6-27). For this question the rank with the highest vote is selected for each flag, to determine an order of importance [LST-URD-REQ-20-O]:

- Day / night
- Summary cloud
- Summary confidence
- Land
- Aerosol

Participants were also asked to identify any other flags that that they may require with the LST_cci data, such as snow / ice, water body, and individual confidence flags (e.g. pixel saturation, suspect calibration, blanking pulse, etc.). Both snow / ice (66%) and water body flags (75%) reached the criteria for a soft requirement [LST-URD-REQ-21-O]. One participant also requested WVC (assumed here to be water vapour content).

Figure 6-27: Summary of responses to Q.40: Please rank the order of importance of these flags for your application (with 1 being the most important and being the least important).

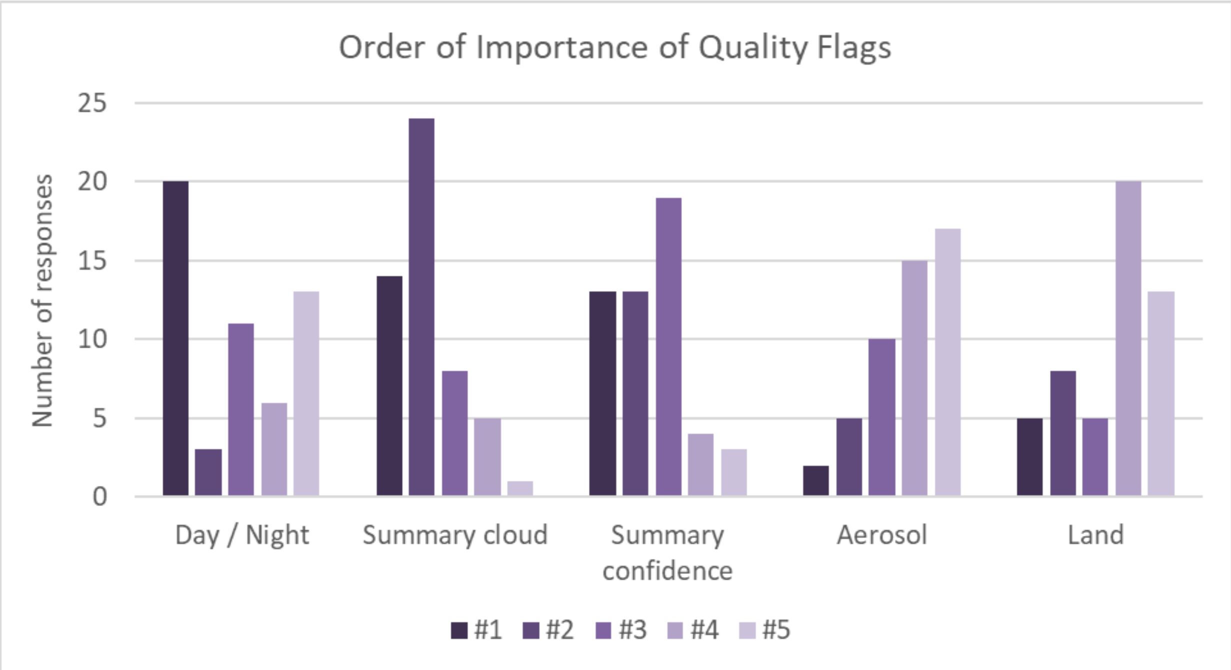
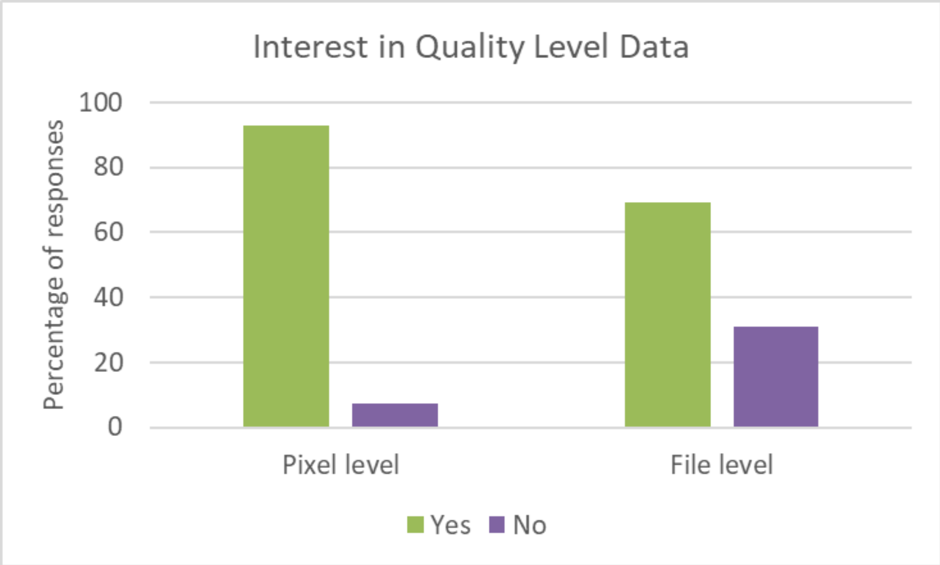


Figure 6-28 shows the requirement for quality level data, which provides more information on the quality of data (for example no data, bad data, worst quality, low quality, acceptable quality, best quality) for a specific pixel [LST-URD-REQ-22-O] and/or file [LST-URD-REQ-23-O]. A clear majority of respondents require this information at both pixel and file level.

Figure 6-28: Summary of responses to the following questions: Q.42: Would you make use of Quality Level data on a pixel level should it be provided? Q.43: Would you make use of Quality Level data on a file level should it be provided? Both questions received 54 responses in total.



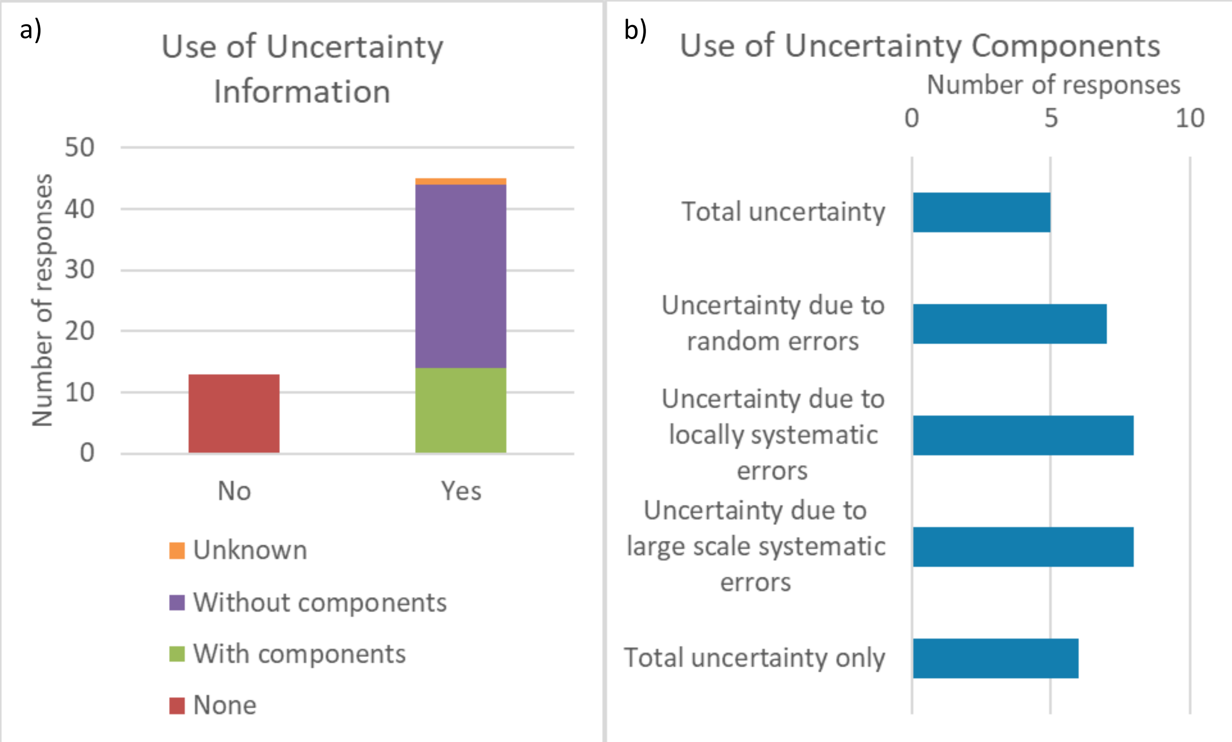
6.4.8. Error and Uncertainty

In this section, a succession of questions were asked to explore the respondent's current and potential use of uncertainty information. The survey begins by asking whether the respondent uses uncertainty data. For respondents that respond positively, further questions are asked to gather information on how uncertainty data are used, and what information is needed. If the respondent indicates they do not use any uncertainty data, subsequent questions focus on establishing why these data are not used. The uncertainty model proposed for LST_cci is to provide an uncertainty budget where possible (Table 6-2).

6.4.8.1. Current use of Uncertainty Information

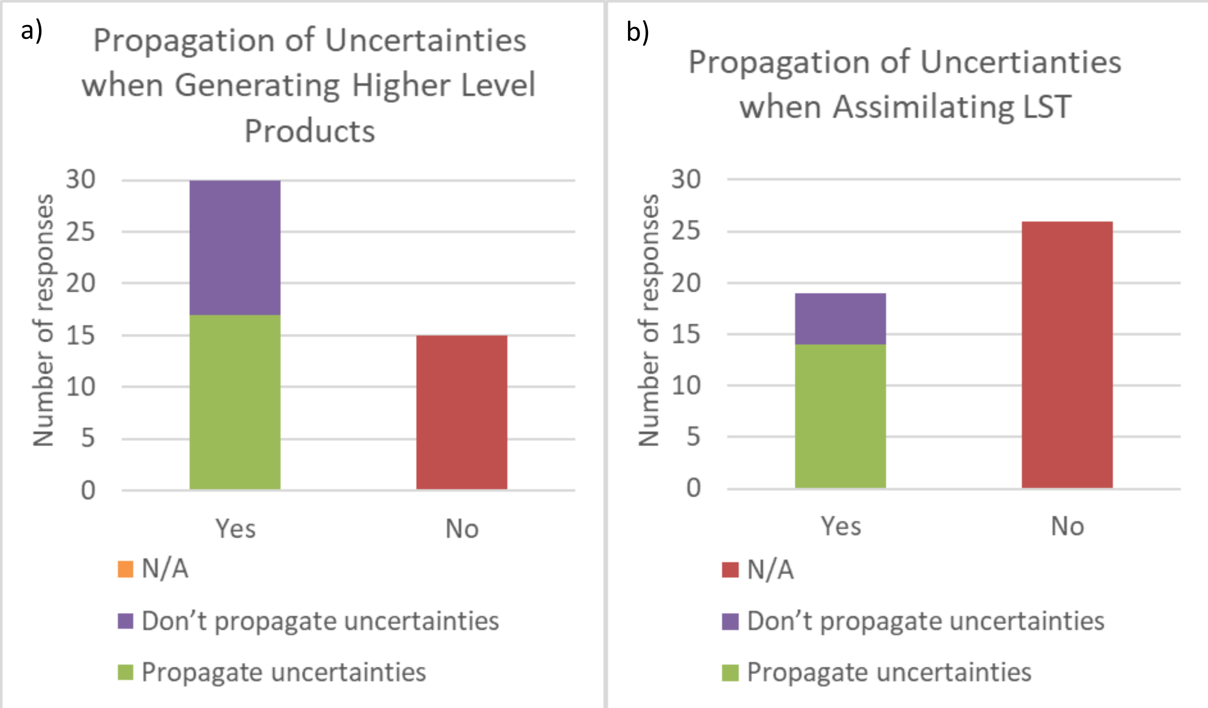
The results of the survey indicate that uncertainty information is used by the majority of respondents; of these, some have used datasets provided with uncertainty components, as shown in Figure 6-29a. Of the 14 participants who have had access to datasets with uncertainty components, eight indicated they had used the components, whilst six had only used the total uncertainty.

Figure 6-29: Summary of current use of uncertainty information. (a) Answers two questions: Q.44: Do you use uncertainty information? And Q.46: Have you used a dataset that is provided with uncertainty information broken down into different components: random, locally systematic, and large scale correlated uncertainties? (b) Describes the components used by those who selected 'yes' to Q.46, in response to questions: Q.47: Which components have you made use of in your work? And Q.48: Which of the uncertainty components did you use?



All participants who stated that they use uncertainty information – whether as a total uncertainty or as individual components – were asked if they generate higher level products or assimilate LST, and whether they propagate uncertainties during these processes. To propagate uncertainties properly, uncertainty components partitioned by their correlation properties are required in order to propagate each component separately; such components have already been provided through GlobTemperature, SST CCI and EUSTACE, and will also be provided with some LST_cci datasets. The majority of participants who generate higher-level products or assimilate LST state in the survey said that they propagate uncertainties appropriately as part of the process. However, these groups are comprised of those who have used uncertainty components, those who have had access to components but not used them (i.e. they had used total uncertainty only), and those who have not used a dataset provided with uncertainty components, indicating that rigorous treatment of uncertainties does not always occur.

Figure 6-30: Summary of propagation of uncertainties when generating higher level products (a) or assimilating LST (b). (a) Shows responses to questions: Q.50: Do you generate higher level products from the LST data provided, for example averaging over longer time periods or larger spatial scales? And Q.51: Do you propagate the relevant uncertainty information in this process? (b) Shows responses to questions: Q.52: Do you assimilate LST data into a model or other system? And Q.53: Do you propagate the relevant uncertainty information in this process?

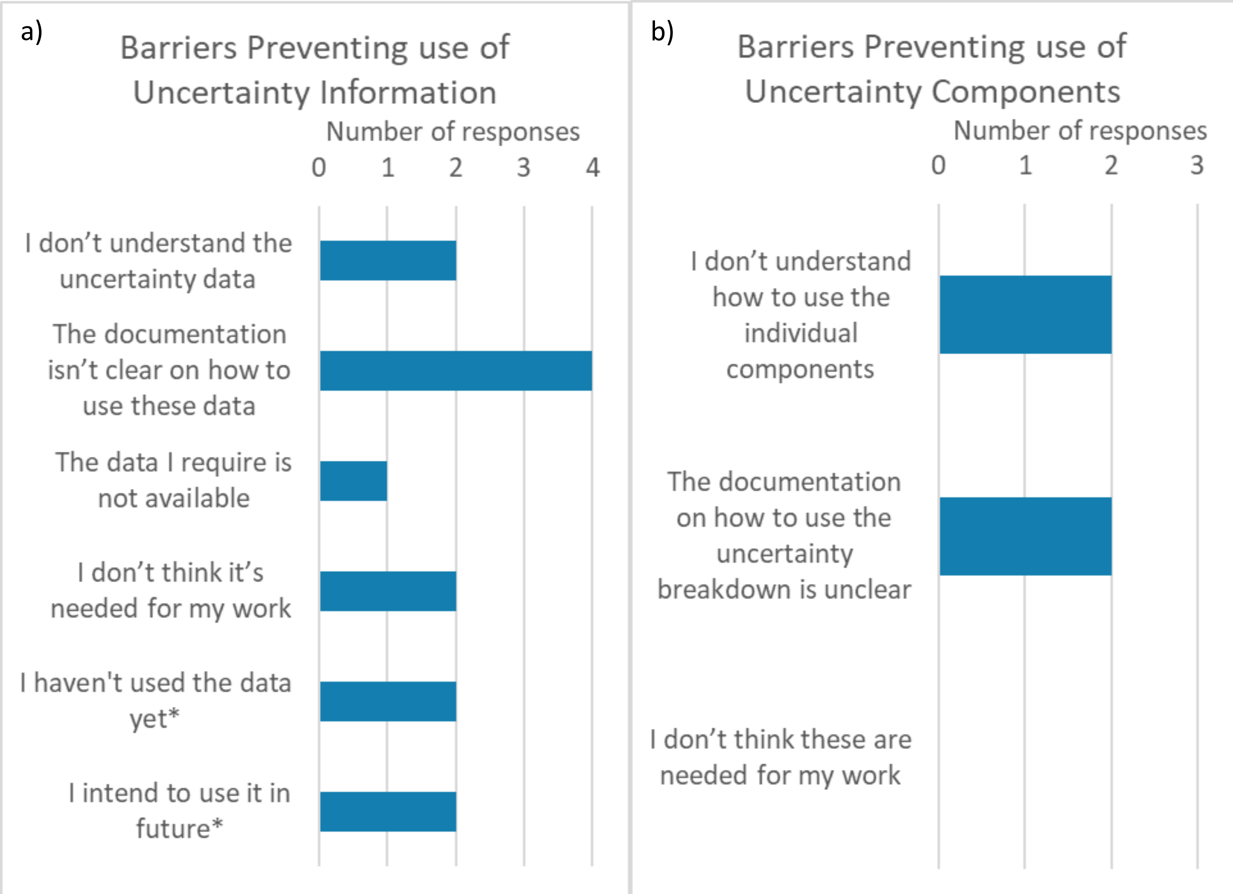


6.4.8.2. Barriers to using Uncertainty Data

Questions are incorporated throughout this section of the survey to understand barriers that exist in preventing the use of uncertainty data at any level, with the aim of providing guidance to the CCI project on what action can be taken to improve use of error and uncertainty data.

From the results of the LST_cci survey, 14 participants indicated they do not use uncertainty data at all. Of these, 12 provided information on the barriers they experience in using uncertainty data (Figure 6-31a). Participants who have access to uncertainty components, but who only use the total uncertainty, were also asked to indicate the reasons why they were not using these component data, and three of the six respondents provided this information (Figure 6-31b). Respondents were hindered predominantly by their lack of understanding of the data, and not having access to sufficient documentation. Some respondents also indicated that they do not use the data yet, or that they intend to use the uncertainty information in future. One participant indicated that the information they require to use uncertainty data is not available, but gave no further information on what would be required.

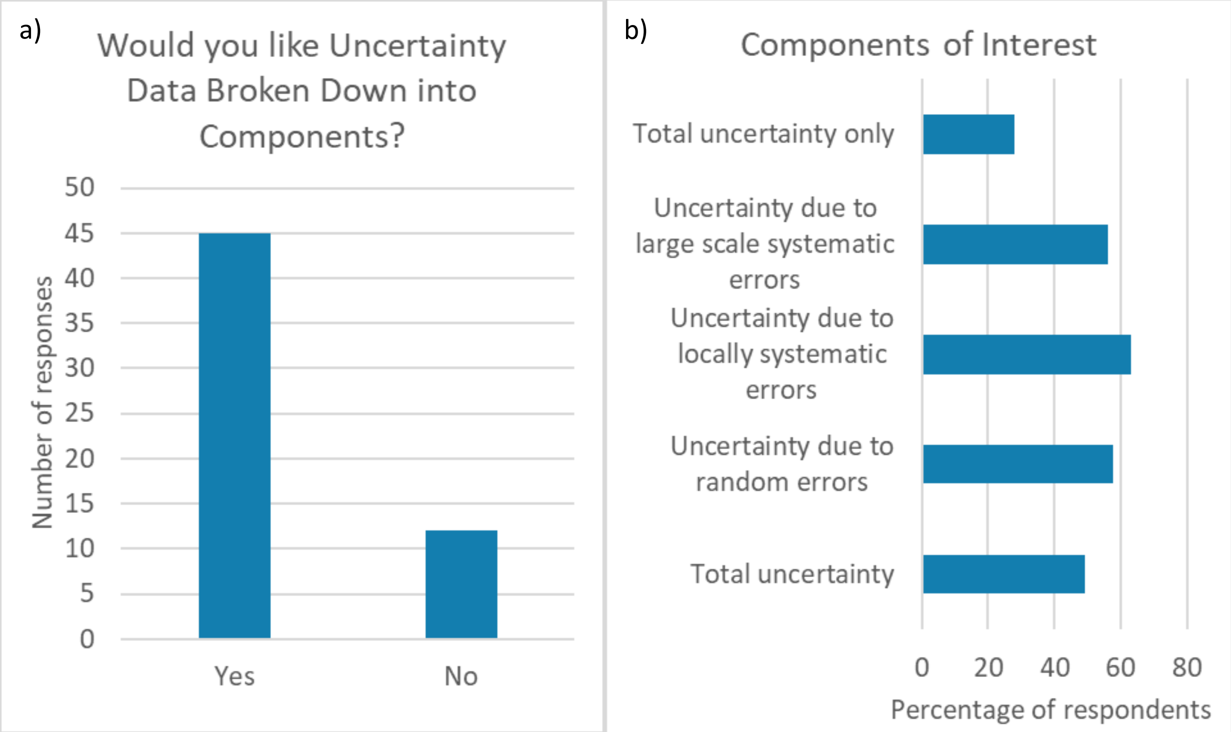
Figure 6-31: Summary of barriers experienced in using uncertainty data (a) and uncertainty components (b). This is in response to the following questions: (a) Q.45: What are the barriers in preventing you from using it? And (b) Q.49: What were the barriers preventing you from using the uncertainty components?



6.4.8.3. Uncertainty Information Requirements

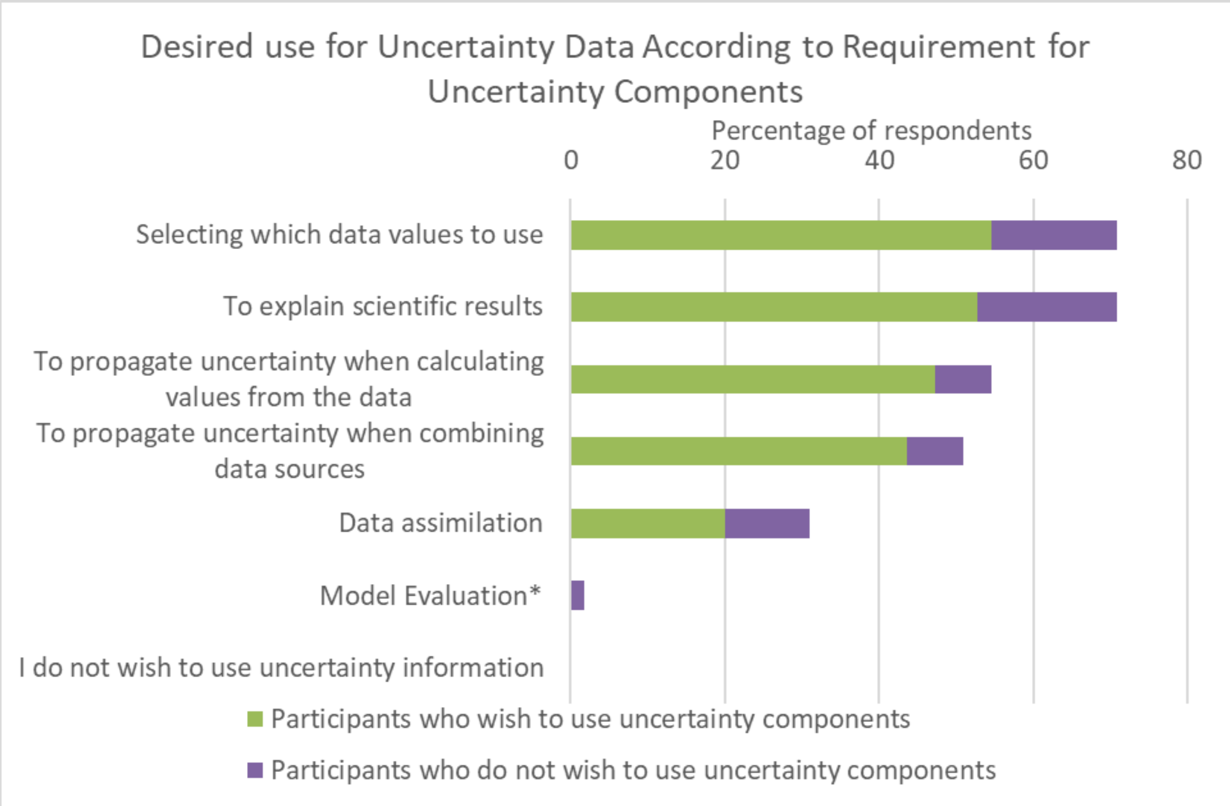
Figure 6-32a shows that 45 participants require the provision of uncertainty components. Of these participants, 41 indicated a need for the total uncertainty and the breakdown of individual uncertainty components, leading to a soft requirement to provide both these data types [LST-URD-REQ-24-LO, LST-URD-REQ-25-O] (Figure 6-32). Although each respondent does not necessarily require each component, the results shown in Figure 6-32b demonstrate that each component is equally important when considering all user responses.

Figure 6-32: Summary of responses to the following questions: (a) Q.55: Would you like uncertainty estimates broken down into different components (random, locally systematic and large-scale systematic) in addition to a total uncertainty? And (b) Q.57: Which components would you need to use?



A total of 55 participants responded to Q.54 (Figure 6-33) indicating a range of uses for uncertainty data. The most popular uses of uncertainty information amongst these respondents are to select which data values to use, and to help explain scientific results. Of these 55 respondents, 45 would use uncertainty components. There is no apparent link between activity and requirement for total uncertainty only or uncertainty components, even though some of these tasks should require components (e.g. re-gridding of data). This may indicate that information is required with uncertainty components detailing how and why users could make use of these data [LST-URD-ADV-23-OI]. A summary is provided in Figure 6-33.

Figure 6-33: Summary of intended use of uncertainty data (Q.54), partitioned by the requirement for total uncertainty budget only, and the provision of uncertainty components (Q.55). Q.54: For what purposes would you like to use uncertainty data? Q.55: Would you like uncertainty estimates broken down into different components (random, locally systematic and large-scale systematic) in addition to a total uncertainty?



The 12 participants who did not want to use uncertainty components were asked why in Q.56 'Please comment on why you do not want uncertainty estimates broken down into components'. Of these, seven provided a reason, which can be summarised as follows:

- I do not need the components for my work* (4 respondents)
- I would not be able to use the components* (3 respondents)

Finally, Q.58 asks: 'What documentation would you require to make use of uncertainty data broken down into components?' Both descriptions (51) and worked examples (35) are requested, and one participant left the following comment:

- Information about spatial and temporal structure of the error components. For example, length and time scales of correlation decay, functional form of the correlation decay. For large-scale systematic errors, information regarding the structure of those errors*

Combining this information with the barriers discussed in section 6.4.8.2 leads to the requirement for any uncertainty information to be provided with clear documentation which includes descriptions of the data, how to use them, and worked examples [LST-URD-REQ-26-O]. Where possible, information on the spatial and temporal structure of the error components should also be provided [LST-URD-ADV-24-O].

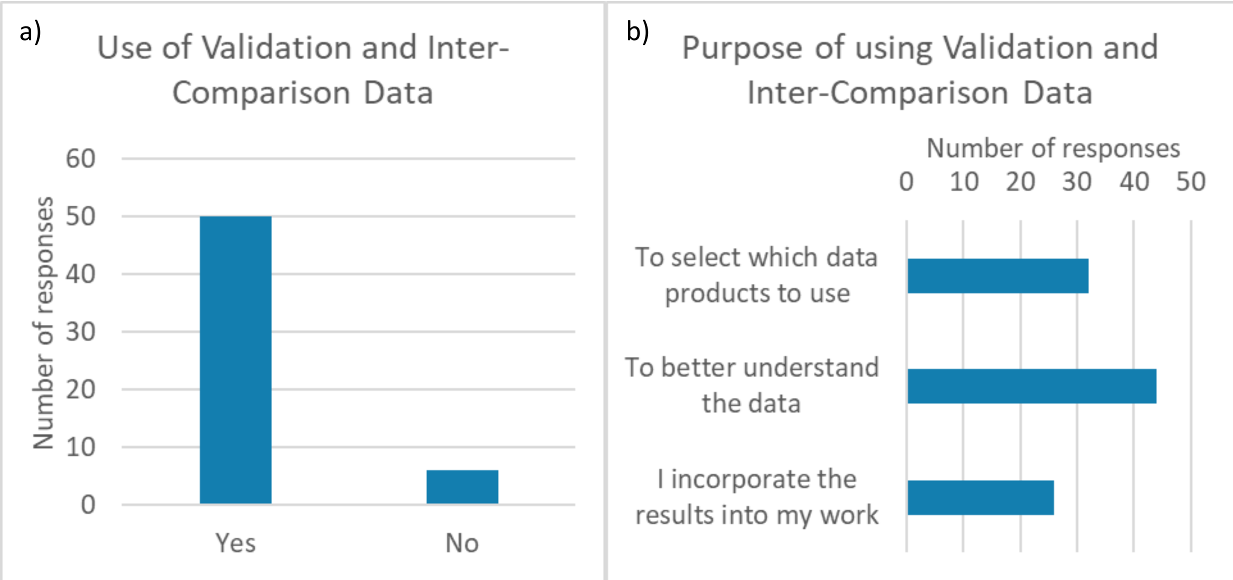
6.4.9. Validation and Inter-comparison

6.4.9.1. Current use of Validation and Inter-comparison Data

Participants were asked to provide information on their current use of validation and inter-comparison information, before providing their requirements. The results displayed in Figure 6-34 show that the vast majority of participants make use of validation and inter-comparison results provided with data sets. These are used for selecting data products to use, to improve understanding of the data, and are directly incorporated into user applications. Two participants provided further information on how they use the data:

- 'Cross-validation of models using different satellite-based LST data'*
- 'Validation and inter comparison are important for understanding whether additional 'error terms' are required to assimilate the data in the statistical schemes we use. Inter-comparison data indicates likely compatibility with other data sources and whether additional work is required to harmonise them before combination'*

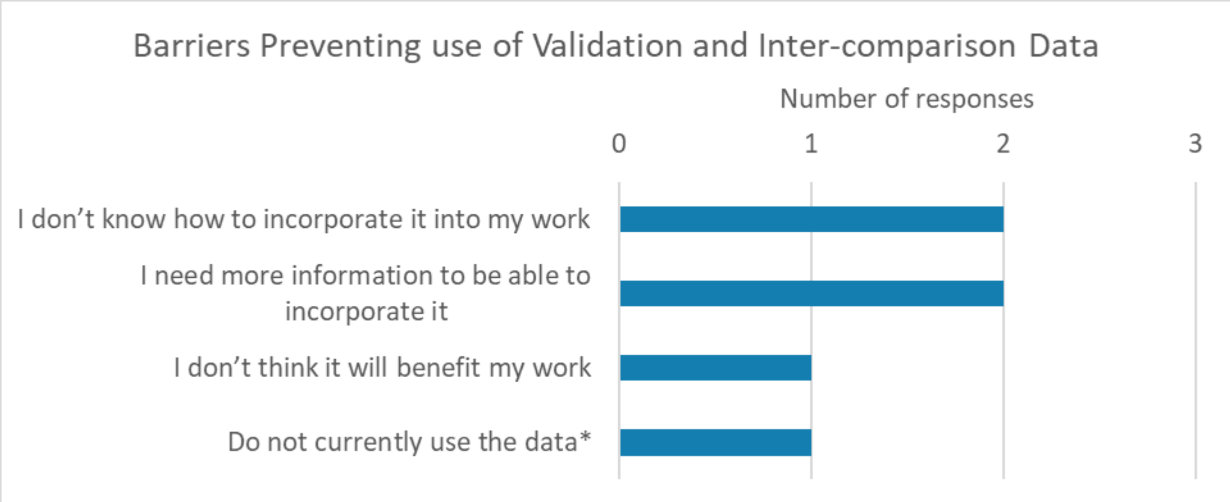
Figure 6-34: Summary of responses to the following questions: (a) Q.59: Do you consider validation and inter-comparison results produced by the data providers in your work (either using results to guide product selection or directly incorporating results)? (b) Q.60: For what purpose do you use validation and inter-comparison data?



6.4.9.2. Barriers in using Validation and Inter-comparison Data

The six respondents who indicated that they did not use validation and inter-comparison data were asked to provide information on why they do not currently make use of these data. Six responses were provided, summarised in Figure 6-35. The main issues experienced were a lack of understanding of how to make use of the information [LST-URD-ADV-29-O], or that more information is needed by the user to enable them to incorporate the data into their work. One participant specified a requirement for detailed information to be provided concerning the time of LEO LST acquisition, and highlighted the difficulties in using L3 satellite data where temporal averaging has been performed given the diurnal cycle of LST. This is particularly important in high latitude regions where there are multiple overpasses each day and the time of capture may be critically lost during temporal averaging [LST-URD-REQ-06-O]. (This comment was also made independently by a member of the CRG – see Section 7.3.2.)

Figure 6-35: Summary of responses to Q.61: What are the barriers preventing you from using validation and inter-comparison data?



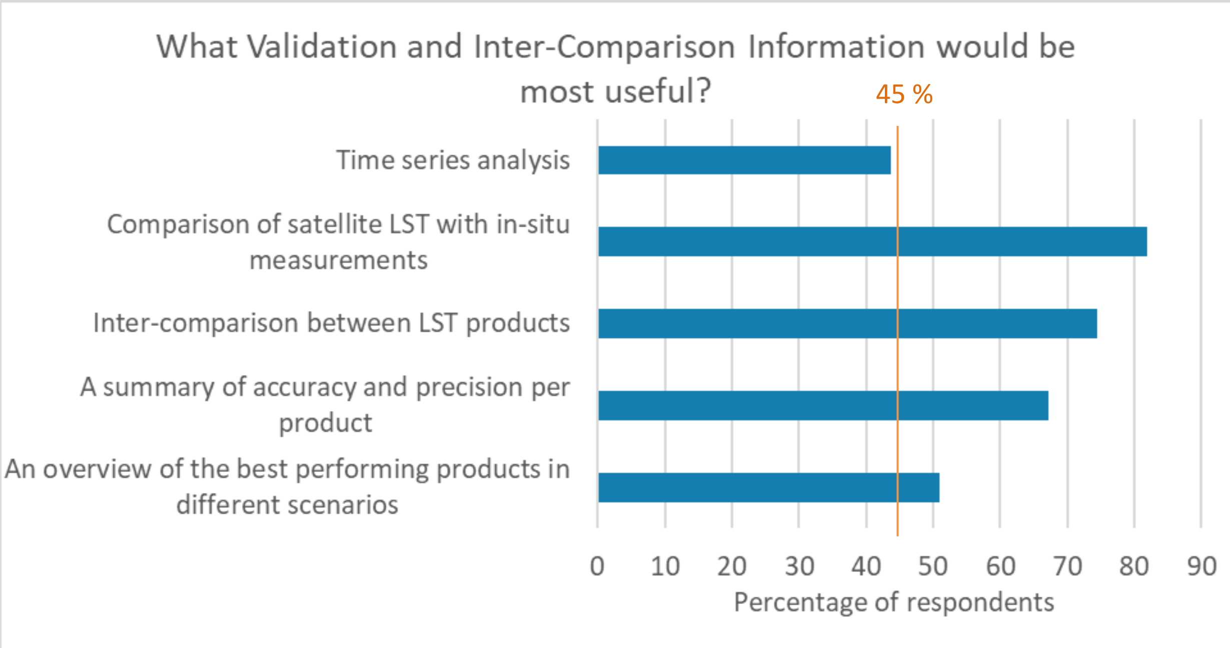
6.4.9.3. Validation and Inter-comparison Requirements

Participants require a range of validation and inter-comparison data, as summarised in Figure 6-36. Three comments were also provided:

- 'Inter-comparison of outputs from ET models, then the sole LST information varies from one product to the other'*
- 'Stability analysis'*
- 'Validation of uncertainty information, if not included in the above'* [LST-URD-ADV-27-O]

Comparisons of satellite LST data with in-situ measurements [LST-URD-REQ-27-O], inter-comparisons between LST products [LST-URD-REQ-28-O], a summary of accuracy and precision per product [LST-URD-REQ-29-LO], and an overview of the best performing products in different scenarios [LST-URD-REQ-30-O] all meet the criterion for a soft requirement. Analyses of time series do not quite meet the criterion for a soft requirement. However, as there is a clear requirement from the CRG to ensure the provision of homogenised time series, free from non-climatic effects, a requirement to perform time series analysis is implicit [LST-URD-ADV-26-O].

Figure 6-36: Summary of responses to Q.62: What validation and inter-comparison information would be most useful for your primary application? (The 45% line is included to show the threshold for a soft requirement – see Section 4.)



6.4.10. Clouds

Bayesian and probabilistic methods of identifying cloud use the Bayesian equation, or a 'naïve-Bayes' algorithm to calculate a clear-sky probability for each LST retrieval. These methods can provide a consistent approach to cloud clearing across different sensors, which is useful when creating products from instrument series, without the barrier to generalisation common for instruments that may operate at slightly different wavelengths. Probabilistic methods also offer the potential for application-specific cloud screening. By providing a clear-sky probability for each pixel, the user can determine the best threshold to use for their specific application, as opposed to using a pre-defined summary cloud mask.

Participants were asked to identify a preference for either a consistent approach, such as probabilistic methods, or a sensor-specific approach to cloud clearing. The results from this survey indicate no overall user preference for either approach (Figure 6-37a). Participants were also asked if they would prefer data pre-screened for cloud by the data provider, or to apply the mask themselves. Again, the results indicate no overall user preference for either option (Figure 6-37b). However, when asked if they would prefer LST data to be provided with a binary cloud mask, clear-sky probabilities, or both, there was an overall preference for both types of information [LST-URD-REQ-31-O, LST-URD-REQ-32-O] (Figure 6-37c).

Figure 6-37: Summary of responses to the following questions: (a) Q.63: Would you prefer a consistent approach to cloud-clearing across sensors, or a 'best for each sensor' approach, even if this means changes between sensors? (b) Q.64: Do you prefer LST data to be pre-screened for cloud-contaminated pixels, or would you prefer to apply a bitmask or probability screening yourself? (c) Q.65: Would you prefer a pre-defined binary cloud mask or clear-sky probabilities to enable you to define your own cloud mask (or both)?

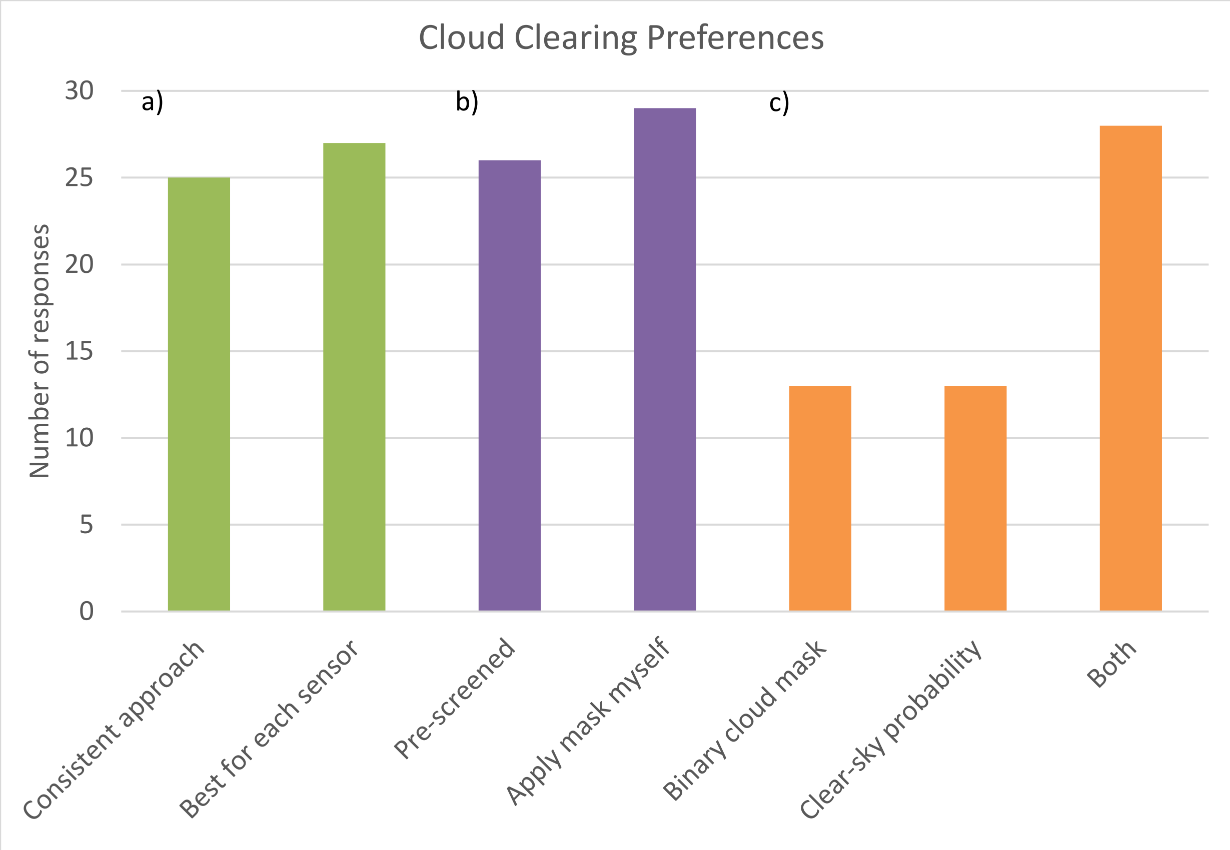
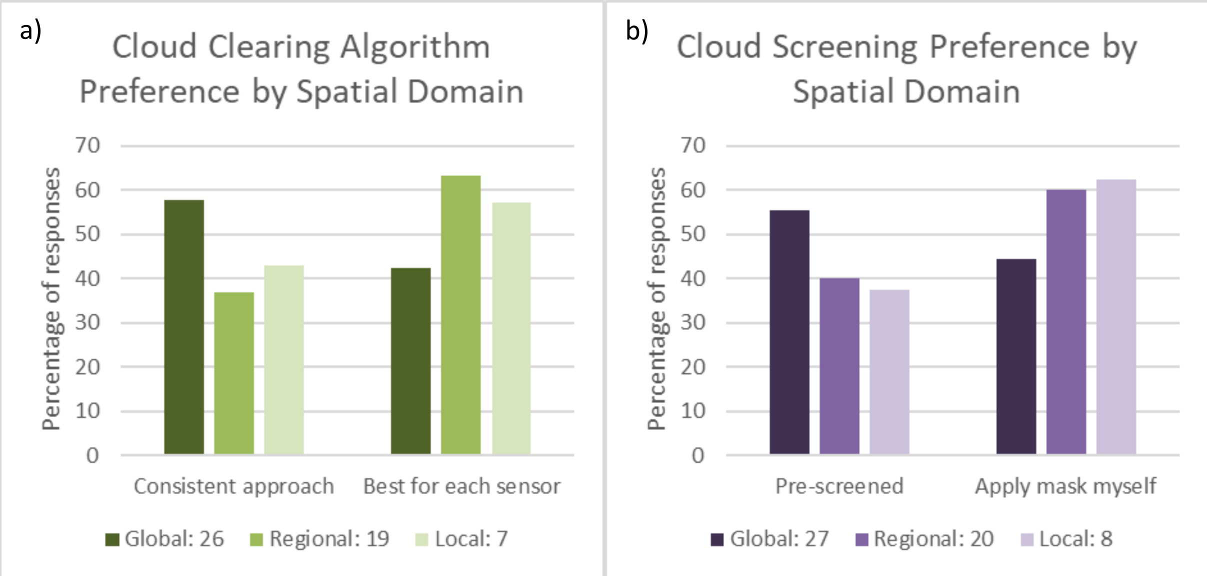


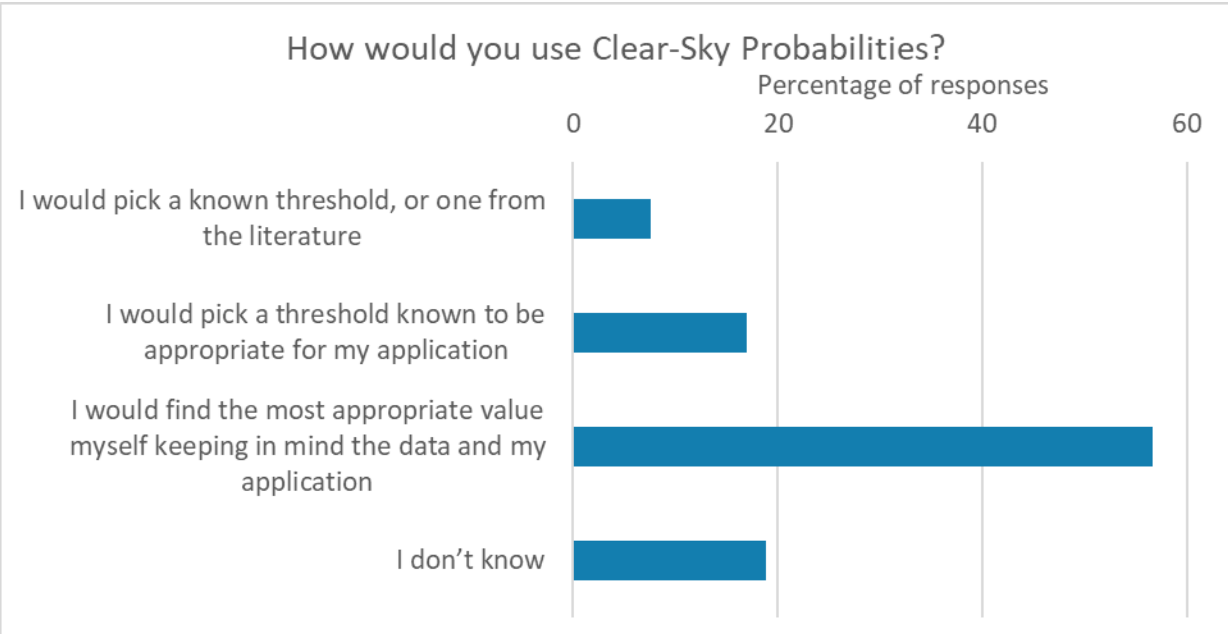
Figure 6-38 presents the results to Q.63 and Q.64 partitioned by user spatial domain. The results indicate that those who work on global studies would prefer a consistent approach to cloud clearing, and data that are pre-screened [LST-URD-ADV-19-O]. By contrast, users conducting regional and local studies prefer a cloud clearing approach considered to be best for the sensor, and to apply a cloud mask themselves [LST-URD-ADV-20-O].

Figure 6-38: Responses to Q.63 (a) and Q.64 (b) partitioned by user spatial domain. Q.63: Would you prefer a consistent approach to cloud-clearing across sensors, or a 'best for each sensor' approach, even if this means changes between sensors? Q.64: Do you prefer LST data to be pre-screened for cloud-contaminated pixels, or would you prefer to apply a bitmask or probability screening yourself?



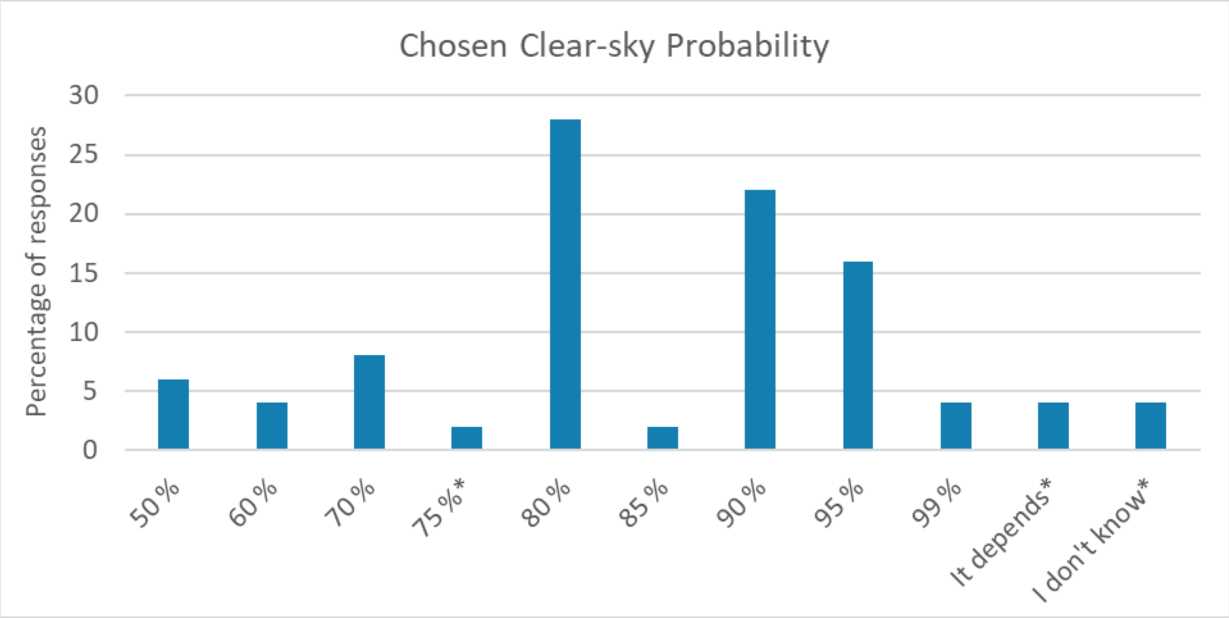
Q.66 asks users how they might expect to use clear-sky probabilities, if provided. Figure 6-39 indicates the clear majority would find the most appropriate threshold value, keeping in mind the data and application, resulting in threshold values that may vary between applications, case studies, and datasets.

Figure 6-39: Summary of responses to Q.66: If you were provided with clear-sky probabilities, how would you use this data to cloud clear LST data?



Q.67 aims to follow up from results shown in Figure 6-39, and gauge what users might consider to be an appropriate threshold value to cloud clear their data using clear-sky probabilities. Figure 6-40 indicates that there is considerable variability in the threshold values selected by participants, with the most popular choices at 80 %, 90 % and 95 % clear-sky probability.

Figure 6-40: Summary of responses to Q.67: If you were to choose a clear-sky probability threshold to define a cloud-contamination mask for your primary application, what value do you feel might be appropriate?



Q.68 asks participants what information they require in order to make use of clear-sky probabilities. Both descriptions and worked examples were required [LST-URD-REQ-33-O], and two participants provided additional information (indicated by *). A summary of these results follows:

- Descriptions (89%)
- Worked examples (57%)
- Validation* [LST-URD-ADV-28-O]
- Documentation providing known thresholds for given applications to use as a starting point to identify the best value for a given case* [LST-URD-ADV-31-O]

6.4.11. Comments

Before participants exit the survey, they are offered the opportunity to provide any other relevant comments. In some cases advice notes are issued from comments and it is advised that these are considered by the project team. A summary of all responses can be seen in Table 6-7, however the key points are summarised here:

- Higher spatial resolution required [LST-URD-ADV-21-LOI]
- Summary information provided on the availability and characteristics of different LST products [LST-URD-ADV-05-O]
- Require access to a temporally complete LST product, which uses either microwave data, or models to estimate LST under cloudy skies [LST-URD-ADV-11-LOI]
- Easy data access – the GlobTemperature portal is a good example [LST-URD-ADV-04-LI]
- Integrate global AVHRR data to extend data record length for climate studies [LST-URD-ADV-14-O]
- Uncertainty breakdown information could be really useful, but consideration needs to be given to whether all errors are captured within the uncorrelated, local and large-scale categories. As an example, residual cloud does not fit neatly into one of these categories [LST-URD-ADV-25-LOI]. Information about likely distributions of errors and their spatial patterns might be useful to understand limitations [LST-URD-ADV-24-O]

- Simplicity is the key to success – data provided with a clear and concise documentation including description of the data, including how it was produced and the known issues all merged into one document; avoid over use of acronyms [LST-URD-ADV-03-I]
- Information on how comparable LST_cci products will be to other CCI products, for example spatial and temporal averaging, uncertainties, or any changes likely to impact LST such as vegetation fractional cover [LST-URD-ADV-08-OI]

Table 6-7: Summary of all comments provided by respondents at the end of the survey Q.69: Do you have any further comments on LST data requirements for climate before exiting and submitting your responses to the survey?

Comments
Higher spatial resolution please!
Information on availability and characteristics of different LST products
I would like to use LST data for climate model evaluation via validation notes. I normally average the observational data into seasonal means and then make climatological averages over as many years as are available. I would compare the LST observation dataset with model data. My main concern is that model data doesn't care whether it is cloudy or not so I would have two options: 1 - create a new model diagnostic which is LST data for cloud free grid boxes, 2 - use an observational product that uses microwave sensors or models to estimate LST under cloudy skies so therefore has a temporally complete set of data going into the monthly means. I would prefer you to make an option 2 if possible.
Nothing about Land Surface Emissivity ?
I like accessing data via the GlobTemperature portal. I hope the CCI data will be similarly easy!
Can we used those data for trend detection, especially merged long time series done with different sensor. Please avoid using too much acronyms
To be more relevant for climate studies, I think it is necessary to integrate global AVHRR data to extend the length of data records.
A break down of uncertainty information would be great, but though needs to be given to whether the uncorrelated/local/large-scale trinity can cover the full range of errors found or suspected to be in the LST products. In particular cloud is a tricky one as residual cloud doesn't fit neatly into any of the three categories. Information about likely distributions of errors and their spatial patterns might be useful to understand the limitations.
I have considered 2 types of applications related to the urban heat load research in my answers: 1) Spatial LST patter over cities; 2) Times series analysis over cities. Because of that my answers can be confusing, as these two applications in fact require a bit different type LST datasets. Please, feel free to contact me in case of any further questions.
Survey was too long!
I think simplicity is the key to success. I love it when data comes with a clear (but concise) description of the data, how it was produced, what the known issues are etc.: all merged in one document, but separate sections, so the user can easily select which sections are useful for their purpose.
I'm interested in comparing LST with other CCI (esp. land cover) datasets, so would appreciate information on how comparable the different CCI datasets are with LST, ie. same temporal and spatial averaging, uncertainties, any considerations likely to have significant influence on LST such as changes in vegetation fractional cover over time/space...

6.5. Summary

Key outcomes from the online survey are summarised below. Many of these points relate to requirements and advice notes described in Section 11. It should be noted that these requirements and advice notes are based on the survey responses received, where it has been assumed that all responses truly reflect user needs for climate applications. However, in practise, responses are subject to participants understanding what a climate application really means, and that there is a risk some of the results may be skewed by non-climate users of LST.

6.5.1. General information

The online user requirements questionnaire collected responses over two months in summer 2018. Overall:

- 76 responses
- 75% completion rate
- Responses from all over the world
- Variety of institutions
- 58 respondents interested in future contact regarding at least one of the options provided

6.5.2. Applications

Respondents to the online questionnaire work in a variety of climate-based applications. Information on respondent applications was gathered to provide context for the results of the questionnaire:

- Model evaluation and evapotranspiration / vegetation or crop monitoring were the most popular primary applications, followed by urban climate, water cycle and validation / inter-comparison
- Secondary applications covered the range of options well, with evapotranspiration / vegetation or crop monitoring and extreme events receiving the most selections, followed by validation / inter-comparison, surface / atmosphere interactions and regional climate

6.5.3. Data Use

Current use of LST data among respondents was collected, together with use of other CCI ECV products:

- Most participants are current users of LST data
- L2 and L3C products are the most commonly used
- MODIS is most popular amongst participants, with 36 users
- Out of 45 responses, 22 use GlobTemperature datasets
- Out of 76 responses, 52 use CCI ECV products
- The majority of participants are either currently using, or may use GlobTemperature and CCI products in the future
- All of the proposed products for the LST_cci project are of interest to participants

6.5.4. Concerns regarding LST

The concerns raised by respondents to the questionnaire regarding the use of LST are (in priority order):

- Spatial resolution is too low [LST-URD-ADV-21-LOI]
- Errors caused by cloud contamination [LST-URD-ADV-33-LOI]
- It is not clear exactly what LST represents [LST-URD-ADV-02-OI]
- Temporal resolution is too low
- Dataset time series are not long enough
- Lack of appropriate or accurate uncertainty information

6.5.5. Data specification

User requirements for spatial domain, observation times, temporal and spatial resolution, dataset length, accuracy, precision and stability are:

- LST data should be provided globally [LST-URD-REQ-09-O]
- Observations should be provided at all times of day [LST-URD-REQ-10-O]
- Temporal, spatial, accuracy, precision and stability requirements are provided in Table 6-8 [LST-URD-REQ-11-O to LST-URD-REQ-16-O, LST-URD-OPT-11-O to LST-URD-OPT-16-O]

Table 6-8: Summary of threshold, breakthrough and objective requirements relating to questions 20-25 shown in Figure 6-15 to Figure 6-20.

	Threshold	Breakthrough	Objective
Dataset length	10 years	30 years	> 30 years
Spatial resolution	1 km	< 1 km	< 1 km
Temporal resolution	6 hours	1 hour	< 1 hour
Accuracy	1 K	0.5 K	0.3 K
Precision	1 K	0.5 K	0.3 K
Stability	0.3 K / decade	0.2 K / decade	0.1 K / decade

User priorities for dataset specification are:

- High quality data more important than spatially complete fields [LST-URD-REQ-18-O]
- High temporal resolution more important for global studies, whilst high spatial resolution is more important for local studies [LST-URD-ADV-17-O, LST-URD-ADV-18-O]
- Dataset length is more important for global studies, whilst high data resolution is more important for local studies [LST-URD-ADV-17-O, LST-URD-ADV-18-O]

6.5.6. Data Format and Metadata

LST_cci data products will be provided in NetCDF format, and questions in the survey focused on the impact of using either the CCI standard format or the GlobTemperature harmonized format, which some participants are already using. The results of the online survey indicate that:

- NetCDF format is acceptable for the majority of participants [LST-URD-REQ-01-O]

- Changes between the standard CCI and GlobTemperature harmonized format are likely to have very little to no impact on the majority of users
- Changes in number of files and file sizes, naming and number of dimensions, and change in global metadata specification are more likely to cause problems than changes in file naming conventions
- Since this questionnaire was issued and analysed the decision has been made to use the CCI standard format for LST_cci.

6.5.7. Quality Control

Quality information will be provided with the LST_cci products. This should include:

- QC flags [LST-URD-REQ-20-O, LST-URD-REQ-21-O] for (in priority order):
  - Summary cloud
  - Summary confidence
  - Day / night
  - Land
  - Aerosol
  - Snow / ice
  - Water body
- Quality level data on a pixel and file level [LST-URD-REQ-22-O, LST-URD-REQ-23-O]

6.5.8. Error and Uncertainty

Uncertainty information will be provided as part of the LST_cci products. The results of the survey indicate:

- Most participants make use of available uncertainty data
- 14 participants have used a dataset provided with uncertainty components, eight of whom made use of this data
- Of the 30 participants who generate higher level products from LST data, 17 propagate uncertainties
- Of the 19 participants who assimilate LST data, 14 propagate uncertainties
- The majority of participants require provision of uncertainty components. Most of these would make use of the total uncertainty alongside other components [LST-URD-REQ-24-L, LST-URD-REQ-25-O]
- Barriers in using uncertainty data and the components largely relate to a lack of understanding of how to use these data, and insufficient clear documentation [LST-URD-ADV-23-OI]
- Both descriptions and worked examples are required to guide use [LST-URD-REQ-26-O]

6.5.9. Validation and Inter-comparison

Validation and inter-comparison will be a significant part of LST_cci, with this work being carried out independently from the data production. The results of the survey indicate that:

- The majority of participants consider validation and inter-comparison results as part of their work

- Barriers in using validation and inter-comparison information are predominantly caused by a lack of understanding of how to incorporate the data, and a lack of available information [LST-URD-ADV-29-O]
- Provision of information on the agreement between satellite LST and in-situ measurements is a priority for most users, but all proposed validation and inter-comparison is of interest [LST-URD-REQ-27-O to LST-URD-REQ-30-O, LST-URD-ADV-26-O]
- Participant comments indicate a need for validation of uncertainty information and clear-sky probabilities [LST-URD-ADV-27-O, LST-URD-ADV-28-O]

6.5.10. Clouds

Existing LST data sets are typically provided with binary cloud masks. Probabilistic cloud clearing methods are proposed for some LST_cci products. The results of the survey indicate that:

- Participants would like the provision of both a binary cloud mask and clear-sky probabilities [LST-URD-REQ-31-O, LST-URD-REQ-32-O]
- Clear-sky probabilities would be used to cloud clear by finding the most appropriate value for the task, considering the data used, and the application
- Clear documentation should be provided with clear-sky probabilities, including descriptions and worked examples [LST-URD-REQ-33-O]

7. Interviews with the Climate Research Group

7.1. Context

The Climate Research Group (CRG) currently consists of the six UCS partners (Met Office, DMI, U. Hamburg, MPI, LIST, MeteoRomania), together with colleagues from MeteoSwiss and members of the CMUG working with LST at the Met Office Hadley Centre. Interviews were held with one or two representatives from each CRG partner group in order to gain an in-depth understanding of their LST user requirements, with a particular focus on the research proposed for the UCS or CCI-related project work.

Aim: To put questionnaire results into context and gather detailed user requirements that cannot be captured via a generalised questionnaire.

7.2. Discussion Structure

During the interviews participants are given the opportunity to discuss their specific application, and thoughts about LST datasets regarding their application. Table 7-1 summarises the questions asked during each interview.

Table 7-1: Overview of discussion topics covered in Climate Research Group (CRG) interviews.

Topic	Detail
Application	❖ Please provide a summary of your application ❖ An application category should be agreed using those from the online survey
Current LST data use	❖ Which datasets do you currently use? ❖ What do you consider to be the advantages and disadvantages of using LST data?
Benefits delivered by the LST_cci project	❖ From the list of proposed datasets/sensors, which datasets are of most interest? ❖ What LST developments of are of most interest? (e.g. provision of uncertainties, improved dataset length, inter-sensor consistency, merged products, etc.)
LST use	❖ Please provide details on how you currently use LST data for your application? ❖ What do you hope to do with LST data from the CCI project, as part of your UCS or project?
Required improvements in LST datasets	❖ What improvements to LST data do you need to see an impact in your application? ❖ What improvements do you hope to see from the LST_cci project, which are not already provided?
Uncertainty components	❖ How will you use the uncertainty data provided in the LST_cci project? ❖ What information do you need to make use of these data? ❖ In detail, how will you apply the data to your work (if known)?
Clouds	❖ How will you use clear-sky probabilities provided with the LST_cci project?

Topic	Detail
	❖ What information do you need to make use of these data? ❖ In detail, how will you apply the data to you work (if known)?
Concerns	❖ What are you main concerns regarding LST data?
Ideal dataset	❖ What is your ideal LST product?
Anything else	❖ Is there anything else you would like to raise that has not already been discussed?

7.3. Results and Analysis

The following sections summarise the each UCS/CRG project and the key requirements provided by each partner. Further details of the information obtained during each interview are provided in Appendix B.

7.3.1. UCS 1 Interview: Global and Regional Trends in LST (Met Office Hadley Centre)

UCS application areas: Climate Monitoring

UCS objectives: To assess regional and global trends in the LST_cci products and compare these with equivalent trends in land surface air temperature (LSAT). In the first instance, the UCS will assess the temporal stability of LST CDR's by comparing time series of LST with spatially and temporally matched homogenised LSAT time series, e.g. homogenised station data from the EUSTACE project. Assuming the temporal stability of the LST products is sufficient, global and regional trends in LST anomalies will be calculated and compared with equivalent trends in LSAT, using at least one key LSAT dataset (e.g. CRUTEM). The UCS will also compare trends in IR LST and MW LST to assess differences that may be due to clear sky (IR) and all-sky sampling (MW).

Summary of LST Application: The Met Office Hadley Centre (MOHC) have existing experience in using satellite LST data, including using SEVIRI LSTs from the LSA-SAF and MODIS Aqua L2 LSTs from GlobTemperature to estimate LSAT, and MODIS Aqua L3 1 km LSTs to characterise surface urban heat islands in China. The MOHC also used the GlobTemperature (A)ATSR CDR to perform a spatio-temporal analysis of the relationship between LST and LSAT, including the comparison of global and regional trends in LST and LSAT. The priority datasets for this UCS will be LEO IR and MW, although GEO IR data may also be considered for the analysis of regional trends. The UCS will make use of the uncertainties provided with the LST_cci products and the MOHC are already experienced in dealing with uncertainty components. Uncertainty components will be propagated when aggregating data to a coarser resolution to compare with the gridded LSAT products, and considered when estimating the uncertainties on calculated trends. They may also be used to discard some LST observations. The MOHC welcome the idea of a probabilistic cloud mask as this will enable them to 'tune' pixel rejection based on the specific requirements for each component of the UCS.

Key requirements:

- ❖ Priority LST_cci products will be LEO IR and MW (L3)
- ❖ Minimum spatial resolution required: 0.05° (for assessment of homogeneity of LST_cci products using homogenised station data)

- Minimum temporal resolution required: daily (for assessment and impact of extreme events)
- Multi-decadal LST CDRs: minimum of 15 years, 30 years preferred
- A homogenised time series is critical for this UCS, i.e. free from non-climatic discontinuities
- Data are ideally required close to 12 noon local solar time as this is when surface temperatures are at their highest
- LST products from multiple sensors are required, thus inter-product consistency is important
- Consistent product performance over different land cover types, at different times of the year, and during different events, e.g. biases should not be land-cover or seasonally dependent, and should not vary with events such as El Niño or heat waves
- Cloud contamination is a major concern - improved cloud screening is required compared with existing LST products
- Well characterised uncertainties with information provided about correlation length scales

7.3.2. UCS 2 Interview: Assimilating Greenland ice sheet surface ice temperature into atmosphere and ice sheet models (DMI)

UCS application areas: Model evaluation, model assimilation, polar climate, dataset production

UCS objectives: To use LST data to evaluate the performance of the regional climate model (RCM) HIRHAM5 in calculating the surface energy budget over the Greenland ice sheet and in determining the extent of surface melt. The LST data will also be integrated into a snow and firn (snow that has survived at least one annual cycle) model derived from HIRHAM5 over the ice sheet and run offline as part of the Retention model inter-comparison project (RetMIP) in order to assess the impact of including observational data to improve simulations of melt and retention.

Summary of LST Application: The Danish Meteorological Institute (DMI*)* currently derive their own estimates of ice surface temperature (a sub-category of LST) from AVHRR observations, which are used in conjunction with station-observed 2m air temperature (T2m) and LST for monitoring the ice sheet on timescales from decadal to daily. LST is not currently used in ice sheet modelling at DMI so this UCS will provide the opportunity to trial this for the first time. This UCS is expected to benefit from the use of multiple LEO IR products from LST_cci. The use of MW LEO products may be considered in the UCS, but their use will be a low priority given the low spatial resolution and anticipated low accuracy of MW LST over snow and ice due to difficulties in determining emissivity (e.g. snow compact affects emissivity). GEO IR products are not likely to be considered given the coarse spatial resolution at high latitudes, and because higher-resolution, high-frequency, IR observations are also available from LEO sensors at these latitudes. Ideally, a high-frequency L3 product would be developed in LST_cci from multiple sensors, specifically for high latitudes where there have been no temporal adjustments (e.g. time averaging). It is believed that such a product would also benefit other users who conduct focused research in these regions. However, it should be noted that DMI have existing capability to process L2 to L3 so this is not an essential requirement for this UCS. Spatially complete LST fields will be beneficial for assimilation, and gap-filling will be performed by DMI if needed. The UCS will make use of the uncertainties provided with the LST_cci products and DMI are already experienced in dealing with uncertainty components. Uncertainties may be used to discard some LST observations but also to determine the possibility of ice melting where the LST uncertainty encompasses zero. DMI welcome the idea of a probabilistic cloud mask as this could enable them to assess any relationship between data quality and cloud probability, and to examine possible errors in the model cloud fields.

Key requirements:

- Priority LST_cci products will be LEO IR (probably L2)
- Minimum spatial resolution required: 0.05° but 1 km preferable
- Minimum temporal resolution required: daily, but 3-hourly or even hourly preferable
- Data are needed around 12 noon local solar time as this is when surface temperatures are at their highest
- No time averaged/temporally-shifted observation times: separated overpasses with actual overpass time are required
- The terms 'ascending' and 'descending' are not helpful for high latitude applications since a single LEO sensor may have multiple overpasses per day, so there should be no division into ascending and descending passes
- LST products from multiple sensors are required, thus inter-product consistency is important
- Cloud contamination is a major concern, particularly over ice and snow, and should ideally be included in the product uncertainties
- The possibility of clear-sky biases in IR data is a concern and should be assessed in LST_cci
- Easy access to the LST_cci datasets is essential and would encourage current non-users of LST, including those outside of this UCS, to trial the data in the applications

Other requirements/comments:

- The high frequency of LEO overpasses at polar latitudes should be exploited: a specialised polar LST product would be beneficial for the high-latitude community
- In situ validation sites at high latitudes are very sparse therefore it is crucial to maximise the use of these data and to evaluate LST retrievals in these regions using alternative approaches. New radiometers are currently being deployed in Greenland as part of the GEM project; these data should be investigated by LST_cci

7.3.3. UCS 3 Interview: Surface Urban Heat Island (University of Hamburg)

UCS application areas: Urban Climate

UCS aims: To characterise the spatial and temporal variability of global surface urban heat islands (SUHI). This will be achieved by modelling annual and potentially the diurnal cycles of LST in urban areas using composited satellite observations. Parameters such as the amplitude, phase and variance of SUHIs will be estimated from the fitted models, which will enable the spatio-temporal patterns and dynamics of SUHI to be assessed. Homogenous time series of LST will also be used to compute trends and analyse the impact of urbanization on spatial extent and temporal characteristics of the SUHI globally. The CCI High Resolution Land Cover Products will be used to identify areas of unchanging, non-urban land types for comparison.

Summary of LST Application: U. Hamburg have existing expertise in using LST data to characterise SUHIs and have previously used MODIS LST global 1 km data (MYDA11/MODA11), the SEVIRI LST product from the LSA-SAF, LST derived from Landsat-8, and ASTER L1b temperature and emissivity. U. Hamburg is likely to use multiple IR products from LST_cci within their UCS. The primary interest is in IR LEO products due to the ~1 km or better spatial resolution of these data, but IR GEO products can also be used for larger urban areas. High-frequency products would be required to characterise the diurnal urban cycle and therefore a merged GEO/LEO product would be appealing. MW LEO products are less likely to be considered in this UCS owing to the coarse spatial resolution, but there may be scope to experiment with the merged IR/MW product if provided at a high enough spatial resolution. U. Hamburg highlighted that access to VIIRS LSTs retrievals through LST_cci would be desirable as this is currently difficult to obtain. U. Hamburg do not currently consider uncertainties on LST, but per-pixel/cell uncertainties could be used in the UCS to discard some LSTs. Clear-sky probabilities could be helpful and it is anticipated that a threshold for discarding data would be established through testing and expert knowledge. Clear-sky probabilities could also be used to weight data when fitting a model, although this is likely to be complex and may be beyond the scope of this UCS.

Key requirements:

- Multi-decadal datasets, ideally 30 years or more
- Spatial resolution: 1 km or better on a regular lat/lon grid
- Temporal resolution: day/night, but 6-hourly is required for diurnal temperature cycle analysis
- IR GEO datasets provided on native grid: projection of pixels results in loss of spatial information
- Merged IR/MW product only useful if at 0.05° or better
- Improved relative pixel-to-pixel accuracy of LST retrievals over urban areas: large errors from poor knowledge of emissivity and inappropriate cloud masking (absolute accuracy less important for this application)
- Improved cloud detection – cloud edges are often missed so could consider extending cloud mask in space to remove cloud edges that may have been missed, or flagging these data as being in proximity of cloud. Referencing to climatology could also be used to screen outliers due to cloud
- Temporal homogeneity of LST data: LST time series must be free from non-climatic effects, such as changes in overpass time. A stability of at least 0.1 K/decade is required
- Careful consideration of across-swath variability in local overpass time: impacts on data averaging/merging as LST can change significantly with local solar time (especially around 10:30)
- Full details of GEO/LEO merging – need to assess impacts on specific urban effects that may be lost during downscaling/merging. A detailed description of the merging process is required for users
- Demonstration / worked examples of how to use LST uncertainties

Other requirements/comments:

- Provision of VIIRS data through LST_cci would be useful as this is difficult to obtain through other routes
- Angular correction / removal of anisotropic effects in LST products
- There is a need for higher-resolution IR sensors: compared to other wavelengths, developments in improving IR spatial resolution is slow
- Multi-angle simultaneous observations are needed for urban and other studies: Propose three sensors in parallel orbits viewing the same place at the same time, one at nadir, one east and one west, each with four viewing angles in flight direction

7.3.4. UCS 4 Interview: Biosphere/Atmosphere Exchange (MPI)

UCS application areas: Surface/Atmosphere interactions, dataset production

UCS aims: The first objective of this UCS is produce global estimates of carbon fluxes that are derived using a model where LST has been identified as an important predictor variable. Machine learning models are trained on daily records of carbon fluxes from ~200 globally distributed sites and eleven predictor variables, including LST. The trained models are then applied to globally gridded predictor variables in order to produce time-varying global gridded estimates of carbon fluxes at 0.05°. In the second part of this UCS, LST derived in situ from eddy covariance data will be compared to satellite observations of LST to assess whether remotely-sensed (radiometric) LST can adequately detect temperature changes occurring in extreme conditions, e.g. under water stress. The UCS will also determine whether, and under what conditions, LST can be used as a proxy for aerodynamic surface temperature. This is desirable as true aerodynamic surface temperature is very difficult to derive as it requires knowledge of a number of land surface properties, e.g. surface roughness, leaf area index (LAI), leaf characteristic dimension, etc. Additionally, satellite LST offers a global perspective.

Summary of LST Application: The Max Planck Institute (MPI) are currently using the full L3 LST record on a sinusoidal grid from MODIS Terra in their carbon flux calculations. They are also conducting some research on the co-variability of LST with vegetation metrics, e.g. NDVI, to detect drought, and are using the SEVIRI LST product from the LSA-SAF for this work. The work on carbon fluxes is expected to benefit from new LST_cci datasets, which are expected to have improved quality. The primary focus is likely to be daily LSTs derived from IR LEO, but MPI may also use IR GEO data in the UCS to produce half-hourly estimates of biosphere-atmosphere fluxes. LSTs with 1 km resolution are required for components of the UCS that also use in situ observations, including training of the machine learning models, but 0.05° data are required to produce the global grids of fluxes. They are interested in using multiple LST products from the LST_cci. MPI require globally complete LSTs and will use a linear interpolation for small data gaps, or climatology for longer gaps. They may be interested in the MW LST and blended IR/MW products as these provide near all-sky LSTs, but the resolution is likely to be an issue given that 1 km data (or better) are required for model training. MPI do not currently consider LST uncertainties, but could use the uncertainty information provided by LST_cci to generate ensemble products. They are particularly interested in knowing more about spatially-correlated errors, and how to incorporate the related uncertainty information into their products. MPI welcome the provision of clear-sky probabilities in LST_cci and would trial different rejection thresholds to explore the effects on the flux data they are producing (data availability vs quality). Cloud contamination in LST products is a concern.

Key requirements:

- Priority LST_cci products will be IR
- Minimum spatial resolution required: 0.05° but 1 km or better preferable (ideal: 250m)
- Minimum temporal resolution required: daily daytime LST, but may also require half-hourly
- Multi-decadal LSTs data are required – ideally back to 1980s
- Consistency between different instruments and products
- Homogeneous time series with day-to-day consistency
- Clear explanation of what is represented by clear-sky probabilities

Other requirements/comments:

- Useful to have emissivity provided with the LST data
- Relative accuracy in LST from day-to-day is more important than absolute biases in the data
- Data quality is more important than spatial resolution

7.3.5. UCS 5 Interview: Inter-comparison and integrated use of LST_cci and other products in urban climate studies (MeteoRomania)

UCS application areas: Urban climate, regional climate, climate variability

UCS aims: To perform an extended inter-comparison between different surface temperature products over urban areas and to explore the possible application of integrated products in urban climate studies. The inter-comparison will utilise data from LST_cci, reanalysis and other gridded surface temperature products, including near-surface air temperatures. Differences between these datasets will be assessed, emphasising the possible reasons for those differences, and recommendations for further use of the datasets in integrated studies. The UCS will consider the development of three applications derived from the combined use of LST_cci and other products: gap-filling in datasets; investigating characteristics of UHI in terms of extent, intensity and sub-diurnal variations; and exploring the impact of the UHI on human comfort. The project will have a regional focus on Romania.

Summary of LST Application: MeteoRomania have existing experience in the use of satellite LST and currently use MODIS Aqua/Terra L3 sinusoidal 1 km products and the LSA-SAF 15-min SEVIRI LST product. MODIS LST data are used to estimate urban air temperatures, to gap-fill existing station air temperature data, and identify urban hot spots. The SEVIRI LST data are used to give countrywide context on surface temperatures. MeteoRomania are also performing experimental downscaling of the urban temperature data using future climate scenarios in order to map possible future UHIs in a changing climate. 1 km LST data are therefore a priority for this UCS, although there is interest in the LST_cci IR GEO products and the merged LEO/GEO product, but this would depend on the spatial resolution. This UCS may also consider using MW LST data during the cold season for the analysis of UHIs when cloud is prevalent, although the low spatial resolution is likely to be a severely limiting factor. The merged IR/MW product – depending on spatial resolution – could also be useful in this framework. MeteoRomania do not currently use uncertainty information, but are interested in doing so in the future; they foresee the use of this information to assess data quality, e.g. identify which data to reject or treat more cautiously. They welcome the proposed clear-sky probabilities, which may be helpful in achieving better cloud screening; currently MeteoRomania find cloud contamination to be a significant issue in their work and implement additional cloud screening using statistical methods, in addition to using the cloud information provided with existing LST products. Data gaps in IR LSTs due to cloud are an issue and severely limit the observation of UHIs.

Key requirements:

- Priority LST_cci products will be LEO IR L3 (regular gridded products)
- Minimum spatial resolution required: 1 km or better
- Minimum temporal resolution required: daily but 3-hourly or better preferred
- Multi-annual LST records – ideally multi-decadal
- Data homogeneous and stable in time
- Easy access to data, ideally in real time – would like to download time series data for a single spatial point
- Detailed user guide on how data are produced and any blending, interpolation, sampling techniques that are applied
- Detailed guidelines on how to use uncertainty information and the meaning of this information

7.3.6. UCS 6 Interview: Integration of LST_cci products into a Surface Energy Balance Model (LIST)

UCS application areas: surface/atmosphere interactions, Evapotranspiration / vegetation or crop monitoring

UCS aims: To integrate LST into a physically-based surface energy balance (SEB) model. LSTs are used to define the lower boundary condition together with other atmospheric variables, such as short and long-wave radiation components, near-surface humidity and air temperature to calculate conductance, which is then passed to the SEB model. The SEB model is then used to determine a number of land surface processes variables that are useful for assessing water stress, such as latent and sensible heat fluxes, evapotranspiration (ET), evaporation, transpiration, surface root zone wetness and water availability. Aerodynamic temperature and conductance, as well as canopy-surface conductance are produced as by-products from the modelling process (possible links with UCS #4). The UCS will focus on assessing the quality of SEB outputs across an aridity gradient over multiple biomes. The target area for this UCS will be the North Australian Tropical Transect (NATT), where data from 5 eddy covariance sites are available. Tropical sites in the Amazon and Congo regions may also be considered as study areas for this UCS.

Summary of LST Application: The Luxembourg Institute of Science and Technology (LIST) have previously used MODIS Aqua/Terra 8-day and daily LSTs at 1 km spatial resolution, the (A)ATSR 0.05° CDR and MTSAT 3-hourly LST from GlobTemperature, and have estimated LSTs themselves from the CM-SAF upwelling longwave radiation product using MODIS emissivity's. This UCS is expected to benefit from the use of multiple LEO IR products from LST_cci. The (A)ATSR-MODIS-SLSTR CDR product is also of interest if produced at sufficiently high spatial resolution (1 km data are required). Spatially complete LST data are required for this UCS: LIST currently uses 8-day MODIS data to bypass the cloudy sky complexities and developed a method to perform gap filling using NWP model output. The all-sky products in LST_cci are therefore of interest for this UCS if produced at high-enough spatial resolution. The UCS will make use of the uncertainties provided with the LST_cci products; the total uncertainty budget per pixel/cell will be particularly useful and could be compared to the residuals from the ET estimates. Uncertainties could also be used in a diagnostic process, linking the daily ET uncertainties to the daily uncertainties of LST to assess the sensitivity of the ET retrievals to uncertainties in the LSTs. LIST welcome the idea of a probabilistic cloud mask as this could enable them to perform a statistical evaluation of surface energy balance models errors due to uncertainty in model input.

Key requirements:

- Priority LST_cci products will be LEO IR (L3)
- Minimum spatial resolution required: 1 km
- Minimum temporal resolution required: daily (LEO LST) and hourly (Geostationary LST)
- Minimum dataset length: 10 years, but 25-30 preferable
- Improved accuracy of LST retrievals in arid/semi-arid regions
- Other collocated variables available with LST retrievals: air temperature, relative humidity/dew point temperature, top of atmosphere brightness temperatures
- Improved cloud detection at night

Other requirements/comments:

- All-sky LST – LIST are currently gap filling IR LSTs

7.3.7. CRG partner Interview: Production of Drought, Urban Heat and Frost Monitoring Maps (MeteoSwiss)

UCS application areas: Climate monitoring, regional climate

Application aims: To produce drought, urban heat and frost monitoring maps using a combination of LST and vegetation metrics observed by satellites over Switzerland. Maps are currently produced at weekly temporal resolution with 1 km spatial resolution using the CM-SAF LST, together with vegetation maps derived from AVHRR. Heat, drought and vegetation indices are first calculated separately for different sensor LST and vegetation products, before being combined to produce the required output maps. Maps are produced at weekly resolution in order to minimise data gaps due to cloud.

Summary of LST Application: MeteoSwiss currently produce the CM-SAF LST product based on MVIRI and SEVIRI, so are data providers as well as users. However, they are very interested in testing the LST_cci products, which are expected to have improved spatial resolution, dataset length, uncertainties, etc., in their drought, urban heat and frost monitoring products. MeteoSwiss are interested in the data merging techniques in LST_cci as they are also merging GEO and LEO data, but are merging the indices derived from each dataset, rather than merging LST directly. For their regional climate applications, the merging of high temporal resolution with high spatial resolution is of interest; global products have a lower priority. Although the minimum temporal resolution required is daily, MeteoSwiss are still interested in data from the (A)ATSR (which has a less-frequent-than daily revisit time), because of the stability and radiometric accuracy of this sensor. This time series – assuming it is temporally stable – can be used to assess the temporal stability of the CM-SAF LST product, which has known non-climatic discontinuities. Their primary interests are in 1 km LEO CDRs, and GEO CDRs (required at 0.05°). MW LSTs are unlikely to be used in this work owing to the low spatial resolution. MeteoSwiss will consider the uncertainty components provided with LST_cci datasets in this work and hope to use these to calculate uncertainties on LST anomalies and to propagate these uncertainties through to the monitoring maps they produce. However, as a data provider, they also warn that some users may get confused about the uncertainty components and that providing these data may result in large data volumes that may be difficult for some users to handle. MeteoSwiss welcome the provision of clear-sky probabilities and used such a scheme to screen out suspected cloud-contaminated LSTs in the CM-SAF LST product, although they did not provide the probabilities to users. They used a 90% clear-sky threshold to remove cloud in this product, although note that the appropriate threshold strongly depends on the probabilistic method used. On reflection, they feel it would have been better to provide the clear-sky probability data directly to users.

Key requirements:

- Priority LST_cci products will be LEO and GEO IR (both L2 and L3)
- Minimum spatial resolution required: 0.05° but <1 km preferable
- Minimum temporal resolution required: daily, but hourly is ideally required for some temperature indices that are calculated (e.g. temperature difference 06:00 to 12:00 contains information on the soil moisture)
- Separate LEO and GEO products
- Detailed information on the merging technology used in LST_cci
- Clear explanation of what the satellite LST products produced in LST_cci represent, i.e. what LST is observed over different regimes and using different sensors – this is required by the user community in general
- Clear explanation of what the different uncertainty components represent
- Thoroughly validated products (in particular mountain regions, model-based validation)
- Stable time series, free from non-climatic discontinuities (bias is acceptable)

7.3.8. CRG partner Interview: Using LST-Air Temperature as a Measure of Vegetation Stress (CMUG / Met Office Hadley Centre)

Application areas: Evapotranspiration / vegetation or crop monitoring, climate projections

Application aims: To use LST in combination with near-surface air temperature (T2m) to get a measure of vegetation stress. This work is being carried out on a global scale, looking at large scale vegetation and moisture stress, but is also focusing on some local case study sites, including the northern Brazil rain gradient, and Cardington in the UK, where the Met Office has a field station. A key aspect of the study is to understand how stress varies across different vegetation types. Another component of the study is to understand how observed vegetation stress may evolve with climate change, and linking current observations with future climate change scenarios. The study will make use of the JULES model to 1) fully understand the difference between the modelled temperatures and a satellite LST observations (this may or may not include MW LST observations), and 2) model sites/regions/biomes in experiments to see if the modelled LST – T2m differences exhibit the same behaviour as the observations.

Summary of LST Application: This is current work that is taking place at the Met Office Hadley Centre, but will be developed further within the CMUG. The group conducting this research is already using MODIS V6 LST at 0.05° (climate model grid) from Aqua for this application. Aqua was chosen over Terra because the overpass time is 1.30 am/pm, which is close to the time of local maximum LST, and therefore likely maximum vegetation stress. The group are also using MODIS land cover data to distinguish between different land cover and vegetation types. The MODIS LSTs are re-projected to 0.5° to match the other datasets used in this work, e.g. satellite soil moisture, WATCH T2m (http://www.eu-watch.org/data_availability), etc. However, the group also have plans to use 1 km LSTs, particularly for the detailed work connected to specific sites, e.g. Cardington in the UK. The study uses JULES to model the canopy temperature as part of the vegetation stress assessment; JULES simulates a single temperature for the whole vertical structure of the canopy. As satellite LST's are sensitive to the top of canopy temperatures, they can also be used to evaluate these temperatures in JULES. The primary datasets of interest for this study are IR, because of the spatial resolution required, but as gaps due to clouds are an issue for this study there is some interest in the MW observations of LST, or merged IR/MW product. However, the latter is likely to be too short in time (one year proposed) to be useful. The group do not currently use LST uncertainties, but would be interested in learning how these data can be used. Uncertainties could be used to inform how reliable the skin-air temperature difference is in indicating vegetation stress. The group are also interested in the provision of clear-sky probabilities, but are concerned that a certain probability could be obtained for multiple different situations, for example, 50% could indicate a thick layer of stratus or patchy cumulus, which would have very different implications for the accuracy and usefulness of the data.

Key requirements:

- Priority LST_cci products will be LEO IR (L3)
- Minimum spatial resolution required: 0.05° but 1 km preferable
- Minimum temporal resolution required: daily, but 3-hourly or even hourly required for site-based studies
- Observations close to solar noon (time of peak LST; currently, the overpass time of MODIS Aqua is sufficient here)
- Satellite view angles provided in data files
- Time series back to at least 1995 (to coincide with Flux tower observations)
- Homogeneous time series, free from non-climatic effects, particularly between sensor changes
- Data on grids that match other ECV's, e.g. land cover, soil moisture, to enable easy use of multiple datasets
- Very clear and obvious statements about any assumptions made in producing the LST datasets

- Consistency in product format between different LST datasets, to enable changing LST datasets with ease
- Clear information on how to use uncertainties
- Clear information on how to use clear-sky probabilities, and what is meant by these data

7.4. Summary

The interviews held with the CRG have highlighted a number of clear and consistent requirements across the eight different applications:

- Nearly all CRG applications specify that **multi-decadal, homogenised datasets** that are free from non-climatic discontinuities are a critical requirement [LST-URD-ADV-09-LI]
- **Level 3 data at 0.05° latitude/longitude** will satisfy most of the CRG applications, although data at **1 km is required, or at least preferred, for several studies** and in particular for those concerned with the urban environment
- Nearly all studies would be satisfied with **data at daily resolution**, although sub-daily observations (e.g. hourly, 3-hourly, 6-hourly) will add value in most cases
- **Observations close to solar noon** (when maximum LST is likely to occur) are required by several CRG partners [LST-URD-ADV-15-OI]
- **Cloud contamination** in current LST products was identified as a significant concern for several members of the CRG [LST-URD-ADV-32-LI, LST-URD-ADV-33-LOI], who also highlighted that they hoped this cloud screening methods would be improved in LST_cci, and even **incorporated into the product uncertainties** [LST-URD-ADV-25-LOI]. Most welcomed the provision of clear-sky probabilities, as this would allow them to tailor their use of the LST products to their particular application. **Detailed information on what is represented by the clear-sky probabilities and how to apply them** was also requested [LST-URD-ADV-30-I]. There were concerns about **clear-sky biases in IR LST data** and that this should be investigated and communicated to users in LST_cci [LST-URD-ADV-32-LI]
- Most CRG partners do not currently use uncertainty information in their work with LST, but are willing to consider using either the total uncertainty budget and/or uncertainty components. There is a clear requirement for **detailed information on how uncertainties are calculated** [LST-URD-ADV-22-I]**, what they represent, and how to use these data** [LST-URD-ADV-23-OI]
- Some CRG partners also hoped that the LST_cci products would have **improved accuracy** compared with existing LST products, particularly over arid/semi-arid and urban areas [LST-URD-ADV-16-I]. The need for **thorough validation** of the LST_cci products was also noted [LST-URD-REQ-27-O]
- Given that most CRG partners will be using several products, the need for **consistency across multiple products** was also highlighted as a requirement by three groups [LST-URD-ADV-06-LI]
- It was noted that a **clear definition of what the satellite observations of LST actually represent** [LST-URD-ADV-02-OI] is required
- Provide details on **any assumptions made during the retrieval process, or product construction** [LST-URD-ADV-03-I]
- The CRG welcome the provision of merged products (GEO + LEO, IR + MW) in LST_cci; several CRG members highlighted the need for **detailed information on the techniques used in merging** different data sources to be provided to users [LST-URD-ADV-03-I]

- **Easy access to data** was specified as a requirement by two CRG members [LST-URD-ADV-04-LI], with one also requesting access to near-real-time data and the ability to download a time series for a single pixel or grid cell
- The need for a **consistent product format** was highlighted during the discussions with the CRG, including across CCI ECV products [LST-URD-ADV-07-OI]. Information on how comparable LST_cci products are with other CCI datasets would facilitate ease of use [LST-URD-ADV-08-OI]

Other requirements specified for individual CRG applications included:

- Provision of geostationary LST data at native resolution (i.e. not re-projected or averaged onto a different latitude/longitude grid) [LST-URD-REQ-06-O]
- Provision of LEO LST data as separate overpasses, i.e. with no temporal/spatial averaging, at high latitudes and to avoid the terms 'ascending' and 'descending' at high latitudes, which become meaningless due to the higher latitudes due to the higher frequency of LEO overpasses [LST-URD-REQ-06-O]
- Provision of other collocated variables within the LST_cci data files on a common grid, e.g. air temperature, surface humidity, etc (links to GlobTemperature requirement REQ-32-TR)
- To consider the across-swath variability in local overpass time, particularly when aggregating data to Level 3 (links to LST-URD-ADV-13-O and LST-URD-ADV-03-I)
- Provision of LST_cci datasets on grids that match other CCI ECV products [LST-URD-ADV-07-OI]
- Provision of VIIRS data

8. Feedback from the 2020 User Workshop

This section summarises feedback gathered during the LST_cci User Workshop 2020, which was a virtual event, and was added for v2 of this URD. More detailed information about the workshop can be found in the appendices of this report. Appendix C - Appendix D - Appendix E - while Appendix F -

8.1. LST_cci User Workshop 2020

The LST_cci User Workshop 2020 was initially planned as 'in person' event at the Met Office in the UK between 24-26 June 2020. However, due to the global Covid-19 pandemic the event was held virtually, requiring a complete revision of the workshop format and agenda. The workshop was advertised via the LST_cci project mailing list, which was also used to advertise the online user survey (Section 6.1). As the event was intercontinental, the workshop comprised both 'live' and 'offline' components to enable participation from all time zones. The live component was conducted through Zoom (https://zoom.us/) through four, 1-hour sessions each day between 11:30 and 17:30 CEST, which included oral presentations and discussions. The offline component took place on Padlet (https://padlet.com/) and included the poster presentations, links to recordings of the live workshop sessions, and discussion, where each poster and oral presentation had a dedicated discussion thread. Participants were encouraged to use the Padlet discussion threads rather than the 'Zoom Chat' to make the discussion easier to follow for those that were not able to attend the live sessions. Nonetheless, the 'Zoom Chat' content was uploaded to Padlet together with the live session recordings each day to enable those that were not able to join the live sessions to follow the workshop in 'real time'. Although participants were encouraged to register through the workshop webpages (https://ws2020-lst-cci.acri-cwa.fr/) both the live Zoom sessions and Padlet pages were unrestricted and open to anyone with the links. All registered participants were emailed a copy of the workshop booklet, which provided joining details, quick-start guides for both Padlet and Zoom, information on meeting etiquette and other general information, session links and the agenda (see 11.2.Appendix C -

The final email distribution list for the event comprised 133 delegates from at least 24 different countries (only an email address and organisation were required to register, which was not always indicative of the country of origin). Daily 'digest' emails were issued via this list, which included updates on the workshop and links to the day's live session recordings and Padlets.

8.1.1. Workshop Attendance

Error! Reference source not found. shows the approximate maximum number of attendees for each 1-hour live Zoom session (in practice, the number of attendees varied through each session). The most popular sessions were those focusing on the LST_cci project (e.g. 67 delegates attended the LST_cci project information session), followed by the other science sessions (e.g. Using LST in land-atmosphere interaction studies). The discussion sessions were the least popular, with only 41 attendees at the final session on discussion feedback. Notably, the number of participants at the live sessions was similar to the number of people that attended previous GlobTemperature User Workshops in person. The live recordings of the Zoom sessions were also widely accessed (final column of **Error! Reference source not found.**), suggesting that many delegates who were not able to attend the live sessions were still engaging with the workshop offline. There were very active discussions on the Padlets during the workshop (11.2.Appendix D -

Table 8-1: Zoom live session attendance ("Approx. Number") & views and downloads of the live session recordings ("Zoom Rec.). Note that the number of views and downloads is the total number for all four sessions on each day. Although each individual session was recorded separately, statistics for each individual session on each day are not available from Zoom.

Session	**Time**	**Approx. Number**	**Zoom Rec.**
Opening Session	11:30-12:30 CEST Wed	50	177 views 44 downloads
LST_cci session	13:00-14:00 CEST Wed	67	
Discussion session: Uncertainties in LST	15:00-16:00 CEST Wed	58	
Data set development and validation	16:30-17:30 CEST Wed	54	
Discussion session: User Requirements for Climate LST	11:30-12:30 CEST Thurs	44	128 views 39 downloads
Using LST in land-atmosphere interaction studies (1)	13:00-14:00 CEST Thurs	55	
Discussion session: Towards Climate Services Using LST	15:00-16:00 CEST Thurs	44	
Using LST in land-atmosphere interaction studies (2)	16:30-17:30 CEST Thurs	53	
Discussion session: Role of satellite LST observations in future assessments	11:30-12:30 CEST Fri	53	89 views 33 downloads
Using LST in land-atmosphere interaction studies (3)	13:00-14:00 CEST Fri	50	
Urban LST / Discussion feedback #1	14:50-15:50 CEST Fri	48	
Discussion feedback #2	16:20-17:20 CEST Friday	41	

8.1.2. LST user feedback

In addition to enabling the project team to update users on the LST_cci project and its products, the User Workshop 2020 provided an opportunity to gather feedback on the early LST_cci products and general views of users that have not been captured through previous surveys and interviews.

The workshop provided three routes to gathering user feedback and requirements:

1) The discussion on Padlet following the individual presentations (Appendix D)

2) The general discussion on the Zoom chat (although scientific discussion here was discouraged, Appendix E)

3) The dedicated break-out and plenary discussion sessions (Appendix D).

The objective of the four discussion sessions (#3 in the list above) was to gather new or updated requirements, focusing in particular on requirements that could not be gathered easily through a survey, issues that were perhaps not explored fully in previous surveys and interviews, or new requirements that had arisen over time. For example, feedback on the provision of new LST_cci data and documentation, which was not available when the original user surveys and interviews were conducted. In each case, the discussion sessions were structured around several 'seed questions' that had been defined before the workshop and were aimed at gathering this targeted feedback. Each breakout discussion was 40 minutes in length and preceded by a 20-minute presentation related to the discussion topic. The plenary discussion session was 20 minutes long and preceded by two relevant 20-minute presentations.

The feedback gathered through these mechanisms is presented in the following sections.

8.1.2.1. General Discussions: Padlet Discussions and Zoom Chat

The majority of the posts on Padlet and Zoom Chat consisted of questions posed to the presenters. However, some useful ideas and requirements were suggested (see Appendices D and E, respectively, for details), which are grouped below by category. The final sub-section below lists some actions for the LST_cci project team.

Product design

The following needs were identified:

- 30-50m lake surface temperature data set for glacial lake temperature studies [LST-URD-ADV-34-U]

- Gap filled products – it is clear (also through the CRG work) that many users require spatially-complete data sets. Users are trying to achieve this themselves through various approaches, but a future aim for the LST_cci project could be to produce gap-filled data using the expert knowledge of the project team. (For example, an all-sky LST from SEVIRI is already being produced at IPMA via the LSA-SAF). [LST-URD-ADV-11-LOI]

Long-term and multi-sensor LST data sets

It was noted that:

- Many users want only one product to use rather than a suite of products, which can be overwhelming. However, this raises issues concerning merging different data sets together, adjusting for inter-calibration and overpass time differences, etc. This will increase the total uncertainty budget. It was also highlighted that uncertainty data can be used to inform data combination (e.g. if calculating an average from multiple observations, they could be weighted by their uncertainty magnitudes). [LST-URD-ADV-35-U]

- There is a need for assessment of the stability/homogeneity of a data set before time series analysis can be performed. It should be recognised that uncertainties in the stability of a data set may be larger than the climate-change signal itself. Lessons could be learned from the SST community here, who are further ahead in this area or research. [LST-URD-ADV-09-LI, LST-URD-ADV-26-O]

- There is a need to demonstrate why LST should be used for assessing long-term changes in surface temperature in place of/in addition to T2m, and what differences (if any) are expected between trends in LST and T2m. LST-influencing factors also need to be considered here, e.g. land use changes. This is important to consider if LST data are ever to be used in the Bulletin of the American Meteorological Society (BAMS) State of the Climate (SOTC) or the Intergovernmental Panel on Climate Change (IPCC) reports for example. [LST-URD-ADV-36-U]

High-latitude information

It was highlighted that:

- LST can add value at high latitudes, where in situ observations are lacking but satellite data are plentiful. The consistency with the Permafrost and snow cover CCI projects should be considered. [LST-URD-ADV-07-OI, LST-URD-ADV-08-OI].
- Improving the cloud masking is a significant challenge over ice and snow [LST-URD-ADV-37-U]
- There is no sea ice surface temperature product in CCI.

Usability of data and tools

The usability of the LST_cci data sets was discussed extensively during the workshop and the following points were noted on Padlet and via the Zoom chat:

- There is a requirement for tools (or example code) to propagate uncertainties in the LST_cci data sets as this is a non-trivial task for users and this will help them to use the data properly. [LST-URD-ADV-38-U]
- It would be extremely valuable to have a platform or online tool where highest resolution data is stored and the platform re-grids the data (and uncertainties) to a user-defined resolution. It was recognised that there are already a few cloud computing tools for Copernicus and Sentinel that could be considered (or used for ideas), e.g. https://www.wekeo.eu/ (uses Jupyter, so users can edit the processing code/process and the code would be freely available). However, it was also noted that any such tool would probably need to offer user-defined options for quality checking and filtering before aggregation. [LST-URD-ADV-38-U, LST-URD-ADV-39-U]
- It was suggested that it would be useful to bring in data engineers/curators into the discussion on format/accessibility/usability. It was highlighted that NOAA and NASA have already addressed this through their Earth Science Information Partners (ESIP) so this should be considered when designing solutions for LST_cci. [LST-URD-ADV-40-U]
- It was suggested that LST_cci could provide more hands-on experience for users at workshops, with demonstrations, Jupyter notebooks, etc (e.g. https://lpdaac.usgs.gov/resources/e-learning/). Examples for users could also be provided in a separate document (not the Product User Guide, or PUG). An example of a good training resource was posted during the workshop: https://dmtclearinghouse.esipfed.org/. This 'Data Management Clearing House' is an effort from ESIP with the support from NASA and NOAA to create a hub of how-to resources for using Earth science data. There are also regular webinar training events with recordings for specific sensor data / products for users. [LST-URD-ADV-41-U, LST-URD-ADV-42-U]

Other

The International Land Surface Temperature and Emissivity Working Group (ILSTE-WG) was mentioned; this could be a forum for establishing community standards for uncertainties. [LST-URD-ADV-43-U]

Future considerations for the project team:

During the workshop, the members of the project team noted some interesting areas of work to pursue. These are listed below for completeness, but are not considered requirements or actions for the project:

- To intercompare LST_cci and Timeline LST data sets and link up with the Timeline project for trend analysis work.

- To consider using the HTESSEL (Hydrology Tiled ECMWF Scheme for Surface Exchanges over Land) model with CCI vegetation corrections to represent diurnal cycle in surface temperatures for input to clear-sky simulations for probabilistic cloud detection. IPMA can potentially share their global simulations.

- To look into the ASOS (Automated Surface Observing System) in situ data from Korean Meteorological Administration, which might be useful for validation depending on quality.

8.1.2.2. Uncertainties Discussion Session

The breakout group discussion on uncertainties took place on the first day of the workshop and was preceded by a presentation on 'Recent advances in the field of satellite data uncertainties' delivered by a member of the LST_cci project team. Delegates were split into six groups of around seven participants to discuss five seed questions. These seed questions are listed below, with bulleted lists indicating the key points that were discussed in each case (focusing on requirements and suggestions). The detailed notes made by each discussion group are provided in Appendix C.

Are you currently or have you in the past used uncertainty information provided with LST products? If so, are these LST CCI products (and which ones?) or products from other data providers?

- Some users report using uncertainties from CCI and/or GlobTemperature.

- Some users report using uncertainties to explain results, e.g. when comparing data sets.

- Some users are generating their own uncertainty estimates, e.g. through comparison with their own in situ observations.

- Many users are not using uncertainty information yet, especially if they are new to the field. Use of quality flags (e.g. in deciding which data to use and which to discard) seems to be more widespread. However, users do seem to recognise the importance of uncertainty information, but effective use depends on the application.

If you use uncertainty information, do you use the total uncertainty or the breakdown of uncertainty components (or both)? How do you use this information? Eg. for data selection, to explain scientific findings, to propagate uncertainties or combine products, for data assimilation or for model evaluation?

- Most users are using uncertainty information to filter out poor-quality data. However, there needs to be a balance between filtering out too many data, so that the data set is not useful, and too few, such that the quality is affected. Some users are also using uncertainty information in data assimilation and upscaling.

- The provision of quality levels for data should be considered to enable users to exclude poor-quality data more easily (easier for users compared with using the uncertainties for this purpose). [LST-URD-REQ-22-O]

- The main output of LST_cci could be a level-4 combined product, even if this has larger uncertainties than the single-sensor products

- Further breakdown of the uncertainty budget by individual surface components (e.g. to better understand the main sources of errors) could be provided. It was noted that an atmospheric uncertainty component was also useful, e.g. for looking at glacial lakes where the atmospheric correction is challenging (e.g. Norway and Patagonia). [LST-URD-ADV-45-U]

- Some users are using uncertainty component information for upscaling.

- It is not clear how uncertainties would be propagated through downscaling.

- It should be recognised that 'uncertainty' means different things to different users: products often come with overall uncertainty information (general statement on accuracy and precision) or uncertainty can provide an estimate of the model/algorithm uncertainty and propagation of input uncertainties. [LST-URD-ADV-22-I, LST-URD-ADV-23-OI, LST-URD-ADV-24-O]

If you don't use uncertainty information what is the reason for this? Is there anything that data producers could do to help you use this information?

- Not all users find uncertainty information accessible or easy to find – improved publicity is needed. [LST-URD-ADV-44-U]

- Some users are just using the attributes in the NetCDF files.

- Users need to know the uncertainties are validated and meaningful. [LST-URD-ADV-27-O]

- Users need to know the appropriate way to use LST uncertainty information, but this is still being established for some applications (e.g. data assimilation). [LST-URD-REQ-26-O, LST-URD-ADV-44-U, LST-URD-ADV-23-OI]

- Some users question how useful uncertainty components are in practice – this may depend on the application. [LST-URD-ADV-44-U]

Have you found the available documentation on uncertainties useful? Do you know where to find it? Is there anything missing or unavailable at present that would be helpful?

- Provision of detailed but comprehensive documentation on uncertainty information is vital, including the related sources of errors and how the uncertainties have been validated – all the information should be available. User feedback is that current Algorithm Theoretical Basis Documents (ATBDs) for operational products are often inadequate and uncertainty information can vary between products so it can be difficult for users to understand. [LST-URD-REQ-26-O, LST-URD-ADV-22-I, LST-URD-ADV-23-OI, LST-URD-ADV-24-O, LST-URD-ADV-27-O, LST-URD-ADV-45-U]

- Request that uncertainty information is well documented in the LST_cci Product User Guide (PUG) with specific easy-to-follow examples for use, including propagation of uncertainties (e.g. when upscaling) and how to deal with uncertainties when downscaling data, guidelines for threshold-based used of uncertainty information (e.g. for screening data). The PUG should include clear and easy-to-follow documentation with links to further information. [LST-URD-REQ-26-O, LST-URD-ADV-44-U, LST-URD-ADV-46-U]

- Some early users of LST_cci data have found it difficult to find documentation on uncertainties in the products. However, one user commented that the merged GEO ATBD and user manual (project not specified, but perhaps Geoland?) is thorough and useful. [LST-URD-ADV-44-U]

- Some users have found it difficult to find information specific to LST_cci. This could be a barrier for some users. [LST-URD-ADV-44-U, LST-URD-ADV-47-U]

- Users are concerned about cloud contamination and whether the current uncertainty derivation includes this component. Some LST data sets (including LST_cci) still clearly suffer from cloud contamination but this may not be captured in the uncertainty information and users need to apply further screening/quality checks to remove cloud-contaminated data. [LST-URD-ADV-25-LOI, LST-URD-ADV-33-LOI, LST-URD-ADV-37-U]

- Ensembles could be used to estimate uncertainties where complexity in the retrieval is significant, for example, characterising uncertainties in the reanalysis inputs used in the LST retrievals and failure in the cloud detection (this approach is already used in NWP). [LST-URD-ADV-48-U]

How aware are you of how uncertainties are calculated? Is it important for you to understand what is included in the uncertainty budget for your application?

- The level of detail in the documentation depends on the user – not every user needs to understand everything in great detail.

- Detailed knowledge of how the uncertainties and their components is useful to some users (e.g. upscaling, data assimilation) but less for others (e.g. screening data based on uncertainty information). [LST-URD-REQ-26-O, LST-URD-ADV-22-I, LST-URD-ADV-23-OI, LST-URD-ADV-44-U]

- Geolocation uncertainties are also important to consider, e.g. when looking at glacial lakes. [LST-URD-ADV-49-U]

8.1.2.3. User Requirements Discussion Session

The breakout group discussion on user requirements took place on the second day of the workshop and was preceded by a presentation on 'Findings from the LST_cci User Requirements Assessment' delivered by a member of the LST_cci project team. Delegates were then split into seven groups of around seven participants to discuss five seed questions. These seed questions are listed below, with bulleted lists indicating the key points that were discussed in each case (focusing on requirements and suggestions). The detailed notes made by each discussion group are provided in Appendix C.

What requirements did we miss in our requirements gathering exercise?

- Daytime average normalised to a given time (e.g. 12 noon) [LST-URD-ADV-50-U]

- It was recognised that requirements are application specific.

- 'A correction for cloudy conditions' (NB: it is not clear exactly what is meant by this comment, but it is included for completeness and assumed to be linked to estimating LST under cloud) [LST-URD-ADV-11-LOI]

- Provision of LST trend information in addition to the LST data themselves. [LST-URD-ADV-51-U]

- Providing advice to users on which products are best suited to different applications. [LST-URD-ADV-35-U]

- Some users cannot use data that have been averaged over multiple overpasses. [LST-URD-ADV-52-U]

- Some users require LST data at <1 km spatial scale. [LST-URD-ADV-12-O]

- Per-pixel quality level information would be useful. However, it was noted that the quality level required is probably application specific. [LST-URD-REQ-22-O]

- Provision of information on how to understand and work with bit-encoded QC – examples using common programming languages for users to follow would be useful. [LST-URD-ADV-53-U]

- Provision of 'data selection' tools, e.g. to extract data for user-defined regions, quality-checking/screening of data. [LST-URD-ADV-54-U]

What spatial resolution is required for different applications? How useful is a 0.01 deg global product, given the huge data volumes involved?

- Some users would be interested in a global 0.01° latitude-longitude product; it could be useful for some models or to downscale microwave LST data. However, others thought a global data set would not be useful although they acknowledged that larger, regional data sets (e.g. pan-Africa) might be useful. It was acknowledged that data volumes for 0.01° latitude-longitude data may be difficult for some users. [LST-URD-REQ-12-O, LST-URD-ADV-39-U, LST-URD-ADV-54-U]

- Data at 0.05° latitude-longitude are useful for many model-based studies. [LST-URD-ADV-38-U]

- For some studies, e.g. urban, fire scan monitoring, 0.01° latitude-longitude (or 1 km) is the minimum requirement. [LST-URD-OPT-12-O, LST-URD-ADV-39-U]

- The highest-resolution data should be available on a platform that could also aggregate data to a user-specified resolution (and also propagating the uncertainty components) over a user-specified region of interest. This could be a facility provided by the CCI toolbox (this concept may be applicable to other ECVs in CCI). If a facility cannot be provided to aggregate the data for users, then clear examples should be provided to demonstrate how this can achieved, including the propagation of uncertainties. [LST-URD-ADV-38-U, LST-URD-ADV-39-U, LST-URD-ADV-54-U]

- It was noted that for some LST applications (e.g. urban), LST at a scale of 300m or better would be very useful. However, a global 300-m LST data is probably not required, given that urban areas only account for a small fraction of the global land classification. [LST-URD-ADV-34-U]

Are you using the beta LST_cci data sets? If so, do you have any feedback? If a previous user of GlobTemperature data, are you finding it easy to adapt to the different CCI format?

- Most users had not yet used the LST_cci data sets, as they are not fully released.

- Users who had used the LST_cci data sets appreciated the consistent formatting across the different products provided as this made processing and analysis much easier.

- One user reported difficulties in obtaining pixel overpass times from the LST_cci data. The documentation should include this information; in addition to indicating how to convert the observation time in the file to other commonly used date-time formats. [LST-URD-ADV-55-U]

- A discrepancy in the dimension/variable naming convention was noted between SEVIRI and MODIS LST_cci products: Both 'lat' and 'lon' and 'latitude' and 'longitude' are used.

- The current provision of the 0.01° latitude-longitude data has been difficult for users to use – data provided on geo-referenced tiles would be easier to handle. [LST-URD-ADV-56-U]

- Provision of 'local solar time' in the LST_cci data files would be useful for users. This can be calculated but requires extra effort for users. [LST-URD-ADV-57-U]

- Issues have been reported along coastlines in the MODIS LST_cci products, which has necessitated masking of 5 pixels along the coastline (inland).

- Cloud contamination is present in the LST_cci IR products. [LST-URD-ADV-33-LOI, LST-URD-ADV-37-U]

- There are inconsistencies between the MW and IR QC flags – it would be better for users if these were consistent. [LST-URD-ADV-58-U]

- The LST_cci product user guide is not obviously available. [LST-URD-ADV-47-U]

CCI does not provide an operational service and the climate data records (CDRs) are typically fixed-length data sets. If LST_cci data can be made available in more 'real time', what timeliness of data would you ideally require?

- The need for real-time updates varies between applications. Some users require updates on timescales of a few days to a week or so (2-3 months was noted as being too long for some applications). Near-daily would be useful for some vegetation- and hydrology-related applications. However, annual updates are also sufficient for some applications (e.g. analysis of fluxes). Some users do not need real-time updates (e.g. some Surface Urban Heat Island studies). [LST-URD-ADV-59-U]

- It was recognised that the timeliness of the data is dependent on the end-goal for delivery of the products. For example, the requirements for C3S-delivered data sets vs Global Land Services.

- Quality requirements for near-real-time data delivery also vary with application. For example, for climate services, high-quality, temporally stable, well-calibrated L1b data is needed but the data are not usually needed within e.g. hours of acquisition. However, for other more 'operational' applications, the L1b data are needed within hours but systems can cope with lower accuracy and stability (e.g. NWP assimilation).

Is there any requirement for component LSTs in gridded data sets? For example, providing the average LSTs for each primary surface type (e.g. grassland, deciduous forest, etc) within each grid cell?

- Provision of component LSTs is of interest to many users, especially for climate studies, validation applications (including model validation, as models are providing similar component temperature information), satellite-flux-tower observations comparisons and SUHI studies. However, it was noted that if the LSTs were modelled (and not based on high-resolution observations), then this information would be less useful. Some users are also sceptical about the reliability/accuracy of the component temperatures. This would also be dependent on the land-cover information (and its uncertainties) used to define the component surfaces. [LST-URD-ADV-60-U]

- Provision of even very basic component temperatures (e.g. vegetation vs non vegetation) would be useful.

8.1.2.4. Climate Services Discussion Session

The breakout group discussion on user requirements took place on the second day of the workshop and was preceded by a presentation on 'Underpinning science to a climate service: examples from Climate Science for Services Partnership-China (CSSP-China)' delivered by a member of the Met Office Climate Services group. Delegates were then split into four groups of around seven participants to discuss four seed questions. These seed questions are listed below, with bulleted lists indicating the key points that were discussed in each case (focusing on requirements and suggestions). The detailed notes made by each discussion group are provided in Appendix C.

Data availability and format – how can we increase visibility and reach to non-scientists/specialists?

- Current data format is aimed at scientists of specialists – further processing/presentation adjustment is needed for non-scientists and -specialists. For example, NetCDF and Python may not be suitable for non-scientists and -specialists and a graphical web interface, e.g. with maps, could be more useful. However, it was acknowledged that many GIS packages can use NetCDF, although some users may not be aware of this facility. By highlighting that GIS packages are often compatible with NetCDF, this may improve user uptake. [LST-URD-ADV-61-U]

- European data portals need to improve data access (access to Sentinel-3 data was highlighted as an example here). Enabling users to visualise (and use) data within the data portal helps the user to select the data they want easily. If users cannot access data, they will go elsewhere. [LST-URD-ADV-62-U]

- It was recognised that data requirements are heavily application-dependent: Users need information different spatial and temporal scales. However, provision of online tools to re-grid, subset, apply QC, etc, which do not require expert knowledge, could be very useful and could also avoid the need to download very large quantities of data. The CCI data portal could provide this functionality but might need further development. [LST-URD-ADV-38-U, LST-URD-ADV-54-U]

- Visibility can be improved by demonstrating the usage of the data, for example, using LST to analyse or monitor heat waves and droughts, or performing an intercomparison with model data. The EUMETSAT Toolbox was noted as a useful tool for such applications. [LST-URD-ADV-42-U]

- There needs to be a concerted effort to raise awareness of satellite LSTs and its benefits. This could be achieved through an LST-focussed white paper in a climate services journal, or more general journal, such as BAMS. This paper could include examples of where LST has already been successfully employed in different applications or services. [LST-URD-ADV-63-U]

- It was noted that some users may be overwhelmed by the variety of single-sensor satellite LST data sets, and the large data volumes associated with high spatiotemporal resolution of these data sets can be a problem. [LST-URD-ADV-35-U]

- There needs to be greater clarity that LST is not the same as T2m; many users are used to dealing with T2m rather than LST. The benefits (and shortfalls) of LST over T2m should be highlighted: For some applications, LST is more suitable and examples should be provided. This information could be added in the LST metadata and documentation. [LST-URD-ADV-36-U]

- Users often perceive that in situ (e.g. weather station) observations are the 'truth'. It needs to be communicated clearly that these data also suffer from errors and may not always be representative of a wider area (e.g. point vs areal average). [LST-URD-ADV-36-U]

What additional information or resources is required? Do you need additional variables? Examples of use? Tools, e.g. Python tutorials?

- Cloud services could be used to house data, together with a set of tools to enable users to interact with these data in the way they need. Such tools have been implemented by existing and previous projects, which could be investigated here. Notebooks (e.g. Jupyter) with tutorials on how to process the data in the cloud could also be provided in a variety of common languages, e.g. Python, R. These cloud platforms could also house complementary data sets, such as ground observations and model fields. [LST-URD-ADV-38-U, LST-URD-ADV-39-U, LST-URD-ADV-46-U, LST-URD-ADV-54-U, LST-URD-ADV-62-U]

- Provide help and guidance to users wishing to convert the data into a different format. This could encourage new users to adopt LST_cci data. However, it was also noted that data standardisation across the CCI programme enables use of a wider range of products. [LST-URD-ADV-64-U]

- A user group of non-specialists needs to be identified. This could include people in government. However, it is not clear who is responsible for identifying such users. There are different actors in the process of providing a climate service, from the user to the data providers, often with boundary actors in between. These boundary actors often take on the role of identifying users and requirements. [LST-URD-ADV-65-U]

Does existing documentation meet climate service user needs? Is a different format of documentation or level of technical detail required?

- Documentation should be targeted at the user identified for a particular data set/delivery. Engaging with users directly would ensure the documentation is useful. Unified/standardised documentation should be considered (e.g. https://lpdaacsvc.cr.usgs/gov/appeears/). [LST-URD-ADV-66-U]

- 'Basic' or quick-start user guides are useful for quick reference and engagement. Product user guides are often too long and can be difficult for readers to engage with. Data providers should avoid repeating information in multiple documents; for example, full details of the algorithm should not be included in validation reports. Links to other documents could be used instead. [LST-URD-ADV-66-U]

- Users often want examples of data use, which are not usually provided – more examples could be included in documentation. However, presentation of these examples is crucial, and they should not be at the end of a long and detailed document where a reader may lose interest before reaching those examples. It was suggested that examples of data use could be housed in a different location. [LST-URD-ADV-42-U]

- Users need to be made aware of what is/is not possible with the available data and resources. Some user needs are unfeasible given current instrumental and technological limits. Documentation should provide examples of what can be achieved with the data. This should include examples of how a particular service has enabled improved decision-making. [LST-URD-ADV-42-U]

- The same information could be communicated in multiple ways. For example, providing infographics with examples of how data can be used can be helpful, in addition to providing more 'traditional' documentation. Dedicated workshops on specific aspects of the data or products could also be useful. Other suggestions for alternative methods for information presentation include short PowerPoint presentations, and videos or podcasts. [LST-URD-ADV-67-U]

Are you aware of Analysis-Ready Datasets (ARD)? These are aimed at downstream applications and non-expert users/non-specialists. Have you used ARD and if so, what has been your experience?

- Some users report little experience with ARD. It was recognised that these could be useful for climate service providers and other downstream users with little scientific background. However, it was also recognised that providing ARD adds additional overheads for data set providers. [LST-URD-ADV-68-U]

- ARD can reduce user flexibility, as a certain amount of data processing has already been performed in generating ARD. Therefore, it is key to understand user needs before creating ARD.

- Data cubes and data set stacking were also discussed and are of particular interest for urban applications. [LST-URD-ADV-68-U]

8.1.2.5. Future Role of LST in Climate Monitoring Discussion Session

The plenary discussion on the role of satellite LST observations in future IPCC Assessments and other reports took place on the third day of the workshop and was preceded by a presentation on 'Global and regional trends' delivered by a member of the LST_cci Climate Research Group and 'BAMS State of the Climate' delivered by the lead editor of the Global Chapter of SOTC (the Met Office). The following seed questions were shared during the discussion; the bullets under each question summarise the discussion in each case.

What is the priority development area to enable LST to be used in these assessments? For example, data set length, stability, accuracy and consistency across different surface types/regions, etc?

- Using LST in e.g. BAMS SOTC requires 'real-time delivery' of LST data to some degree. C3S could provide a route to providing these data, together with other ECVs. However, for transitioning to C3S it first needs to be demonstrated that the LST data have the quality required for climate science. [LST-URD-ADV-59-U]

- The scientific monitoring community needs to be convinced of the value of LST compared to other surface temperature data sets (i.e. T2m) – T2m is usually thought to be the temperature that relates more directly to the temperature felt by humans. [LST-URD-ADV-36-U]

- Providing both LST and T2m data sets of sufficient length for long-term climate monitoring is challenging.

What aspects of LST should we focus on for these assessment reports? For example, extreme events, variability, providing information in regions sparsely-observed *in situ*, etc?

- Proving near-real-time LST anomalies (e.g. monthly) would be a good starting point. This would help the community and users to engage and begin to understand how to interpret these data. However, the anomalies would need to be produced in a manner that is consistent with Climate Data Record production. [LST-URD-ADV-59-U]

- There is a need to educate the wider community on the difference between LST and T2m. LST is closely linked to the surface energy balance and making this connection clear could enable the community to understand the link with climate. [LST-URD-ADV-36-U]

- Targeting satellite LST data provision in sparsely-observed regions also has challenges from a remote-sensing perspective, as LST data at very high and low latitudes, including deserts and the Arctic/Antarctica can have very large uncertainties, for example in cloud detection. [LST-URD-ADV-37-U, LST-URD-ADV-69-U]

- Gaps due to cloud in IR LST data sets are an issue, but all-sky microwave LSTs could be used. [LST-URD-ADV-11-LOI]

- The Arctic and other high-latitude regions, such as Siberia, should be prioritised as these are regions that are experiencing rapid climate change and are poorly observed in situ. However, there are challenges associated with providing these data, e.g. reliable cloud screening. [LST-URD-ADV-37-U, LST-URD-ADV-69-U]

How could we exploit links with other Essential Climate Variables (ECVs)? E.g. sea surface temperatures, permafrost, air temperature, land cover?

- Provision of LST data over the Arctic would complement T2m observations, which are sparse in this region. As the Arctic is experiencing rapid climate change, it is critical to confront knowledge gaps with high-quality LST over permafrost, ice sheets and sea ice. In particular, there is currently no sea-ice surface temperature from CCI. [LST-URD-ADV-69-U, LST-URD-ADV-07-OI]

9. Feedback from early LST_cci data users in Phase I

This section summarises feedback from early LST_cci data users and was added for v2 of this URD. The information presented consists mostly of requirements gathered through the first Climate Assessment Report (CAR) (available from https://admin.climate.esa.int/media/documents/LST-CCI-D5.1-CAR_-_i1r0_-_Climate_Assessment_Report.pdf). The CAR v1 comprises of reports from the six dedicated LST_cci project User Case Studies (UCS) (Section 7) and reports from other studies that have used beta versions of the LST_cci data sets produced during the first two years of the project. None of the studies are complete, but the early feedback collected here is very useful to consider in further developing and improving the LST_cci data sets and plan for the next phases of the project.

9.1. Requirements identified from the LST_cci CAR v1

Feedback from early users who contributed to the CAR v1 is generally very positive, and users find the data easy to use, of good quality and in particular appreciate the consistency in format between the different LST_cci products. However, several requirements/requests for improvements were noted in the CAR v1, many of which are already being addressed by the project science team, who have been in close contact with these users throughout the project so far. The reader is referred to the CAR v1 for further information, but the main points are summarised below. (Note that errors in the data files or processing, e.g. incorrect attributes or global field values, known processing errors, are not included here as these have already been resolved by the project science team.)

9.1.1. Dataset accuracy, stability and precision

Several UCS have identified cloud contamination in the IR LST_cci products, and in particular in the MODIS Aqua data sets. Although some of this cloud contamination can be attributed to a known bug in the LST processor, it is clear that the cloud screening still needs further improvement [LST-URD-ADV-33-LOI]. However, it should be highlighted that a probabilistic cloud screening approach will be implemented for v2.0 products, which should offer significant improvements compared with v1.0.

Evidence presented in the CAR v1 suggests there may be errors in the emissivity data used in the MODIS LST retrievals. It is suggested that the source emissivity data is revisited and improved where possible [LST-URD-ADV-70-U]. However, an updated emissivity data set is being implemented in v2.0 of the LST_cci MODIS products. The LST_cci v1.0 products are based on an older emissivity data set and it is expected that the updated version in v2.0 will improve the accuracy of the LST_cci retrievals in this case.

Results presented in the CAR v1 suggest that the multi-sensor products suffer from significant non-climatic discontinuities, for example, when a new sensor is introduced into the record. This is seen in both the IR and MW multi-sensor products. Many climate applications have a critical dependency on data set stability, e.g. monitoring, calculation of trends; therefore ensuring the stability of these products meets the specified user requirements should be a priority [LST-URD-REQ-16-O, LST-URD-OPT-16-O]. It should be noted that improvements to both the MW and IR multi-sensor product stability are currently being implemented by the project science team and will be included in the v2.0 release.

9.1.2. Data set artefacts and issues

Issues in the L3 IR products due to averaging over multiple overpasses were identified in some of the UCS. Users would prefer that observations are not averaged over multiple observation times, and that data from only one observation time is considered for each grid cell [LST-URD-ADV-52-U]. It should be noted that this is already being implemented for LST_cci v2.0 products, based on this early user feedback.

9.1.3. Data file issues and recommendations

Based on feedback from the UCS, it is clear that the method chosen to deliver the 0.01° data set is not optimal. Users have had difficulty in using and understanding these data and it would be preferable if the data from each orbit were mosaicked beforehand and provided as tiles, similar to the gridded MOD11/MYD11 data products from NASA [LST-URD-ADV-56-U]. All baseline LEO IR data products will be delivered as global day/night 0.01° files. A new LST_cci regridding and subsetting tool will provide users with the functionality they need to acquire the data to their specific requirements.

Although the MW and IR product formats are broadly consistent, there are some discrepancies between the information presented in each case. For example, classification is by day/night for IR but ascending/descending for MW. In addition, the QC information is inconsistent. Users would prefer a more consistent approach between these data sets [LST-URD-ADV-58-U].

The current land cover class information provided in the LST_cci files is static; provision of dynamic/annual land cover data would be preferred (note that users appreciate the provision of land cover class data in the LST_cci data files) [LST-URD-ADV-71-U]. However, dynamic land cover information will be implemented for the v2 release of the LST_cci data files.

Provision of satellite view zenith angles with sign (i.e. '-' or '+') that indicates whether the view is towards the east or west would be useful for some users (although this will not be meaningful at very high latitudes but for the majority of the orbit this is useful information) [LST-URD-ADV-72-U]. Users currently have to obtain this information from the satellite azimuth angle, which is an extra step.

The latitude and longitude values of the LST_cci MODIS/(A)ATSR 0.01° products global attributes "geospatial_lat_min", "geospatial_lat_max", "geospatial_lon_min", and "geospatial_lon_max" need to be corrected by half pixel in order to be equal to the actual bounding box coordinates of each LST image [LST-URD-ADV-73-U]. The values currently provided are the latitudes and longitudes of the centre of the four corner pixels. This should be corrected.

The spatial extent of the SEVIRI disk changes at some point in the record, so only in the later part do north-eastern Europe and parts of south America have valid data. This should be rectified in some way, or at least a guidance note should be issued to users [LST-URD-ADV-74-U].

The fields 'ncld' and 'variance' in the LST_cci MSG_SEVIRI_L3U products are included in the files but have no meaning, as the values are instantaneous and nearest neighbour gridding was performed. As the LST_cci files have a standardised format across all products, it is suggested that a comment is added to inform the user of the fields for SEVIRI that are not meaningful, in the file attributes [LST-URD-ADV-75-U].

Finally, users have requested that a 'readme' file in the current public directory for the beta products that includes a list of acronyms and information on the directory structure is provided in addition to further information about the products (e.g. provision of PUG) [LST-URD-ADV-47-U].

9.1.4. Other recommendations

The following other recommendations were made in the CAR v1:

- Dedicated effort towards improving Ice Surface Temperature (IST) algorithms should be considered [LST-URD-ADV-76-U].
- Extend SEVIRI data record beyond 2008-2010 [LST-URD-ADV-77-U]. It is believed this is already planned for the v2 release.
- Implement a geometrical correction to 'adjust' the LSTs to nadir-equivalent LSTs for all sensors [LST-URD-ADV-78-U]. For the current LST_cci phase, this will only be implemented in the merged product.
- Provide downscaled (higher spatial resolution) SEVIRI data (e.g. downscaled with MODIS) [LST-URD-ADV-79-U].
- Provide instantaneous LSTs in L3 products as additional fields in the LST_cci products (e.g averaged LSTs over each orbit separately) [LST-URD-ADV-80-U].
- Provide in-filled LST products where IR data have been used [LST-URD-ADV-11-LOI].
- Provide LST products for AVHRR/3 and VIIRS (note AVHRR/3 is already included in the list of proposed products for LST_cci Phase I) [LST_URD_ADV-82-U].
- In addition, it is noted that the uptake of uncertainty information in UCS and other studies is minimal so effort should focus on improving this in the user community [LST-URD-ADV-38-U, LST-URD-ADV-44-U, LST-URD-ADV-46-U].

9.2. Requirements identified from other CCI projects

Very little feedback from other CCI projects using LST_cci products has been received so far. LST_cci products have been shared with Permafrost_cci, who could not use the 0.05° data and required data at 0.1° latitude-longitude [LST-URD-REQ-12-O]. One month of these higher-resolution LST_cci products has now been provided to the project, which have provided positive feedback on these initial data and have requested more once available.

10. Feedback from the 2022 User Workshop

10.1. LST_cci User Workshop 2022 Overview

The LST_cci 2022 User Workshop was held online on 27-29 September 2022. An online format was chosen following the success of the LST_cci 2020 User Workshop (see Section 8). Twelve 1-hour live sessions were held over the three-day event, comprising oral and poster presentations, demonstrations and practical sessions using LST_cci datasets, discussion sessions with interactive questions for participants to answer online, and a virtual social event.

Further details of the workshop are provided in the 2022 User Workshop Report (UWR) [AD-01], which include:

- Motivation for the workshop format and content.
- Full agenda with a summary of the main points from each presentation.
- Results from a workshop feedback survey.
- Outcomes from each discussion session, including the results of the questions posed to the workshop participants.
- A list of recommendations collated during the workshop.

10.2. LST_cci User Workshop 2022 Outcomes

Feedback collected via an online survey after the 2022 workshop event was generally very positive [AD-01]. However, the live Zoom sessions were not as well attended as the 2020 event, despite a slightly larger number of registrations for the 2022 event (n=136 vs n=133), with the number of delegates varying between 19 and 42 at the 2022 event compared with 41 and 68 in 2020. However, the access logs for the live sessions' recordings suggest that many delegates engaged offline, either watching or downloading the recordings in their own time. As for the 2020 workshop, the LST_cci project live sessions on day 1 were the most widely attended/viewed. The reason for the comparatively smaller number of delegates attending the live sessions is unknown, but it is notable that the 2020 event took place in the very early stages of the Covid-19 pandemic, when attending online meetings was still a novel experience. Nevertheless, responses to the delegate feedback survey issued after the event were generally very complimentary and confirmed that the event was well run, and the content was of interest to members of the LST user community. In general, it was concluded that:

- The format and content of the LST_cci 2022 User Workshop was well received and should be considered for future virtual events. Eventbrite should be used for the event registration.
- A strategy to increase the number of participants in the live sessions in future online events is required. Holding a combined workshop with another CCI Essential Climate Variable (ECV) project is one potential solution.
- Other types of virtual events could be considered in the future, for example, targeted knowledge-exchange meetings, open question & answer sessions, seminars, etc.
- An LST_cci code repository could be considered for both users and the project team to upload useful computer code to process LST_cci datasets. However, it should be made clear that the repository is maintained on a best-efforts basis and the code in the repository should be used with caution as it is not guaranteed to be free from errors. The repository could also include code made available to users during workshop practical sessions.

In addition, some specific recommendations were identified during the workshop discussion sessions in response to pre-defined questions asked using the online tool, 'Slido' (www.slido.com). These recommendations are shown in Table 10-1, grouped by subject. In each case, the background of each recommendation is provided in the 'Notes' column of the table, which also provides the recommendation number, e.g. 'Recommendation #1'-'Recommendation #30' used in the UWR for traceability. These recommendations provide a snapshot of some of the user needs at the time of the 2022 workshop. All recommendations are considered here as potential requirements for the LST_cci project. However, given the low number of delegates participating in the discussion sessions and providing answers to the questions posed using Slido (n≤13), all new requirements are considered to be 'Advice Notes' as some result from suggestions made by just one or two meeting delegates (see Section 4). Nevertheless, these are still considered to be valid requirements provided they are sensible and achievable suggestions. It should also be noted that some of the recommendations from the workshop duplicate existing LST_cci project requirements defined earlier in this URD. For each recommendation listed in Table 10-1, an outcome is included in the final column of the table to indicate how the recommendation is actioned in this URD, i.e. whether a new Advice Note is defined, or whether the recommendation duplicates an existing requirement already identified in this URD.

*Table 10-1: List of specific recommendations resulting from the LST_cci 2022 User Workshop. The recommendations are explained and numbered in Section **Error! Reference source not found.** of the UWR and are indicated in the 'Notes' column of this table, e.g., LST-UWR2022-REC-01 refers to Recommendation #01 [AD-01].*

Recommendation	Notes	Action
Data Format and Accessibility		
Provide easy access to LST_cci products and facilities to improve data download.	LST-UWR2022-REC-30. Requested by 1 respondent and combined with LST-UWR2022-REC-09 "Provide a direct link to download LST_cci data on the LST_cci web pages", a consensus from the discussion.	Duplicates existing requirement LST-URD-ADV-04-LI 'Ensure long term, easy access to data'
Provide reprocessed LST_cci datasets at least annually.	LST-UWR2022-REC-04. At least 11 of 12 respondents would like at least annual reprocessing.	New requirement LST_URD_ADV-82-U
Provide LST_cci data within 48 hours of acquisition.	LST-UWR2022-REC-01 and combined with LST-UWR2022-REC-29 "Provide LST_cci products in real-time". 5 of 11 respondents require data within 48 hours of acquisition.	Duplicates existing requirement LST-URD-ADV-59-U 'Provide LST_cci data sets in real time, ideally with near-daily updates' – add note specifically highlighting need for data within 48 hours of acquisition.
Provide LST data on a Polar EASE grid.	LST-UWR2022-REC-14. Requested by 3 users (1 post-workshop in response to a specific email sent to the LST_cci distribution list).	New requirement LST_URD_ADV-83-U
Ensure LST_cci ARDs are provided with good documentation, in easy-to-access formats with simple quality flags.	LST-UWR2022-REC-19. Each list item was requested by one user.	New requirement LST_URD_ADV-84-U

Recommendation	Notes	Action
Provide LST data that are stable over time and free from non-climatic discontinuities.	LST-UWR2022-REC-21. Requested by 2 of 9 respondents.	Duplicates existing requirement LST-URD-ADV-09-LI 'Provide multi-decadal, homogenised datasets, free from non-climatic discontinuities'
Provide fill values in files for missing data products and an inventory of files with missing data.	LST-UWR2022-REC-12. Requested by some users during discussion. Some users would prefer to have e.g. days of missing data with 100% fill values, rather than having a missing data file.	New requirement LST_URD_ADV-85-U
Extend LST_cci Regridding Tool to produce temporal means (e.g. weekly, pentads, etc).	LST-UWR2022-REC-15. Requested by 2 of 6 respondents.	New requirement LST_URD_ADV-86-U
Develop a wrapper for the LST_cci Regridding Tool to process multiple files.	LST-UWR2022-REC-16. Requested by 1 of 6 respondents.	New requirement LST_URD_ADV-87-U
Provide detailed information on what satellite-observed LST fields represent and how this relates to climate model parameters.	LST-UWR2022-REC-24. Requested by 1 of 9 respondents. Combined with LST-UWR2022-REC-28 "Provide detailed information on what satellite-observed LST fields represent and how the data can be used most effectively", also requested by 1 respondent.	Duplicates existing requirement LST-URD-ADV-02-OI 'Disseminate clear information on what LST data represents, potential applications and how the data may be used' – add to existing requirement notes about linking to model parameters.
Maintain a webpage/blog as a permanent resource that can be accessed for historical issues.	LST-UWR2022-REC-05. Consensus during discussion.	New requirement LST_URD_ADV-88-U
Provide users with the option to be sent email notifications when new issues are discovered and added to the issues list.	LST-UWR2022-REC-06. Requested by 11 of 12 respondents.	New requirement LST_URD_ADV-89-U

Recommendation	Notes	Action
Provide information on data gaps, e.g. due to sensor outages or satellite manoeuvres.	LST-UWR2022-REC-11. Requested by several users during discussion.	New requirement LST_URD_ADV-90-U
Product Types		
Provide LST_cci data as 10-day means.	LST-UWR2022-REC-02. 3 of 12 respondents require 10-day means.	New requirement LST_URD_ADV-91-U
Provide gap-filled LST_cci products.	LST-UWR2022-REC-03 and combined with LST-UWR2022-REC-23 "provide gap-filled LST data". 7 of 12 respondents might use gap-filled data with large uncertainties. E.g. based on model data, heavily interpolated, or a climatology.	Duplicates existing requirement LST-URD-ADV-11-LOI 'Provision of all-sky LST datasets'. Add note to indicate that it is not clear whether users want gap-filled LSTs to be clear-sky or all-sky.
Provide LST climatologies.	LST-UWR2022-REC-17. At least one user requested this.	New requirement LST_URD_ADV-92-U
Provide selected properties derived from LST, for example, anomalies, daily minimum and maximum LST, annual means and LST- 2m air temperature differences.	LST-UWR2022-REC-18. Each list item was requested by one user.	New requirement LST_URD_ADV-93-U
Data Specification		
Provide LST_cci products on UTC grids.	LST-UWR2022-REC-25. Requested by 1 of 9 respondents. Provide time-consistent fields with time stamp 00:00, 01:00....23:00 UTC e.g. to match model output.	New requirement LST_URD_ADV-94-U
Provide LST data with increased frequency and spatial resolution.	LST-UWR2022-REC-22. Requested by 1 of 9 respondents. For example, to match that of high-resolution climate models.	Covered by existing requirements LST-URD-REQ-10-O, LST-URD-OPT-12-O, LST-URD-OPT-13-O and LST-URD-ADV-34-U, which

Recommendation	Notes	Action
		essentially request hourly observations at <1 km or even ≤300m spatial resolution.
Priorities		
Prioritise dealing with cloud cover in IR data sets.	LST-UWR2022-REC-13. Requested by 7 of 12 respondents. Improve cloud masking and gap-filling.	New requirement LST_URD_ADV-95-U
Error and Uncertainty		
Provide detailed information on uncertainties.	LST-UWR2022-REC-10 from UWR 2022. Request from a single user during discussion; consider including this information in individual file metadata.	Covered by existing requirements LST-URD-REQ-26-O, LST-URD-ADV-22-I and LST-URD-ADV-23-OI, e.g. detailed information on how uncertainties are calculated, what they represent and how they can be useful.
Cloud		
Improve IR cloud screening.	LST-UWR2022-REC-07. Requested by 6 of 12 respondents, e.g. incorrect cloud mask.	Covered by existing requirements LST-URD-ADV-33-LOI 'Reduce errors due to cloud contamination in IR LST data sets' and LST-URD-ADV-37-U 'Improve cloud screening over ice and snow'
Provide detailed information on IR cloud screening processes.	LST-UWR2022-REC-08. Consensus during discussion.	New requirement LST_URD_ADV-96-U
Other		
Provide observation time, view angles, total uncertainty and land cover classification in LST_cci ARD products.	LST-UWR2022-REC-20. Combined response from 4 respondents.	New requirement LST_URD_ADV-97-U

Recommendation	Notes	Action
Provide observation operators to convert LST to T2m and potentially other variables.	LST-UWR2022-REC-26. Based on information provided by 9 respondents. For example, to soil moisture, below- and within-canopy temperatures and temperatures associated with different PFTs.	New requirement LST_URD_ADV-98-U
Include additional variables in LST_cci products where possible to support climate services using LST.	LST-UWR2022-REC-27. Based on feedback from 10 respondents, include T2m and land cover classification (both high priority); other variables such as surface humidity, modelled surface 'skin' temperature, emissivity, NDVI, fractional vegetation and total column water vapour could also be considered (low priority).	New requirement LST_URD_ADV-99-U

11. Requirements of Satellite LST for Climate Applications

Climate user requirements for satellite LST have been assessed here in the following ways: 1) from the 22 responses to a short paper questionnaire issued at the Joint Land Workshop in 2018 (Section 5), 2) from the 76 respondents to the a longer online survey, active for two months during summer 2018 (Section 6), 3) in-depth interviews conducted with eight members of the CRG (Section 7), and 4) feedback received from the User Workshop 2020 (Section 8), early users of the LST_cci beta products (Section 9) and the User Workshop 2022 (Section 10). This section reviews the major findings of this assessment and derives user requirements from the information gathered that can be used to guide the products delivered by the LST_cci project.

User requirements are considered using nine categories, which broadly follow the format of the questionnaires and interviews. These categories are:

- Data format and accessibility
- Product types
- Data specification
- Quality control
- Error and uncertainty
- Validation and inter-comparison
- Clouds
- Other requirements

Where they provide additional information, e.g. user requirements not obtained in LST_cci, relevant requirements from the GlobTemperature RBD are included at the beginning of a section. The GlobTemperature requirements are also included as they provided much of the framework for gather requirements in LST_cci: Not all the questions asked in the GlobTemperature survey were asked in LST_cci in order to prioritise climate requirements for LST, whist ensuring that the LST_cci questionnaire was not excessively long. The GlobTemperature requirements are followed by requirements and advice notes originating from the LST_cci user requirements gathering exercise, which is described in detail in the previous sections of this document. An overview of the requirement outcomes is provided in Section 11.

Requirements from the GlobTemperature RBD retain their original numbering: these have the prefix 'REQ', followed by either 'TR' (threshold level responses) or 'BR' (breakthrough level responses). For example: 'REQ-1-BR' would be breakthrough requirement number 1.

Requirements derived in this document for LST_cci have the following naming convention:

LST-URD-<*type*>-<*number*>-<*source*>

Where:

- LST-URD indicates that the requirement or advice note has originated from this LST_cci User Requirements Document (URD)
- <*type*> can be one of three options:
    - "REQ": A requirement that must be addressed. When questions are asked in terms of a threshold, breakthrough or objective requirement, the threshold requirement is used here.
    - "OPT": An optional requirement that should be met where possible. This aligns with the breakthrough requirement definition.

   - “ADV”: An advisory requirement that should be considered where feasible. These are used where requirements cannot be analysed quantitatively, for example the CRG interviews or free text questions provided in the Lisbon and Online questionnaires.
- <*number*> is a two-digit counter
- <*source*> identifies where the requirement originated from, in this case it can be one or more of four options:
   - ‘L’: Joint Land Workshop held in Lisbon [Section 5]
   - ‘O’: Online questionnaire [Section 6]
   - ‘I’: Interviews with members of the CRG [Section 7]
   - ‘U’: User interactions, e.g. workshop, other feedback [Section 8, 9 and 10]]

For each requirement or advice note issued, the source and any relevant notes, including the percentage of respondents with that requirement where appropriate, are provided.

The LST_cci project should address all the ‘REQ’ requirements identified in this URD. The ‘OPT’ requirements are more stringent versions of the six ‘REQ’ requirements concerning spatial and temporal resolution, and accuracy, stability and precision, and should be addressed by the project where possible. The ‘ADV’ requirements should be considered where feasible and are essentially recommendations identified through user engagement. It is recognised that some of the OPT and ADV requirements will not be achieved during Phase I of LST_cci but through later phases of the project. Many of the ADV requirements in particular are ambitious and require additional work that is beyond the scope of this first phase of the project. For example, holding additional workshops that focus on demonstrating how to use different LST_cci data sets and their uncertainties, and provision of LST data for additional sensors or in near real time. Therefore, the ADV requirements should also be used to inform the design of future LST_cci project phases as they provide information on what is most important to current and potential LST data users.

11.1. Summary Requirements and Recommendations

11.1.1. Data Format and Accessibility

For reasons of continuity and consistency, LST_cci data will be provided in either the GlobTemperature harmonised format, or the CCI standard format used elsewhere within the CCI project. Relevant requirements from the GlobTemperature RBD relating to data format, metadata specification and data access are summarised in

Table 11-1. GlobTemperature requirements relating to timely delivery of data (e.g. near-real-time or ‘NRT’) are excluded here, as it was not an original objective of LST_cci to provide Interim Climate Data Records (ICDR) or NRT data. However, as a question about NRT delivery was asked at the User Workshops in 2020 and 2022, a requirement relating to this has been included in the updated version of this URD (v3). The user needs gathered in LST_cci aim to build on this existing information and focus on establishing the impact for LST users of choosing either the GlobTemperature harmonised format, or the CCI standard format, for the LST_cci products.

Table 11-1: Summary of requirements from the GlobTemperature project relating to data format and accessibility, which are also relevant to LST_cci (Bulgin & Merchant, 2016).

Number	Requirement	Comment
REQ-9-TR	Provide surface emissivity assumed in the LST retrieval as an ancillary data field	This was requested by 83 % of respondents
REQ-16-TR	Establish a single file specification covering all metadata requirements	This was requested by 89 % of respondents
REQ-19-TR	Provide a detailed description of externally linked datasets within a data portal	This was requested by 75 % of respondents
REQ-20-TR	Provide links to product specification documents for LST products	This was requested by 77 % of respondents
REQ-32-TR	Provide information on 2 m air temperature, aerosol affected pixels, the diurnal cycle, data adjustment, total column water vapour, wind speed and humidity	These were requested by > 45 % of respondents (to either the original user survey or the UCM3 mini-questionnaire)
REQ-33-TR	Provide land cover type, fraction of vegetation cover, albedo assumed in the retrieval and NDVI with LST data	These were requested by > 45 % of respondents
REQ-37-TR	Provide descriptions of dataset length and coverage and a link to the main provider web page for data accessed via a portal	This was requested by > 66 % of respondents
REQ-38-TR	Provide dataset validation reports, detailed descriptions of file content and dissemination options and interactive map services for LST data	

NetCDF data is acceptable for the majority of participants in the LST_cci online survey (Table 11-2), but the development of a data converter could be considered for those unable to use NetCDF (Table 11-3). The impact for the majority GlobTemperature and CCI users of changing to either the CCI or GlobTemperature data format was deemed to be very little to none. Considering most of the participants in this survey already use, or are interested in using CCI data, and potentially in conjunction with LST data, the use of the CCI standard format is recommended for LST_cci products. This recommendation is endorsed by the CRG, where the need for consistent formats between CCI products was also noted (Section 7.4).

Table 11-2: Summary of requirements relating to data format and accessibility.

ID	Requirement	Type	Source	Notes
LST-URD-REQ-01-O	Provide LST products in NetCDF format	Majority	Online questionnaire Q.31	90% of respondents were able to use NetCDF data

Through both the online questionnaire (Section 6.5.4), interviews with members of the CRG (Section 7.4), and user workshops it is apparent that users are concerned about the interpretation of satellite LST, i.e. what exactly satellite LST represents as a physical quantity. This may also discourage more widespread use of LST in the climate science community, including in climate modelling. Where possible, clear information on what satellite LST_cci products represent, and how they can be used within different applications, should be provided. This information should be readily and easily available to users. Any assumptions made during the retrieval process or product construction, including detailed information on the techniques used for any data merging, should be stated clearly and provided with the data. Data should also be easily accessible – one respondent to the online survey suggested that the GlobTemperature data portal was a good model for data dissemination (Table 11-3). At the User

Workshop 2020, it was clear that users thought information could be presented to users in a range of ways, for example, using videos, workshops and podcasts in addition to traditional documentation. They also felt that documentation targetted at different user levels would be beneficial, for example, providing more basic documentation for non-specialists. At the 2022 User Workshop, several new requirements relating to provision of information were also defined, for example, providing users with information on missing data/files, historical instrumental issues that may affect data, and enabling users to sign up to a mailing list where users can be informed about new issues. Some extensions to the new LST_cci regridding tool were also requested.

Table 11-3: Summary of advice notes issued relating to data format and accessibility.

ID	Advice	Source	Notes
LST-URD-ADV-01-O	CCI standard format is recommended for LST_cci products	Online questionnaire Q.13, Q.14, Q.37, Q.38	52 participants currently use CCI products, 32 use these in conjunction with LST data
LST-URD-ADV-02-OI	Disseminate clear information on what LST data represents, potential applications and how the data may be used	Online questionnaire Q.16, CRG interviews	Aim to improve understanding of what LST data represents, including linking to model parameters.
LST-URD-ADV-03-I	Provide documentation detailing assumptions made during the retrieval process or product construction, including detailed information on any techniques used for merging	CRG interviews	Aim to make it as easy as possible to understand the data
LST-URD-ADV-04-LI	Ensure long term, easy access to data	Lisbon questionnaire Q.10, CRG interviews	CCI Open Data Portal will be used (note that the GlobTemperature portal suggested as a good model)
LST-URD-ADV-05-O	Provide a summary of the availability and characteristics of different LST products	Online questionnaire Q.69	
LST-URD-ADV-06-LI	Consistency should be maintained between different LST products within LST_cci	Lisbon questionnaire Q.3, CRG interviews	Users often require data from multiple sensors
LST-URD-ADV-07-OI	Consistency between LST_cci and other CCI products should be maintained	Online questionnaire Q.14, CRG interviews	32 participants use CCI ECV products in conjunction with LST data
LST-URD-ADV-08-OI	Provide information on how comparable LST_cci products are with other CCI datasets, for example, spatial and temporal averaging, uncertainties, changes likely to impact LST	Online questionnaire Q.69, CRG interviews	

ID	Advice	Source	Notes
	(e.g. vegetation fractional cover)		
LST-URD-ADV-35-U	Provide guidance to users on which LST products should be used for different applications	User Workshop	Users can be overwhelmed by the choice of LST products, e.g. many single-sensor products.
LST-URD-ADV-40-U	Regularly consult with users on appropriateness of data format, accessibility and usability.	User Workshop	Good examples provided by NOAA and NASA through ESIP.
LST-URD-ADV-41-U	Provide hands-on experience for users at dedicated workshops	User Workshop	Hold demonstrations, provide Jupyter notebooks, example code, etc.
LST-URD-ADV-42-U	Provide LST use examples (with code) in a dedicated document. Include information on what can be achieved with the data (e.g. limitations).	User Workshop	
LST-URD-ADV-47-U	Ensure all LST_cci documentation is readily and easily available to users.	User Workshop	Links to documentation and info about data storage structure needs to be added to data portal, including public area on Jasmin for Beta products.
LST-URD-ADV-51-U	Provide information on LST trends	User Workshop	Calculated trends for multi-decadal LST products could be provided within user documentation. This could include information on known trends in the underlying raw satellite data.
LST-URD-ADV-54-U	Provide tools to enable users to select the data they want themselves.	User Workshop	E.g. for specific regions, with specific QC or other screening applied, etc.
LST-URD-ADV-59-U	Provide LST_cci data sets in real time, ideally with near-daily updates.	User Workshop	11 of 12 respondents require data within 48 hours of acquisition. Some applications require less-frequent updates, e.g. monthly. Provision of real-time anomalies could also be considered.
LST-URD-ADV-61-U	Highlight in LST_cci documentation that most GIS packages can use netCDF data.	User Workshop	
LST-URD-ADV-62-U	Improve delivery of data via data portals – enable users	User Workshop	

ID	Advice	Source	Notes
	to visualise and use data within the portal.		
LST-URD-ADV-63-U	Raise awareness of satellite LST and its benefits through improved publicity.	User Workshop	E.g. a white paper could be produced.
LST-URD-ADV-64-U	Provide information and/or tools to convert LST_cci data into different formats.	User Workshop	
LST-URD-ADV-65-U	Establish a non-specialist user group to consult for data provision to non-specialist users.	User Workshop	
LST-URD-ADV-66-U	Provide a range of documentation targeted at different user levels/details.	User Workshop	Consider unified/standardised documentation, e.g. https://lpdaacsvc.cr.usgs/gov/appeears/
LST-URD-ADV-67-U	Provide information to users in a variety of ways, e.g. traditional documentation, videos, podcasts, etc.	User Workshop	In addition to holding workshops [LST-URD-ADV-41-U]
LST-URD-ADV-68-U	Make LST_cci data available in ARD and/or data cube formats.	User Workshop	
LST_URD_ADV-82-U	Provide reprocessed LST_cci datasets at least annually	User Workshop	
LST_URD_ADV-83-U	Provide LST data on a Polar EASE grid	User Workshop	Low priority – only 2-3 users identified with this need.
LST_URD_ADV-84-U	Ensure LST_cci ARDs are provided with good documentation, in easy-to-access formats with simple quality flags.	User Workshop	Low priority – only a few users have identified a need for ARD so far.
LST_URD_ADV-85-U	Provide fill values in files for missing data products and an inventory of files with missing data.	User Workshop	Some users would prefer to have e.g. days of missing data with 100% fill values, rather than having a missing data file.
LST_URD_ADV-86-U	Extend LST_cci Regridding Tool to produce temporal means (e.g. weekly, pentads, etc).	User Workshop	
LST_URD_ADV-87-U	Develop a wrapper for the LST_cci Regridding Tool to process multiple files.	User Workshop	
LST_URD_ADV-88-U	Maintain a webpage/blog as a permanent resource that can be accessed for historical issues.	User Workshop	High priority action.
LST_URD_ADV-89-U	Provide users with the option to be sent email	User Workshop	High priority action.

ID	Advice	Source	Notes
	notifications when new issues are discovered and added to the issues list.		
LST_URD_ADV-90-U	Provide information on data gaps, e.g. due to sensor outages or satellite manoeuvres.	User Workshop	High priority action.

11.1.2. Product Types

A range of products are proposed for the LST_cci data sets (Table 3-2). Requirements summarised in Table 11-4 highlight the outcomes of the two questionnaires, which indicate the priority products LST_cci should make available at L2, L3C, and L4 (described in Table 6-1). Interviews with members of the CRG highlighted why these datasets are so important:

- L2 data
  - Re-projection of pixels in GEO datasets can cause loss of spatial information
  - LEO overpasses at the poles are more frequent, therefore providing a time-averaged product may not be helpful
- L3C data
  - Provision of regularly gridded, time averaged datasets, with consistent grids used across datasets facilitates the use of multiple products
  - Using consistent grids across the CCI project will also make it easier to make synergistic use of these products
- Merging LEO and GEO LST datasets improves the spatial coverage and helps to resolve the diurnal cycle

Table 11-4: Summary of requirements relating to product type.

ID	Requirement	Type	Source	Notes
LST-URD-REQ-02-O	Provide LST from IR LEO satellites	Soft	Online questionnaire Q.30	68% of respondents are interested in these data
LST-URD-REQ-03-O	Provide LST from IR GEO satellites	Soft	Online questionnaire Q.30	66% of respondents are interested in these data
LST-URD-REQ-04-O	Provide products which merge LST from multiple IR LEO satellite datasets to create a long running, near-global CDR	Soft	Online questionnaire Q.30	54% of respondents are interested in these data
LST-URD-REQ-05-LO	Provide products produced by merging LEO and GEO datasets	Majority / Soft	Lisbon questionnaire Q.7, Online questionnaire Q.30	90% (Lisbon) / 63% (Online) of participants were interested in merged products
LST-URD-REQ-06-O	Provide LST data products at level 2	Soft	Online questionnaire Q.29	47% of respondents selected Level 2 data
LST-URD-REQ-07-O	Provide LST data products at level 3C	Soft	Online questionnaire Q.29	55% of respondents selected Level 3C data

ID	Requirement	Type	Source	Notes
LST-URD-REQ-08-O	Data from MODIS instruments should be given high priority	Soft	Online questionnaire Q.10	75% of respondents currently use MODIS LST data for climate applications

Using the results of both questionnaires and discussions with the CRG, advice notes concerning LST products are provided in Table 11-5. For climate studies, it is particularly important to have long-term consistency between products; often projects will require data from multiple sensors to obtain the dataset length required. For this reason, CDRs can be valuable, but consistency between other products also allows participants to select which instruments to use. It was found that some members of the CRG are already gap filling datasets themselves, particularly for model input purposes, providing a standard gap filed product would maintain consistency, and reduce the workload for these projects. This was also highlighted at the User Workshops in 2020 (Section 8 and 2022 (Section 10). However, clarity is needed on whether users require gap-filled data to represent clear-sky or all-sky; this could be a focus question for a future workshop.

Table 11-5: Summary of advice issued in relation to product types.

ID	Advice	Source	Notes
LST-URD-ADV-09-LI	Provide multi-decadal, homogenised datasets, free from non-climatic discontinuities	Lisbon questionnaire Q.3, CRG Interviews	Long term, consistent datasets are required for climate science. Links to LST-URD-REQ-13-O and LST-URD-OPT-13-0
LST-URD-ADV-10-OI	Provision of MW LST products	Online questionnaire Q.30, Interviews with CRG	43% of respondents were interested in MW products
LST-URD-ADV-11-LOI	Provision of all-sky LST datasets	Lisbon questionnaire Q.10, Online questionnaire Q.30, Interviews with the CRG	Some members of the CRG are gap-filling IR LST data sets already; a standard option would be useful Not clear whether users want gap-filled LSTs to represent clear-sky or all-sky. 38% of respondents to the online survey are interested in a merged IR and MW product.
LST-URD-ADV-12-O	Provision of Meteosat data	Online questionnaire Q.10	Meteosat was the second most popular instrument out of respondents currently use LST data for climate applications
LST-URD-ADV-13-O	Provision of Landsat data	Online questionnaire Q.10	Landsat was the third most popular instrument out of respondents who currently use LST data for climate applications
LST-URD-ADV-14-O	Provision of AVHRR data	Online questionnaire Q.69	To extent data record length
LST-URD-ADV-58-U	Improve consistency between MW and IR LST_cci data sets.	User Workshop	Currently the QC flags are not the same.

ID	Advice	Source	Notes
LST-URD-ADV-76-U	Provide a dedicated Ice Surface Temperature retrieval.	CAR v1	
LST-URD-ADV-79-U	Provide downscaled SEVIRI data (e.g. using MODIS).	CAR v1	
LST-URD-ADV-81-U	Provide LST products for VIIRS.	CAR v1	
LST_URD_ADV-91-U	Provide LST_cci data as 10-day means.	User Workshop	Low priority: At least 3 users requested this.
LST_URD_ADV-92-U	Provide LST climatologies.	User Workshop	Low priority: At least one user requested this.
LST_URD_ADV-93-U	Provide selected properties derived from LST, for example, anomalies, daily minimum and maximum LST, annual means and LST- 2m air temperature differences.	User Workshop	Low priority: Each list item was requested by at least one user.

MODIS data are particularly popular with participants in the survey, and hence it should be considered a priority. Although MODIS LST products are already available from NASA, LST_cci can add value by providing them in a format that is consistent with other LST_cci and CCI products to aid multi-product users, including the provision of improved cloud and uncertainty information, and the application of algorithms that are consistent with other LST ECV products. Meteosat instruments are also popular, along with Landsat and VIIRS data, which are not part of the first phase of the project, but should be considered during phase 2. User feedback captured in the CAR v1 also indicated that provision of downscaled SEVIRI data and a dedicated Ice Surface Temperature (IST) product would also be useful.

11.1.3. Data Specification

11.1.3.1. Coverage and resolution

Table 11-6 summarises requirements for data coverage, observation times, dataset length, spatial resolution and temporal resolution. Some of these requirements are specified at the threshold and breakthrough level, which are defined in Table 4-2. Interviews with the CRG provided some context:

- For global climate studies, 0.05° resolution data is acceptable for many, but 1 km is preferred
- For localised studies, such as for urban areas, require higher resolution – data at both 30-50m and 300m were requested at the User Workshop 2020
- Data should be at daily resolution as a minimum, ideally close to solar noon – participants of the User Workshop 2020 also expressed an interest in data that has been ‘normalised’ to a specific time, e.g. solar noon
- Day / night would provide an improvement
- 3 hourly data would enable users to resolve the diurnal cycle

Table 11-6: Summary of requirements relating to data specification.

ID	Requirement	Type	Source	Notes
LST-URD-REQ-09-O	Provide global coverage of LST data	Soft	Online questionnaire Q.17	47% of respondents require global data
LST-URD-REQ-10-O	Provide observations at all hours of the day	Soft	Online questionnaire Q.18	52% of respondents requested observations at all hours of the day
LST-URD-REQ-11-O	Provide minimum dataset length of 10 years	Hard, Threshold	Online questionnaire Q.20	Satisfies 82% of respondents at the threshold level
LST-URD-OPT-11-O	Provide minimum dataset length of 30 years	Hard, Breakthrough	Online questionnaire Q.20	Satisfies 87% of respondents at the breakthrough level
LST-URD-REQ-12-O	Provide datasets with a spatial resolution of 1 km	Hard, Threshold	Online questionnaire Q.21	Satisfies 83% of respondents at the threshold level
LST-URD-OPT-12-O	Provide datasets with a spatial resolution finer than 1 km	Hard, Breakthrough	Online questionnaire Q.21	Satisfies 100% of respondents at the breakthrough level
LST-URD-REQ-13-O	Provide data with temporal resolution of 6 hours	Hard, Threshold	Online questionnaire Q.22	Satisfies 75% of respondents at the threshold level
LST-URD-OPT-13-0	Provide data with a temporal resolution of 1 hour	Hard, Breakthrough	Online questionnaire Q.22	Satisfies 94% of respondents at the breakthrough level

Whilst LST observations are required at all times of day, the questionnaire results and CRG interviews indicate that it is particularly important to cover times close to solar noon and early afternoon as this is when peak LSTs are often observed. At the 2022 User Workshop, there was also a request for LST output on UTC grids, e.g. hourly UTC fields to match the output from models.

Table 11-7: Summary of advice notes relating to data specification.

ID	Advice	Source	Notes
LST-URD-ADV-15-OI	Provision of LST observations close to solar noon / early afternoon should be prioritised	Online questionnaire Q.18, CRG interviews	31% of respondents who did not request observations at all times of day selected 12 noon: this option received the highest number of selections
LST-URD-ADV-34-U	Provide high-resolution LST ≤300 m	User Workshop	Needs for both 30-50 m and 300 m data were noted.
LST-URD-ADV-39-U	Provide data at the highest resolution possible	User Workshop	Links with LST-URD-ADV-38-U: Highest resolution data stored, user re-grids and sub-sets as required.
LST-URD-ADV-50-U	Provide LST 'normalised' to a specific time, e.g. solar noon	User Workshop	Requires use of a diurnal model for LST
LST-URD-ADV-56-U	Improve provision of 0.01° data, e.g. using geo-referenced tile-based system.	User Workshop	

ID	Advice	Source	Notes
LST_URD_ADV-94-U	Provide LST_cci products on UTC grids.	User Workshop	Low priority: Requested by 1 of 9 respondents. Provide time-consistent fields with time stamp 00:00, 01:00….23:00 UTC e.g. to match model output.

11.1.3.2. Quality

Table 11-8 summarises requirements relating to data quality, following the GCOS specifications for accuracy, precision and stability. Requirements are provided at the threshold and breakthrough level, as defined in Table 4-2.

Table 11-8: Summary of requirements relating to data quality specification.

ID	Requirement	Type	Source	Notes
LST-URD-REQ-14-O	Provision of data with accuracy of 1 K	Hard, Threshold	Online questionnaire Q.23	Satisfies 84% of respondents at the threshold level
LST-URD-OPT-14-O	Provision of data with accuracy of 0.5 K	Hard, Breakthrough	Online questionnaire Q.23	Satisfies 87% of respondents at the breakthrough level
LST-URD-REQ-15-O	Provision of data with precision of 1 K	Hard, Threshold	Online questionnaire Q.24	Satisfies 80% of respondents at the threshold level
LST-URD-OPT-15-O	Provision of data with precision of 0.5 K	Hard, Breakthrough	Online questionnaire Q.24	Satisfies 85% of respondents at the breakthrough level
LST-URD-REQ-16-O	Provision of data with stability of 0.3 K	Hard, Threshold	Online questionnaire Q.25	Satisfies 85% of respondents at the threshold level
LST-URD-OPT-16-O	Provision of data with stability of 0.2 K	Hard, Breakthrough	Online questionnaire Q.25	Satisfies 88% of respondents at the breakthrough level

Discussions with members of the CRG highlighted the need for LST product accuracy to be improved, particularly in arid and urban areas. The need for well-homogenised data sets, free from non-climatic discontinuities was highlighted very strongly by both responses from the questionnaires, and from the interviews with the CRG (links to stability-related requirements noted above). Feedback from early users of LST_cci beta products suggest that the emissivity data used in the IR LST retrievals could also be improved. This is shown in Table 11-9.

Table 11-9: Summary of advice relating to data quality specification.

ID	Advice	Source	Notes
LST-URD-ADV-16-I	Improve accuracy of LST retrievals for urban and arid biomes	CRG interviews	Current LST products often perform poorly for these land cover types
LST-URD-ADV-70-U	Improve emissivity data used in the IR LST retrievals.	CAR v1	This issue has only been identified for MODIS so far but may also be relevant to other IR LST data sets.

11.1.3.3. Priorities

Both the Lisbon and online surveys asked users to prioritise certain requirements for LST data sets that may be technically incompatible. When considering dataset specification, it is possible to arrive at a set of requirements that cannot be met simultaneously due to the fundamental nature of remote sensing instruments. As an example, high temporal and spatial resolution cannot be obtained together without merging different types of products. Whilst this is an option, it is not suitable for all use cases. To determine if there is an overall priority within climate research, questions were posed in both the Lisbon and online questionnaires regarding known conflicting requirements. In both questionnaires, data quality and accuracy were considered by users to be more important than long-term stability and spatially complete fields. These requirements are shown in Table 11-10.

Table 11-10: Summary of requirements relating to dataset priorities.

ID	Requirement	Type	Source	Notes
LST-URD-REQ-17-L	Product accuracy should be prioritised over long term stability and global spatially complete fields	Majority	Lisbon questionnaire Q.4	62% of participants agreed with this statement
LST-URD-REQ-18-O	High data quality should be prioritised over spatially complete fields	Majority	Online questionnaire Q.27	67% of participants agreed with this statement

As part of all requirement-collecting activities, participants were asked about key concerns regarding LST data use, or what an ideal data product might look like for their application. The answers to these questions help to identify issues that are most important to users. Some themes were re-occurring:

- Spatial resolution
- Cloud effects
    - Cloud contamination errors
    - Clear-sky bias
    - Gaps in space and time
    - Desire for all-sky datasets
- Discrepancies between sensors, data continuity, long term stability
- Lack of understanding of what LST represents
- Temporal resolution
- Accuracy
- Data access

Whilst these are important to address, it is also important to refer back to the requirements stated in Table 11-10, as although participants desire improvements in these areas (many of which were mentioned more frequently than data quality), it is of little use if the quality is poor.

It is also necessary to consider that any individual use cases may not require all of the specifications covered in Table 11-6 and Table 11-8 from one product alone, and it is likely that different applications will prioritise different requirements. However, issues with cloud screening in the IR LST datasets are clearly a priority across most user groups, as this has been highlighted repeatedly by users in all requirement-gathering exercises. Table 11-11 summarises the advice notes concerned with other user priorities. This includes the need to prioritise satellite LST data over regions that are sparsely observed in-situ, as this is seen to be an opportunity for LST to add value in reports, such as IPCC and BAMS State of the Climate.

Table 11-11: Summary of advice issued in relation to dataset priorities.

ID	Advice	Source	Notes
LST-URD-ADV-17-O	Datasets intended for global studies should prioritise high temporal resolution and long datasets	Online questionnaire Q.26 and Q.28	Of those requiring data globally: 56% prioritised high temporal resolution over spatial 63% prioritised long datasets over high resolution
LST-URD-ADV-18-O	Datasets intended for local studies should prioritise high spatial resolution	Online questionnaire Q.26 and Q.28	Of those requiring data for local studies: 75% prioritised high spatial resolution over temporal 88% prioritised high resolution over long datasets
LST-URD-ADV-19-O	Datasets intended for global studies should prioritise using a consistent approach to cloud clearing and provide a pre-screened dataset	Online questionnaire Q.63 and Q.64	Of those requiring data globally: 58% preferred a consistent approach to cloud clearing 56% preferred pre-screened data
LST-URD-ADV-20-O	Datasets intended for regional or local studies should prioritise using the best cloud clearing algorithm for each sensor, and allow the user to apply the cloud mask themselves	Online questionnaire Q.63 and Q.64	Of those requiring data for regional or local studies: 62% preferred a best for each sensor approach 61% preferred to apply a cloud mask themselves
LST-URD-ADV-21-LOI	Improvements in LST spatial resolution should be prioritised	Lisbon questionnaire Q.10, Online questionnaire Q.69 (comments), CRG interviews	
LST-URD-ADV-69-U	LST observations over sparsely-observed regions should be prioritised (e.g. Arctic, deserts)	User Workshop	
LST_URD_ADV-95-U	Prioritise dealing with cloud cover in IR data sets.	User Workshop	This is clearly a very high priority for many users.

11.1.4. Quality Control

Participants in the Lisbon questionnaire indicated that they would use quality flags provided with LST data. This was explored further in the online questionnaire, where participants were asked to rank their preference for certain QC flags, and note any additional flags required. User requirements were also obtained for quality level data, which provides a value representing the following:

- No data
- Bad data
- Worst quality
- Low quality
- Acceptable quality
- Best quality

These requirements are summarised in Table 11-12.

Table 11-12: Summary of requirements regarding quality control information.

ID	Requirement	Type	Source	Notes
LST-URD-REQ-19-L	Provide LST data with quality flags	Soft	Lisbon questionnaire Q.9	64% of participants would use quality flags
LST-URD-REQ-20-O	Provide the following QC flags (in order of preference): ❖ Day / night ❖ Summary cloud ❖ Summary confidence ❖ Land ❖ Aerosol	Order	Online questionnaire Q.40	Participants were asked to order the importance of these QC flags
LST-URD-REQ-21-O	Provide the following QC flags in addition to the above: ❖ Water body ❖ Snow / ice	Soft	Online questionnaire Q.41	75% of participants requested a water body flag 66% of participants requested a snow / ice flag
LST-URD-REQ-22-O	Provide LST data with QC level data on a pixel level	Majority	Online questionnaire Q.42	93% of participants requested these data
LST-URD-REQ-23-O	Provide LST data with QC level data on a file level	Majority	Online questionnaire Q.43	69% of participants requested these data

Provision of per-pixel or grid-cell quality levels, e.g. indicating 'excellent', 'good', 'fair', 'poor', 'very poor' data was requested at the User Workshop 2020. Many users are using uncertainty information to screen data, and these quality level data would make this much easier. However, it was noted that the level required was probably application dependent. Participants at the User Workshop also requested worked examples to show how to decode bit-encoded QC information, which is commonly provided in satellite products. These additional advice notes are shown in Table 11-13.

Table 11-13: Summary of advice issued in relation to quality control information.

ID	Advice	Source	Notes
LST-URD-ADV-53-U	Provide worked examples to show how to decode bit-encoded QC information.	User Workshop	Examples, e.g. in PUG, using common programming languages would be useful.

11.1.5. Error and Uncertainty

As part of the GlobTemperature user requirements questionnaire, an assessment of the common understanding of error and uncertainty terms within the LST user community found that there is considerable discrepancy in understanding of some terms. As a result, a requirement to establish common nomenclature was issued. Other questions determined the preferences for LST error and uncertainty information provision, with requirements defined as appropriate. These GlobTemperature requirements are summarised in Table 11-14, and are the basis on which requirements are developed for the LST_cci project.

Table 11-14: Summary of requirements from the GlobTemperature project relating to error and uncertainty, which are also applicable here (Bulgin & Merchant, 2016).

Number	Requirement	Comment
REQ-4-TR	Provide an LST uncertainty budget split into a number of different components e.g. uncertainties from random and systematic effects	This was requested by 88 % of respondents
REQ-28-TR	Establish a common nomenclature for the expression of error and uncertainty terms and provide information on the definition of terms	Of the descriptions provided for definition in the survey, only two terms had a common understanding amongst respondents
REQ-29-TR	Provide uncertainty information as confidence intervals, estimated root mean square total error or estimated mean and standard deviation of total error	These options were ranked most highly in the user requirements survey
REQ-30-TR	Provide the 95 % confidence interval with confidence level information	This was requested by 74 % of respondents

The focus of questions in the LST_cci online questionnaire is on the current uptake of uncertainty data, and understanding any barriers preventing further use, together with understanding the types of error and uncertainty information required within the climate community. A summary of requirements is found in Table 11-15.

Interviews with members of the CRG provided further context for the information required for users to fully understand uncertainty data, in particular uncertainty components, and enable users to make best use of these data. A focused discussion on uncertainties was also held during the User Workshop 2020. This focused discussion highlighted the need to provide more information to users on how to use uncertainties, propagate them and interpret these data. In particular, users wanted more worked examples and tools to help them with this non-trivial task. Being able to propagate uncertainties correctly is considered to be a major barrier for users and this is reflected in the UCS and feedback from early users, who are rarely using uncertainty information. The outcomes of these discussions are summarised in Table 11-16.

Table 11-15: Summary of requirements relating to error and uncertainty.

ID	Requirement	Type	Source	Notes
LST-URD-REQ-24-LO	Provide per pixel total uncertainty values	Soft	Lisbon questionnaire Q.9, Online questionnaire Q.55 and Q.57	73% requested this data

LST-URD-REQ-25-O	Provide uncertainty data partitioned into components according to correlation properties	Soft	Online questionnaire Q.55 and Q.57	72% of respondents required more than just a total uncertainty Interviewees also expressed interest in these data 27% of Lisbon survey respondents requested this information
LST-URD-REQ-26-O	Uncertainty information should be provided with clear documentation including descriptions of how to use the data and worked examples	Soft	Online questionnaire Q.58	93% of participants requested descriptions of how to use uncertainty data 64% of participants requested worked examples

Table 11-16: Summary of advice issued regarding error and uncertainty data.

ID	Advice	Source	Notes
LST-URD-ADV-22-I	Provide detailed information on how uncertainties are calculated	CRG interviews	
LST-URD-ADV-23-OI	Provide information on what the uncertainties represent and why they are useful	Online questionnaire Q.54 and Q.55, CRG interviews	
LST-URD-ADV-24-O	Provide information about spatial and temporal structure of the uncertainty components	Online questionnaire Q.58	Comment left by a participant
LST-URD-ADV-25-LOI	Include cloud effects in uncertainty data	Lisbon survey Q.8, Online questionnaire Q.69 (comments), CRG interviews	
LST-URD-ADV-38-U	Provide tools to re-grid data and propagate uncertainties	User Workshop	Example code, Jupyter notebooks, online gridding facility delivered via the cloud, etc
LST-URD-ADV-43-U	Use ILSTE-WG to establish community standards for uncertainty information.	User Workshop	
LST-URD-ADV-44-U	Provide more detailed information on uncertainties in the LST_cci PUG.	User Workshop	
LST-URD-ADV-45-U	Investigate providing further breakdown of surface uncertainty components	User Workshop	Provide further breakdown into different sources, e.g. uncertainty in emissivity/biome due to

ID	Advice	Source	Notes
			geolocation, uncertainty in emissivity/biome, shadowing, etc.
LST-URD-ADV-46-U	Provide specific, easy-to-follow examples of how to propagate uncertainties (downscaling and upscaling), guidelines for threshold-based use.	User Workshop	
LST-URD-ADV-48-U	Consider using ensembles to represent uncertainty, especially where retrieval complexity is significant.	User Workshop	Likely a trade-off here with processing time and memory. Not always necessary to take this approach.
LST-URD-ADV-49-U	Consider errors in geolocation in uncertainty budget	User Workshop	

11.1.6. Validation and Inter-comparison

As part of the LST_cci project, validation and user assessment activities will be carried out independently to data production to ensure products meet the requirements of the climate community. However the output of these activities can also be valuable to LST users for their work. A summary of the validation and inter-comparison results required by participants is shown in Table 11-17.

In addition to the requirements summarised in Table 11-17, 44% of participants were interested in the results from time-series analyses. Further recommendations are shown in Table 11-18 regarding validation information requested, and information which could aid the uptake of these data.

Table 11-17: Summary of requirements relating to validation and inter-comparison results.

ID	Requirement	Type	Source	Notes
LST-URD-REQ-27-OI	Provide comparisons of satellite LST data with in-situ measurements as part of the validation and inter-comparison results	Soft	Online questionnaire Q.62, CRG interviews	82% of respondents requested this information
LST-URD-REQ-28-O	Provide inter-comparisons between LST products as part of the validation and inter-comparison results	Soft	Online questionnaire Q.62	75% of respondents requested this information
LST-URD-REQ-29-LO	Provide a summary of accuracy and precision per product as part of the validation and inter-comparison results	Soft	Lisbon questionnaire Q.9, Online questionnaire Q.62	67% of respondents requested this information 59% of respondents to Lisbon questionnaire Q.9 also requested this information

ID	Requirement	Type	Source	Notes
LST-URD-REQ-30-O	Provide an overview of the best performing products in different scenarios as part of the validation and inter-comparison results	Soft	Online questionnaire Q.62	51% of respondents requested this information

Table 11-18: Summary of advice issued relating to validation and inter-comparison results.

ID	Advice	Source	Notes
LST-URD-ADV-26-O	Provide results from time series analysis	Online questionnaire Q.62	44% of respondents require this information
LST-URD-ADV-27-O	Consider including validation of uncertainty components	Online questionnaire Q.62	Comment left by participant
LST-URD-ADV-28-O	Consider including validation of clear-sky probabilities	Online questionnaire Q.68	Comment left by participant
LST-URD-ADV-29-O	Where possible provide advice on how validation and inter-comparison results can benefit users, and how the results can be incorporated into their work	Online questionnaire Q.61	

11.1.7. Clouds

Two requirements gathered during the GlobTemperature project form the baseline of requirements here and are summarised in Table 11-19.

Table 11-19: Summary of requirements from the GlobTemperature project relating to clouds, which are also applicable here (Bulgin & Merchant, 2016).

Number	Requirement	Comment
REQ-8-TR	Provide cloud screening information with LST data	This was requested by 83 % of respondents. This is supported by responses from UCM1
REQ-46-TR	For each L3 observation provide information on the percentage of clear-sky pixels	88.5 % of respondents to the UCM4 mini-questionnaire requested this information

The online questionnaire asked participants how they would like cloud information to be provided with the data. Questions were aimed at establishing user preference for a consistent approach to cloud clearing or a 'best for each sensor' approach; provision of pre-screened data or the ability to apply the mask at the time of use; and preference for a binary cloud mask, clear-sky probabilities or both. The results demonstrated a preference for the provision of both a binary cloud mask and clear-sky probabilities, giving users the freedom to tune cloud clearing at a level appropriate for their application. The related requirements are summarised in Table 11-20. Overall, no preference was discernible between a consistent approach to cloud clearing or best for each sensor, and the provision of pre-screened data or the ability to apply the mask at the time of use. When results are partitioned by the spatial domain required by the participant, different preferences arise, which are summarised in Table 11-11, and the varying use of datasets for different applications even within climate science should be taken into consideration in the production of datasets.

Table 11-20: Summary of requirements relating to clouds.

ID	Requirement	Type	Source	Notes
LST-URD-REQ-31-O	Provide a binary cloud mask	Soft	Online questionnaire Q.65	52% of participants requested both binary cloud mask and clear-sky probability
LST-URD-REQ-32-O	Provide clear-sky probabilities	Soft	Online questionnaire Q.65	52% of participants requested both binary cloud mask and clear-sky probability
LST-URD-REQ-33-O	Where clear-sky probabilities are provided, include descriptions of how to use these data and worked examples	Soft	Online questionnaire Q.68	89% requested descriptions 57% requested worked examples

Throughout the surveys, interviews and other interactions with users, concerns regarding cloud effects arise repeatedly, primarily relating to cloud contamination errors and clear sky bias, hence consideration should be put into an investigation of clear sky biases. It is hoped the provision of clear-sky probabilities will enable users to tune cloud clearing to make the most out of the data for their specific application, including minimising the inclusion of cloud contamination errors.

It is advised that clear-sky probability data should be provided with a description of what exactly is represented by the probabilities, and how they are calculated. Descriptions of how to use these data should also be provided, perhaps with suggested starting values for defining a cloud mask. This information is summarised in Table 11-21. At the 2022 User Workshop, delegates also requested that detailed information on IR cloud screening processes was provided to users.

Table 11-21: Summary of advice issued regarding provision of cloud information.

ID	Advice	Source	Notes
LST-URD-ADV-30-I	Provide a description of what is represented by clear-sky probabilities and how they are calculated	CRG interviews	
LST-URD-ADV-31-O	Provide a recommended starting value to be used by users for cloud clearing, ideally for a set of different applications	Online questionnaire Q.68	Comment left by participant
LST-URD-ADV-32-LI	Investigate and provide information to users concerning clear-sky bias in IR LST data	Lisbon Survey Q.8, CRG Interviews	
LST-URD-ADV-33-LOI	Reduce errors due to cloud contamination in IR LST data sets	Lisbon questionnaire Q.8, Online questionnaire Q.16, CRG interviews	73% were concerned about cloud contamination errors (Lisbon) Cloud contamination errors were the second highest concern in the online survey
LST-URD-ADV-37-U	Improve cloud screening over ice and snow	User Workshop	

ID	Advice	Source	Notes
LST_URD_ADV-96-U	Provide detailed information on IR cloud screening processes.	User Workshop	

11.1.8. Other requirements

A number of other requirements were highlighted at the 2020 and 2022 User Workshops and through the CAR v1 that do not fall into any of the previous categories. These requirements cover a wide range of areas, including provision of information on the differences between LST and T2m data, highlighting the strengths and weaknesses of both types of data. This information may encourage more use of LST and wider uptake in assessment reports, such as IPCC and BAMS SOTC. These advice notes are listed in Table 11-22.

Table 11-22: Summary of advice issued for other requirements.

ID	Advice	Source	Notes
LST-URD-ADV-36-U	Provide information on LST vs T2m data	User Workshop	Highlight advantages and disadvantages of LST vs T2m, expected differences, etc.
LST-URD-ADV-52-U	Provide L3 data where data have not been averaged over multiple overpasses.	User Workshop	Some users cannot use data that have been averaged over multiple overpasses.
LST-URD-ADV-55-U	Provide information and worked examples on how to convert pixel overpass times to other date-time formats.	User Workshop	
LST-URD-ADV-57-U	Provide local solar time in the LST_cci data files.	User Workshop	Users can calculate this, but it requires additional effort.
LST-URD-ADV-60-U	Provide component LSTs in gridded data sets based on observations (no modelling).	User Workshop	Even basic vegetation vs non-vegetated would be useful.
LST-URD-ADV-71-U	Provide dynamic land cover class information in the LST_cci data files.	CAR v1	
LST-URD-ADV-72-U	Provide satellite view zenith angles with sign (i.e. '-' or '+') that indicates whether the view is towards the east or west.	CAR v1	
LST-URD-ADV-73-U	Correct global attributes "geospatial_lat_min", "geospatial_lat_max", "geospatial_lon_min", "geospatial_lon_max" by half a pixel	CAR v1	Currently these values correspond to the centre of the pixel, rather than a corner, which would indicate the true geo-bounding box, which is confusing for users.
LST-URD-ADV-74-U	Correct or provide user guidance regarding the change in spatial extent of the SEVIRI disk part-way through the record.	CAR v1	

ID	Advice	Source	Notes
LST-URD-ADV-75-U	Provide information regarding fields ‘ncld’ and ‘variance’ in the LST_cci MSG_SEVIRI_L3U, which have no meaning.	CAR v1	
LST-URD-ADV-77-U	Extend SEVIRI data record beyond 2008-2010.	CAR v1	
LST-URD-ADV-78-U	Provide nadir-equivalent LST retrievals (implement geometrical correction).	CAR v1	
LST-URD-ADV-80-U	Provide instantaneous LSTs in L3 products as extra fields in the LST_cci products (e.g averaged LSTs over each orbit separately)	CAR v1	Partly addressed through LST-URD-ADV-52-U.
LST_URD_ADV-97-U	Provide observation time, view angles, total uncertainty and land cover classification in LST_cci ARD products.	User Workshop	Combined response from 4 respondents.
LST_URD_ADV-98-U	Provide observation operators to convert LST to T2m and potentially other variables.	User Workshop	Based on information provided by 9 respondents. For example, to soil moisture, below- and within-canopy temperatures and temperatures associated with different PFTs.
LST_URD_ADV-99-U	Include additional variables in LST_cci products where possible to support climate services using LST.	User Workshop	Based on feedback from 10 respondents, include T2m and land cover classification (both high priority); other variables such as surface humidity, modelled surface ‘skin’ temperature, emissivity, NDVI, fractional vegetation and total column water vapour could also be considered (low priority).

11.2. Requirements

A summary of all requirements and advice notes is provided in Table 11-23. Requirements are grouped into the following three categories, which are also shaded differently in Table 11-23 for clarity:

- “REQ”: A requirement that must be addressed. When questions are asked in terms of a threshold, breakthrough or objective requirement, the threshold requirement is used here. (No shading in Table 11-23.)
- “OPT”: An optional requirement that should be met where possible. This aligns with the breakthrough requirement definition. (Grey shading in Table 11-23.)

- "ADV": An advisory requirement that should be considered where feasible. These are used where requirements cannot be analysed quantitatively, for example the CRG interviews or free text questions provided in the Lisbon and Online questionnaires. (Blue shading in Table 11-23.)

Table 11-23: Summary of all requirements, optional requirements and advice notes relating to the LST_cci project. Optional requirements are highlighted in light grey and advice notes are highlighted in light blue in the table below.

ID	Requirement	Notes
Data Format and Accessibility		
LST-URD-REQ-01-O	Provide LST products in NetCDF format	90% of respondents were able to use NetCDF data
LST-URD-ADV-01-O	CCI standard format is recommended for LST_cci products	52 participants currently use CCI products, 32 use these in conjunction with LST data
LST-URD-ADV-02-OI	Disseminate clear information on what LST data represents, potential applications and how the data may be used	Aim to improve understanding of what LST data represents, including linking to model parameters.
LST-URD-ADV-03-I	Provide documentation detailing assumptions made during the retrieval process or product construction, including detailed information on any techniques used for merging	Aim to make it as easy as possible to understand the data
LST-URD-ADV-04-LI	Ensure long term, easy access to data	CCI Open Data Portal will be used (note that the GlobTemperature portal suggested as a good model)
LST-URD-ADV-05-O	Provide a summary of the availability and characteristics of different LST products	
LST-URD-ADV-06-LI	Consistency should be maintained between different LST products within LST_cci	Users often require data from multiple sensors
LST-URD-ADV-07-OI	Consistency between LST_cci and other CCI products should be maintained	32 participants use CCI ECV products in conjunction with LST data
LST-URD-ADV-08-OI	Provide information on how comparable LST_cci products are with other CCI datasets, for example, spatial and temporal averaging, uncertainties, changes likely to impact LST (e.g. vegetation fractional cover)	
LST-URD-ADV-35-U	Provide guidance to users on which LST products should be used for different applications	Users can be overwhelmed by the choice of LST products, e.g. many single-sensor products.
LST-URD-ADV-40-U	Regularly consult with users on appropriateness of data format, accessibility and usability.	Good examples provided by NOAA and NASA through ESIP.
LST-URD-ADV-41-U	Provide hands-on experience for users at dedicated workshops	Hold demonstrations, provide Jupyter notebooks, example code, etc.
LST-URD-ADV-42-U	Provide LST use examples (with code) in a dedicated document. Include	

ID	Requirement	Notes
	information on what can be achieved with the data (e.g. limitations).	
LST-URD-ADV-47-U	Ensure all LST_cci documentation is readily and easily available to users.	Links to documentation and info about data storage structure needs to be added to data portal, including public area on Jasmin for Beta products.
LST-URD-ADV-51-U	Provide information on LST trends	Calculated trends for multi-decadal LST products could be provided within user documentation. This could include information on known trends in the underlying raw satellite data.
LST-URD-ADV-54-U	Provide tools to enable users to select the data they want themselves.	E.g. for specific regions, with specific QC or other screening applied, etc.
LST-URD-ADV-59-U	Provide LST_cci data sets in real time, ideally with near-daily updates.	11 of 12 respondents require data within 48 hours of acquisition. Some applications require less-frequent updates, e.g. monthly. Provision of real-time anomalies could also be considered.
LST-URD-ADV-61-U	Highlight in LST_cci documentation that most GIS packages can use netCDF data.	
LST-URD-ADV-62-U	Improve delivery of data via data portals – enable users to visualise and use data within the portal.	
LST-URD-ADV-63-U	Raise awareness of satellite LST and its benefits through improved publicity.	E.g. a white paper could be produced.
LST-URD-ADV-64-U	Provide information and/or tools to convert LST_cci data into different formats.	
LST-URD-ADV-65-U	Establish a non-specialist user group to consult for data provision to non-specialist users.	
LST-URD-ADV-66-U	Provide a range of documentation targetted at different user levels/details.	Consider unified/standardised documentation, e.g. https://lpdaacsvc.cr.usgs/gov/appeears/
LST-URD-ADV-67-U	Provide information to users in a variety of ways, e.g. traditional documentation, videos, podcasts, etc.	In addition to holding workshops [LST-URD-ADV-41-U]
LST-URD-ADV-68-U	Make LST_cci data available in ARD and/or data cube formats.	
LST_URD_ADV-82-U	Provide reprocessed LST_cci datasets at least annually	
LST_URD_ADV-83-U	Provide LST data on a Polar EASE grid	Low priority – only 2-3 users identified with this need.
LST_URD_ADV-84-U	Ensure LST_cci ARDs are provided with good documentation, in easy-to-	Low priority – only a few users have identified a need for ARD so far.

ID	Requirement	Notes
	access formats with simple quality flags.	
LST_URD_ADV-85-U	Provide fill values in files for missing data products and an inventory of files with missing data.	Some users would prefer to have e.g. days of missing data with 100% fill values, rather than having a missing data file.
LST_URD_ADV-86-U	Extend LST_cci Regridding Tool to produce temporal means (e.g. weekly, pentads, etc).	
LST_URD_ADV-87-U	Develop a wrapper for the LST_cci Regridding Tool to process multiple files.	
LST_URD_ADV-88-U	Maintain a webpage/blog as a permanent resource that can be accessed for historical issues.	High priority action.
LST_URD_ADV-89-U	Provide users with the option to be sent email notifications when new issues are discovered and added to the issues list.	High priority action.
LST_URD_ADV-90-U	Provide information on data gaps, e.g. due to sensor outages or satellite manoeuvres.	High priority action.
Product Types		
LST-URD-REQ-02-O	Provide LST from IR LEO satellites	68% of respondents are interested in these data
LST-URD-REQ-03-O	Provide LST from IR GEO satellites	66% of respondents are interested in these data
LST-URD-REQ-04-O	Provide products which merge LST from multiple IR LEO satellite datasets to create a long running, near-global CDR	54% of respondents are interested in these data
LST-URD-REQ-05-LO	Provide products produced by merging LEO and GEO datasets	90% (Lisbon) / 63% (Online) of participants were interested in merged products
LST-URD-REQ-06-O	Provide LST data products at level 2	47% of respondents selected Level 2 data
LST-URD-REQ-07-O	Provide LST data products at level 3C	55% of respondents selected Level 3C data
LST-URD-REQ-08-O	Data from MODIS instruments should be given high priority	75% of respondents currently use MODIS LST data for climate applications
LST-URD-ADV-09-LI	Provide multi-decadal, homogenised datasets, free from non-climatic discontinuities	Long term, consistent datasets are required for climate science. Links to LST-URD-REQ-13-O and LST-URD-OPT-13-0
LST-URD-ADV-10-OI	Provision of MW LST products	43% of respondents were interested in MW products
LST-URD-ADV-11-LOI	Provision of all-sky LST datasets	Some members of the CRG are gap-filling IR LST data sets already; a standard option would be useful. Not clear whether users want gap-filled LSTs to represent clear-sky or all-sky.

ID	Requirement	Notes
		38% of respondents to the online survey are interested in a merged IR and MW product
LST-URD-ADV-12-O	Provision of Meteosat data	Meteosat was the second most popular instrument out of respondents currently use LST data for climate applications
LST-URD-ADV-13-O	Provision of Landsat data	Landsat was the third most popular instrument out of respondents who currently use LST data for climate applications
LST-URD-ADV-14-O	Provision of AVHRR data	To extent data record length
LST-URD-ADV-58-U	Improve consistency between MW and IR LST_cci data sets.	Currently the QC flags are not the same.
LST-URD-ADV-76-U	Provide a dedicated Ice Surface Temperature retrieval.	
LST-URD-ADV-79-U	Provide downscaled SEVIRI data (e.g. using MODIS).	
LST-URD-ADV-81-U	Provide LST products for VIIRS.	
LST_URD_ADV-91-U	Provide LST_cci data as 10-day means.	Low priority: At least 3 users requested this.
LST_URD_ADV-92-U	Provide LST climatologies.	Low priority: At least one user requested this.
LST_URD_ADV-93-U	Provide selected properties derived from LST, for example, anomalies, daily minimum and maximum LST, annual means and LST- 2m air temperature differences.	Low priority: Each list item was requested by at least one user.
Data Specification		
LST-URD-REQ-09-O	Provide global coverage of LST data	47% of respondents require global data
LST-URD-REQ-10-O	Provide observations at all hours of the day	52% of respondents requested observations at all hours of the day
LST-URD-REQ-11-O	Provide minimum dataset length of 10 years	Satisfies 82% of respondents at the threshold level
LST-URD-OPT-11-O	Provide minimum dataset length of 30 years	Satisfies 87% of respondents at the breakthrough level
LST-URD-REQ-12-O	Provide datasets with a spatial resolution of 1 km	Satisfies 83% of respondents at the threshold level
LST-URD-OPT-12-O	Provide datasets with a spatial resolution finer than 1 km	Satisfies 100% of respondents at the breakthrough level
LST-URD-REQ-13-O	Provide data with temporal resolution of 6 hours	Satisfies 75% of respondents at the threshold level
LST-URD-OPT-13-O	Provide data with a temporal resolution of 1 hour	Satisfies 94% of respondents at the breakthrough level

ID	Requirement	Notes
LST-URD-ADV-15-OI	Provision of LST observations close to solar noon / early afternoon should be prioritised	31% of respondents who did not request observations at all times of day selected 12 noon: this option received the highest number of selections
LST-URD-ADV-34-U	Provide high-resolution LST ≤300 m	Needs for both 30-50 m and 300 m data were noted.
LST-URD-ADV-39-U	Provide data at the highest resolution possible	Links with LST-URD-ADV-38-U: Highest resolution data stored, user re-grids and sub-sets as required.
LST-URD-ADV-50-U	Provide LST 'normalised' to a specific time, e.g. solar noon	Requires use of a diurnal model for LST
LST-URD-ADV-56-U	Improve provision of 0.01° data, e.g. using georeferenced tile-based system.	
LST_URD_ADV-94-U	Provide LST_cci products on UTC grids.	Low priority: Requested by 1 of 9 respondents. Provide time-consistent fields with time stamp 00:00, 01:00….23:00 UTC e.g. to match model output.
Data Quality Priorities		
LST-URD-REQ-14-O	Provision of data with accuracy of 1 K	Satisfies 84% of respondents at the threshold level
LST-URD-OPT-14-O	Provision of data with accuracy of 0.5 K	Satisfies 87% of respondents at the breakthrough level
LST-URD-REQ-15-O	Provision of data with precision of 1 K	Satisfies 80% of respondents at the threshold level
LST-URD-OPT-15-O	Provision of data with precision of 0.5 K	Satisfies 85% of respondents at the breakthrough level
LST-URD-REQ-16-O	Provision of data with stability of 0.3 K	Satisfies 85% of respondents at the threshold level
LST-URD-OPT-16-O	Provision of data with stability of 0.2 K	Satisfies 88% of respondents at the breakthrough level
LST-URD-ADV-16-I	Improve accuracy of LST retrievals for urban and arid biomes	Current LST products often perform poorly for these land cover types
LST-URD-ADV-70-U	Improve emissivity data used in the IR LST retrievals.	This issue has only been identified for MODIS so far, but may also be relevant to other IR LST data sets.
Data Specification Priorities		
LST-URD-REQ-17-L	Product accuracy should be prioritised over long term stability and global spatially complete fields	62% of participants agreed with this statement
LST-URD-REQ-18-O	High data quality should be prioritised over spatially complete fields	67% of participants agreed with this statement
LST-URD-ADV-17-O	Datasets intended for global studies should prioritise high temporal resolution and long datasets	Of those requiring data globally: 56% prioritised high temporal resolution over spatial

ID	Requirement	Notes
		63% prioritised long datasets over high resolution
LST-URD-ADV-18-O	Datasets intended for local studies should prioritise high spatial resolution	Of those requiring data for local studies: 75% prioritised high spatial resolution over temporal 88% prioritised high resolution over long datasets
LST-URD-ADV-19-O	Datasets intended for global studies should prioritise using a consistent approach to cloud clearing and provide a pre-screened dataset	Of those requiring data globally: 58% preferred a consistent approach to cloud clearing 56% preferred pre-screened data
LST-URD-ADV-20-O	Datasets intended for regional or local studies should prioritise using the best cloud clearing algorithm for each sensor, and allow the user to apply the cloud mask themselves	Of those requiring data for regional or local studies: 62% preferred a best for each sensor approach 61% preferred to apply a cloud mask themselves
LST-URD-ADV-21-LOI	Improvements in LST spatial resolution should be prioritised	
LST-URD-ADV-69-U	LST observations over sparsely-observed regions should be prioritised (e.g. Arctic, deserts)	
LST_URD_ADV-95-U	Prioritise dealing with cloud cover in IR data sets.	This is clearly a very high priority for many users.
Quality Control		
LST-URD-REQ-19-L	Provide LST data with quality flags	64% of participants would use quality flags
LST-URD-REQ-20-O	Provide the following QC flags (in order of preference): ❖ Day / night ❖ Summary cloud ❖ Summary confidence ❖ Land ❖ Aerosol	Participants were asked to order the importance of these QC flags
LST-URD-REQ-21-O	Provide the following QC flags in addition to the above: ❖ Water body ❖ Snow / ice	75% of participants requested a water body flag 66% of participants requested a snow / ice flag
LST-URD-REQ-22-O	Provide LST data with QC level data on a pixel level	93% of participants requested these data
LST-URD-REQ-23-O	Provide LST data with QC level data on a file level	69% of participants requested these data
LST-URD-ADV-53-U	Provide worked examples to show how to decode bit-encoded QC information.	Examples, e.g. in PUG, using common programming languages would be useful.

ID	Requirement	Notes
Error and Uncertainty		
LST-URD-REQ-24-LO	Provide per pixel total uncertainty values	73% requested this data
LST-URD-REQ-25-O	Provide uncertainty data partitioned into components according to correlation properties	72% of respondents required more than just a total uncertainty Interviewees also expressed interest in these data 27% of Lisbon survey respondents requested this information
LST-URD-REQ-26-O	Uncertainty information should be provided with clear documentation including descriptions of how to use the data and worked examples	93% of participants requested descriptions of how to use uncertainty data 64% of participants requested worked examples
LST-URD-ADV-22-I	Provide detailed information on how uncertainties are calculated	
LST-URD-ADV-23-OI	Provide information on what the uncertainties represent and why they are useful	
LST-URD-ADV-24-O	Provide information about spatial and temporal structure of the uncertainty components	Comment left by a participant
LST-URD-ADV-25-LOI	Include cloud effects in uncertainty data	
LST-URD-ADV-38-U	Provide tools to re-grid data and propagate uncertainties	Example code, Jupyter notebooks, online gridding facility delivered via the cloud, etc
LST-URD-ADV-43-U	Use ILSTE-WG to establish community standards for uncertainty information.	
LST-URD-ADV-44-U	Provide more detailed information on uncertainties in the LST_cci PUG.	
LST-URD-ADV-45-U	Investigate providing further breakdown of surface uncertainty components	Provide further breakdown into different sources, e.g. uncertainty in emissivity/biome due to geolocation, uncertainty in emissivity/biome, shadowing, etc.
LST-URD-ADV-46-U	Provide specific, easy-to-follow examples of how to propagate uncertainties (downscaling and upscaling), guidelines for threshold-based use.	
LST-URD-ADV-48-U	Consider using ensembles to represent uncertainty, especially where retrieval complexity is significant.	Likely a trade-off here with processing time and memory. Not always necessary to take this approach.
LST-URD-ADV-49-U	Consider errors in geolocation in uncertainty budget	
Validation and Inter-comparison		
LST-URD-REQ-27-OI	Provide comparisons of satellite LST data with in-situ measurements as	82% of respondents requested this information

ID	Requirement	Notes
	part of the validation and inter-comparison results	
LST-URD-REQ-28-O	Provide inter-comparisons between LST products as part of the validation and inter-comparison results	75% of respondents requested this information
LST-URD-REQ-29-LO	Provide a summary of accuracy and precision per product as part of the validation and inter-comparison results	67% of respondents requested this information 59% of respondents to Lisbon questionnaire Q.9 also requested this information
LST-URD-REQ-30-O	Provide an overview of the best performing products in different scenarios as part of the validation and inter-comparison results	51% of respondents requested this information
LST-URD-ADV-26-O	Provide results from time series analysis	44% of respondents require this information
LST-URD-ADV-27-O	Consider including validation of uncertainty components	Comment left by participant
LST-URD-ADV-28-O	Consider including validation of clear-sky probabilities	Comment left by participant
LST-URD-ADV-29-O	Where possible provide advice on how validation and inter-comparison results can benefit users, and how the results can be incorporated into their work	
Clouds		
LST-URD-REQ-31-O	Provide a binary cloud mask	52% of participants requested both binary cloud mask and clear-sky probability
LST-URD-REQ-32-O	Provide clear-sky probabilities	52% of participants requested both binary cloud mask and clear-sky probability
LST-URD-REQ-33-O	Where clear-sky probabilities are provided, include descriptions of how to use these data and worked examples	89% requested descriptions 57% requested worked examples
LST-URD-ADV-30-I	Provide a description of what is represented by clear-sky probabilities and how they are calculated	
LST-URD-ADV-31-O	Provide a recommended starting value to be used by users for cloud clearing, ideally for a set of different applications	Comment left by participant
LST-URD-ADV-32-LI	Investigate and provide information to users concerning clear-sky bias in IR LST data	
LST-URD-ADV-33-LOI	Reduce errors due to cloud contamination in IR LST data sets	73% were concerned about cloud contamination errors (Lisbon)

ID	Requirement	Notes
		Cloud contamination errors were the second highest concern in the online survey
LST-URD-ADV-37-U	Improve cloud screening over ice and snow	
LST_URD_ADV-96-U	Provide detailed information on IR cloud screening processes.	
Other		
LST-URD-ADV-36-U	Provide information on LST vs T2m data	Highlight advantages and disadvantages of LST vs T2m, expected differences, etc.
LST-URD-ADV-52-U	Provide L3 data where data have not been averaged over multiple overpasses.	Some users cannot use data that have been averaged over multiple overpasses.
LST-URD-ADV-55-U	Provide information and worked examples on how to convert pixel overpass times to other date-time formats.	
LST-URD-ADV-57-U	Provide local solar time in the LST_cci data files.	Users can calculate this, but it requires additional effort.
LST-URD-ADV-60-U	Provide component LSTs in gridded data sets based on observations (no modelling).	Even basic vegetation vs non-vegetated would be useful.
LST-URD-ADV-71-U	Provide dynamic land cover class information in the LST_cci data files.	
LST-URD-ADV-72-U	Provide satellite view zenith angles with sign (i.e. '-' or '+') that indicates whether the view is towards the east or west.	
LST-URD-ADV-73-U	Correct global attributes "geospatial_lat_min", "geospatial_lat_max", "geospatial_lon_min", "geospatial_lon_max" by half a pixel	Currently these values correspond to the centre of the pixel, rather than a corner, which would indicate the true geo-bounding box, which is confusing for users.
LST-URD-ADV-74-U	Correct or provide user guidance regarding the change in spatial extent of the SEVIRI disk part-way through the record.	
LST-URD-ADV-75-U	Provide information regarding fields 'ncld' and 'variance' in the LST_cci MSG_SEVIRI_L3U, which have no meaning.	
LST-URD-ADV-77-U	Extend SEVIRI data record beyond 2008-2010.	
LST-URD-ADV-78-U	Provide nadir-equivalent LST retrievals (implement geometrical correction).	
LST-URD-ADV-80-U	Provide instantaneous LSTs in L3 products as an extra fields in the	Partly addressed through LST-URD-ADV-52-U.

ID	Requirement	Notes
	LST_cci products (e.g. averaged LSTs over each orbit separately)	
LST_URD_ADV-97-U	Provide observation time, view angles, total uncertainty and land cover classification in LST_cci ARD products.	Combined response from 4 respondents.
LST_URD_ADV-98-U	Provide observation operators to convert LST to T2m and potentially other variables.	Based on information provided by 9 respondents. For example, to soil moisture, below- and within-canopy temperatures and temperatures associated with different PFTs.
LST_URD_ADV-99-U	Include additional variables in LST_cci products where possible to support climate services using LST.	Based on feedback from 10 respondents, include T2m and land cover classification (both high priority); other variables such as surface humidity, modelled surface ‘skin’ temperature, emissivity, NDVI, fractional vegetation and total column water vapour could also be considered (low priority).

Bibliography

Bosilovich, M., Hook, S., Knuteson, R., Pinheiro, A., Prigent, C., Rossow, W., & Viterbo, P. (2008). *International Workshop on the Retrieval and Use of Land Surface Temperature: Bridging the Gaps, Summary Report.*

Bulgin, C. E., Embury, O., Corlett, G., & Merchant, C. J. (2016). Independent Uncertainty Estimates for Coefficient Based Sea Surface Temperature Retrieval from the Along-Track Scanning Radiometer Instruments. *Remote Sensing of Environment, 178*, 213-222. doi:10.1016/j.rse.2016.02.022

Bulgin, C., & Merchant, C. (2016). *DUE GlobTemperature Requirements Baseline Document.*

(2017). *CCI+ Phase 1 - New ECVs: Land Surface Temperature - Technical Proposal.*

Christidis, N., & Stott, P. A. (2014). Change in the Odds of Warm Years and Seasons Due to Anthropogenic Influence on the Climate. *Journal of Climate, 27*, 2607-2621. doi:10.1175/JCLI-D-13-00563.1

Christidis, N., Stott, P. A., Scaife, A. A., Arribas, A., Jones, G. S., Copsey, D., . . . Tennant, W. J. (2012). A New HadGEM3-A-Based System for Attribution of Weather- and Climate-Related Extreme Events. *Journal of Climate, 26*, 2756-2783. doi:10.1175/JCLI-D-12-00169.1

ESA. (2018, 05 22). *LST CCI: About the Project*. Retrieved 10 2018, from ESA Climate Change Initiative: http://cci.esa.int/lst#about%20the%20project

European Space Agency. (2016a). *Generating satellite-based Essential Climate Variables to support the UNFCCC and IPCC*. Retrieved 10 2018, from ESA Climate Change Initiative: http://cci.esa.int/

European Space Agency. (2016b). *GlobTemperature: an ESA DUE Initiative*. Retrieved 10 2018, from GlobTemperature: http://www.globtemperature.info/

European Space Agency. (c2018). *ESA's Climate Change Initiative*. Retrieved 10 2018, from European Space Agency: http://www.esa.int/Our_Activities/Observing_the_Earth/Space_for_our_climate/ESA_s_Climate_Change_Initiative/(print)

European Space Agency Climate Office. (2018). *CCI Data Standards.*

Ghent, D. (2011). *LST User Exploitation Document.*

GlobTemperature: An ESA DUE Initiative. (2016). Retrieved 10 2018, from GlobTemperature: http://www.globtemperature.info/

Good, E. J. (2015). Daily minimum and maximum surface air temperatures from geostationary satellite data. *Journal of Geophysical Research: Atmospheres, 120*(6), 2306-2324. doi:10.1002/2014JD022438

Good, E. J., Ghent, D. J., Bulgin, C. E., & Remedios, J. J. (2017). A spatiotemporal analysis of the relationship between near-surface air temperature and satellite land surface temperatures using 17 years of data from the ATSR series. *Journal of Geophysical Research: Atmospheres, 122*(17), 9185-9210. doi:10.1002/2017JD026880

Good, J. E. (2016). An in situ-based analysis of the relationship between land surface 'skin' and screen-level air temperatures. *Journal of Geophysical Research: Atmospheres, 121*(15), 8801–8819. doi:10.1002/2016JD025318

Hook, S. (2006). *NASA White Paper on LST and Emissivity Needs.*

Janatian, N., Sadeghi, M., Sanaeinejad, S. H., Bakhshian, E., Farid, A., Hasheminia, S. M., & Ghazanfari, S. (2016). A statistical framework for estimating air temperature using MODIS land surface temperature data. *International Journal of Climatology, 37*(3), 1181-1194. doi:10.1002/joc.4766

Karnieli, A., Agam, N., Pinker, R. T., Anderson, M., Imhoff, M. L., Gutman, G. G., . . . Goldberg, A. (2010). Use of NDVI and Land Surface Temperature for Drought Assessment: Merits and Limitations. *Journal of Climate, 23*, 618-633. Retrieved from https://www.researchgate.net/publication/259841877_Use_of_NDVI_and_land_surface_temperature_for_assessing_vegetation_health_merits_and_limitations

Kilibarda, M., Hengl, T., Heuvelink, G. B., Graler, B., Pebesma, E., Tadic, M. P., & Bajat, B. (2014). Spatio-temporal interpolation of daily temperatures for global land areas at 1 km resolution. *Journal of Geophysical Research: Atmospheres, 119*(5), 2294-2313. doi:10.1002/2013JD020803

King, A. D., Alexander, L. V., & Donat, M. G. (2013). The Efficacy of using Gridded Data to Examine Extreme Rainfall Characteristics: A Case Study for Australia. *International Journal of Climatology, 33*(10), 2376-2387. doi:10.1002/joc.3588

Lian, X., Zeng, Z., Yitong, Y., Shushi, P., Kaicun, W., & Shilong, P. (2017). Spatiotemporal variations in the difference between satellite-observed daily maximum land surface temperature and station-based daily maximum near-surface air temperature. *Journal of Geophysical Research: Atmospheres, 122*(4), 2254-2268. doi:10.1002/2016JD025366

Rayner, N. (2017). *SSI CCI Phase 2: User Requirements Document.*

Remedios, J. J., & Humpage, N. (2012). *Sentinel Convoy for Land Applications: Workshop Report.*

van Oldenborgh, G. J., Philip, S., Kew, S., van Weele, M., Uhe, P., Otto, F., . . . AchutaRao, K. (2018). Extreme Heat in India and Anthropogenic Climate Change. *Natural Hazards and Earth System Sciences, 18*, 365-381. doi:10.5194/nhess-18-365-2018

WMO. (2011). *Requirements for Observational Data: the Rolling Review of Requirements.*

WMO. (2016). *The Global Observing System for Climate: Implementation Needs.* World Meteorological Organziation.

Appendix A - Joint Land Workshop Questionnaire: Free text responses

Table 0-1: Full responses to Q.3 of the Joint Land Workshop: "If you use satellite LST, please explain the main challenges you experience in using the data. If you do not currently use LST data, please explain any concerns about using it, or the reason you have not yet used, or considered using LST."

Response
Access, data characterisation, currently using surface soil moisture
Clear sky only products limit the range on conclusions you might draw from climate studies. High uncertainties also limit the use of LST over certain regions. Discrepancies between sensors / algorithms difficult global studies
Explain the discrepancies between different products. Suitable approach for model evaluation (LSM, etc.)
LST interesting for use in surface DA for NCD? Not used so far due to resources. Both interesting global skin and more high resolution time (<~6 hrs) desired
Data availability. Possibility to programmatically query spatial and temporal intervals via an API
Not using yet, but planned to use in near future
Accuracy and temporal resolution
Consisting of LST data and other ECV's + resolution / temporal / spatial for diff. app.
Uncertainty in arid and semi-arid ecosystem. It would also be good to have surface emissivity
Cloudiness
Biases, Continuity
Accuracy and no data under cloud with data stability over regional area
Temporal consistency, limited due to cloud cover, limits application to irrigation detection on short timescales
Combining advantages of LEO (spatial) and GEO (frequency)
Try to directly use radiances, or measurements directly rather than an LST product. For historical cases an LST product which can be treated as an in-situ measurement would be helpful.

Table 0-2: Full responses to Q.10 of the Join Land Workshop Questionnaire: "If you use/might use LST, what would you want in an ideal satellite LST dataset?"

Response
Easy and fast access, standard formats
High resolution in time and space, high quality, long term stability
Global harmonised LSTs are definitely something useful. Diurnal cycle should be well resolved.
Considering question 6, I would want a combination of both a regional sub-daily dataset with moderate (or high) spatial resolution
Accuracy and high resolution (spatial)
Co-location variables / meteo variables, surface albedo, rough veg. coverage (height)
Diurnal LST at 1 km spatial resolution for both clear and cloudy sky
All weather (merged products), high frequency date, 1-5 km resolution
Diurnal observations, product skilful in capturing human management impacts
For regional products using LST, better have good quality LST product. For climate use, stability with long term accessibility.
Consistency with emissivity
Daily or diurnal resolution at ≤1 km resolution
Accuracy ≤0.5 K. Spatial resolution 300m or better, observation time early afternoon or even several sample over day for LEO. Improvement spatial resolution and accuracy for GEO.

Appendix B - Interviews with the CRG: Summaries

Table 0-3: Summary of all information collected during the interview with CRG members from the Met Office Hadley Centre.

Name	Lizzie Good & Freya Aldred
Organisation	Met Office Hadley Centre
Country	UK
User Case Study	UCS #1 - Regional and Global Trends in LST
Application	Climate monitoring
Current data use	Datasets: • MODIS Aqua / Terra 1km L2 and L3 • SEVIRI LST from LSA-SAF (15 min, native grid) • Station and gridded air temperatures • Reanalysis – LST & 2m air temperature (T2m) Dataset use: • Estimating global land surface air temperatures (LSAT) from satellite observations, including LST, within the EURO4M (http://www.euro4m.eu/) and EUSTACE (https://www.eustaceproject.eu/) projects • Climate monitoring & comparison with LSAT datasets (ESA DUE GlobTemperature: http://www.globtemperature.info/) • Other project work: urban heat islands in China
Interest in CCI	• Multi-decadal homogeneous datasets free from non-climatic discontinuities – essential for detection of trends • CDR with at least daily resolution to look at extreme temperature events • CDRs with observations close to solar noon • Improved cloud screening • Provision of uncertainty components so uncertainties can be propagated properly when re-gridding • Microwave CDR – an objective of this UCS is also to assess whether IR LST time series are influenced by clear-sky sampling
CCI data use plan	• Priority datasets will be the (A)ATSR-MODIS-SLSTR CDR, MODIS Aqua/Terra L3 and MW CDR • Assess temporal stability of LST CDRs: Compare LST and spatially and temporally matched homogenised LSAT time series. In particular, with station data that have been homogenised (non-climatic discontinuities removed), e.g. from the EUSTACE project • Calculate global and regional trends: anomaly will be calculated for the LST_cci products, considering the uncertainty information provided with the data, and using an appropriate method for testing the statistical significance of the calculated trends • Compare LSAT and LST trends (considering uncertainties), using at least one key LSAT dataset (e.g. CRUTEM) • Compare IR LST and MW LST trends and assess differences that may be due to clear sky vs all sky sampling
Improvements you hope / need	• Consistent multi-sensor CDRs • Improved accuracy of LST

to see from CCI for it to be better than other products	• Improved cloud screening • Improved uncertainty characterisation • All-sky data
Uncertainties	• Interested in uncertainty components – have used these in other work (EUSTACE) • Propagate uncertainties when re-gridding LST to coarser resolution to match LSAT datasets in order to compare trends for each grid cell • Will calculate uncertainties on trends
Cloud clearing	• Probabilities expected to be very useful – user can control level of data rejection (balance between data volume and influence of cloud-contaminated LSTs) • Likely to find suitable threshold through trial-and-error – expected to be application specific (e.g. for single-cell LST vs LSAT, may need to be stricter than for global trend calculation)
Concerns	• Cloud contamination • Variation of LST accuracy with land cover type – large scale biases are less of a concern as this UCS will largely be working with anomalies, but if there is a difference in precision between different land cover types, with season, or with events such as El Niño or heat waves, this could be an issue
Ideal dataset	0.05 degrees lat/lon, global all-sky (and with no cloud contamination), homogeneous in time (stability <<0.1 deg/decade), small errors (<0.5 K), accurate uncertainty estimates, direct observations of daily maximum and minimum LST

Table 0-4: Summary of all information collected during the interview with CRG members from DMI.

Name	Jacob Høyer & Ruth Mottram
Organisation	DMI
Country	Denmark
User Case Study	UCS #2 - Assimilating Greenland Ice Sheet Surface Ice Temperature into Atmosphere and Ice Sheet Models
Application	Model verification Data assimilation Polar climate Ice sheets Cryosphere (Also produce data)
Current data use	Datasets: • AVHRR ice surface temperature • Station data – 2m air temp, some radiometers Dataset use: • Produce AVHRR datasets for EUSTACE • Do not currently use LST for ice sheet modelling • Pros: Cons:
Interest in CCI	• 0.05° is current model resolution, but this is going to 1 km, so the higher resolution the better

	• Daily resolution at least, 3 hourly better, hourly preferred. • Need data in the middle of the day • Polar areas have much higher frequency overpasses, a high frequency data product would be really helpful and much better than any aggregated / averaged product • General interest in polar specific products – such a product (previous bullet) may be of wider interest • Do not want any time averaged / shifted products • L2 preferable (for Jacob) • Ruth requires L3 but need specific processing (from Jacob) • 'Ascending' and 'descending' terminology not useful for high latitude applications • MW data second priority, retrievals difficult on ice – would only really be useful for large scale verification • Also less interested in GEO data due to low spatial resolution at high latitudes

CCI data use plan	Jacob
	• Ingest L2 LST from several sensors
	• Run through EUSTACE L2 -> L3 aggregation for each product
	• Look for difference in products
	• If no major differences, products are merged, if major differences possibly need to work out what to reject
	• End up with L3 IST, 3 hourly, 0.05 deg
	
	Ruth (this has only been done with SSTs before)
	• Take NetCDF output, interpolate to model grid
	• Plot data, compare to model data
	• Statistical analysis where there is model, satellite and station data available
	    ○ Compare daily cycle, annual cycle, monthly averages to check for differences
	    ○ If there are any cloud gaps in the satellite data, time interpolation done to fill them – cannot have any gaps for data assimilation (this produces L4 data)
	• If model looks ok, sum up energy balance at surface
	    ○ If this is above zero then melting is occurring
	    ○ LST is set to zero in this case
	• This is used to calculate the surface mass balance

Improvements you hope / need to see from CCI for it to be better than other products	• Consistent multi-sensor CDR • Range of sensors looking at the same thing • Better quality of data and cloud screening • Accessibility – opens data to further uses
Uncertainties	• Interested in uncertainty values • Familiar with components • For ice the highest uncertainty comes from cloud contamination – this is not currently included in the uncertainties • Propagate uncertainties in L2 -> L3

	• Uncertainties important for model evaluation to tell you if you should trust observations – uncertainties used to select observational values to use • If LST not at zero, but uncertainties cover zero, then there is the possibility of melting
Cloud clearing	• These data could be useful • Look at relationship between poor data and cloud probability to see if there is a connection • Useful for examining biases in the model and where they might come from • Would also be interested on the probable impact of cloud on the retrieval • Data available from multiple sensors that have different spectral properties, could this help with cloud problems? • Could also be interesting to compare cloud locations to models as we know this is good in some places, but bad in others
Concerns	• Difference in cloud screening / possible cloud contamination • Takes a long time to get to know the characteristics of each dataset • Quality of the data – could find a 'bias' in the model which is actually due to bad observational data • Will validation be done in Polar Regions in LST_cci? • LST data not been used for this purpose before – have no real idea if it will work

Table 0-5: Summary of all information collected during the interview with CRG member from U. Hamburg.

Name	Benjamin Bechtel
Organisation	University of Hamburg
Country	Germany
User Case Study	#3 – Characterisation of Surface Urban Heat Islands
Application	Urban Climate

Current data use	Datasets:
	• MODIS Terra + Aqua - A11 product
	• SEVIRI - LandSAF product on irregular grid
	• Landsat – using different retrieval algorithms
	  ○ Single channel LST retrieval from Landsat-8
	  ○ Emissivity from NDVI
	  ○ Compared with ASTER emissivity
	  ○ NCAR re-analysis data for atmospheric correction data
	• ASTER level 1b product – temp and emissivity for 5 spectral bands, 2011
	• VIIRS test data set, hard to get data – three bands, colleague performed retrieval
	Dataset use:
	• Time series analysis
	• MODIS data taken as is
	  ○ Utilise quality assessment as is
	  ○ Often urban LSTs are noted as low quality values, so have to use relaxed filtering to allow enough values through
	  ○ Comes from uncertainty in emissivity / anisotropy
	  ○ High reflectance confuses cloud masking
	• Process one tile at a time (1.4 million pixels)

	• Time series analysis for each pixel at a time
	    ○ Fit model to the annual cycle
	    ○ Additional analysis e.g. look at quality of model fit (RMSE, r^2)
	    ○ Look at time series of residuals to find trends or gaps
	• Sometimes compare urban to rural
	    ○ Average urban values and rural areas
	    ○ Use morphological operators to define boundaries and ensure not using the outer urban pixels
	    ○ Avoid using rural pixels adjacent to urban, specific land cover (trees, water), or significantly different altitude
	• Annual cycle can be used for cloud clearing
	    ○ Annual cycle predicts mean LST for each day of the year
	    ○ When looking at actual values, you would expect spatial patterns of residuals to be fairly homogeneous
	    ○ Some pixels may be significantly cooler than surrounding residuals – this is likely due to cloud
	• Sometimes apply morphological operators to extend cloud gaps as these are the most likely pixels to be cloud contaminated
	Pros:
	• Extensive area of observations almost simultaneously – difficult to achieve with any other observation method
	• For urban climate you really need the coverage as it is so heterogeneous
	Cons:
	• Snapshot image
	• Trade-off between high temporal and spatial resolution – ideally would like both
	• Data are very noisy – influenced by lots of different characteristics of the atmosphere and surface so individual acquisitions have a high degree of randomness
	• Clouds – both gaps, and cooling effect of clouds that have been there but moved
	• VIIRS data very hard to get hold of
	• Generally data access improved much recently – the easier it is to get hold of, the more likely it is to be used
	• Limited images from ASTER – on request only
	• Spatial resolution has limitations especially for urban climate
	• Compared to other bands, developments in IR spatial resolution is slow

Interest in CCI	• Gridded products preferred, but can use L2 swath data
	• Any 1km resolution datasets – this is threshold
	• Interested in all GEO products (also looks globally)
	    ○ GEO products preferred on native grid (or even higher resolution/over-sampled) – re-projecting the data can mean losing spatial resolution
	    ○ Preferred temporal resolution of hourly at least
	• Interested in IR CDR product, but concerns raised about difficulty correcting for the changes in overpass time – it depends on land use, heating rate etc.
	    ○ Observation time variations for individual sensors due to wide swath even – advise to look at this
	• Anisotropy – relevant problem for MODIS / SLSTR

	• Merged GEO / LEO interesting, would need to look into detail about the process – ensuring specific urban effects were preserved during the downscaling / merging
	  ○ Willing to provide expert input on plans
	  ○ Have done downscaling with SEVIRI using MODIS / Landsat
	• Have not used MW data so far
	  ○ Other studies found good correlation between MW and urban in-situ data
	  ○ Potentially interesting, but low resolution big problem for urban
	• Merged IR + MW could be interesting as experimental product
	• Non-sinusoidal grid would be of interest – something that represents distances more accurately

CCI data use plan	• Transfer the above method to new data products and different sensors, in particular the long time series
	  ○ Can relate changes to seasonal urban cycle to changes in land cover (urbanisation) as this is happening quicker than climate change
	  ○ This is unique as previously people have only looked at individual images, dataset over 30 years will allow us to analyse this properly
	• Hope to do this for combined annual and diurnal cycle
	  ○ Need 4 observations per day so start with GEO data to obtain diurnal cycle, then apply to LEO to get higher resolution

Improvements you hope / need to see from CCI for it to be better than other products	• Long time series
	  ○ If we get close to 30 years, a proper climatology can be done
	  ○ Urban areas changing quicker than climate so can relate urban change to climate change
	• Better resolution and accuracy
	  ○ Accuracy this is not the end of the world for urban studies – looking at spatial differences rather than absolute accuracy, and atmospheric effects likely to be quite homogeneous at 10s km scale so relative LST differences are more important
	  ○ Directional effects are same order of magnitude as accuracy that we are looking at
	• VIIRS data would be good as it is so hard to get hold of

Uncertainties	• Do not consider uncertainties at the moment
	  ○ Using long time series so statistical error will ‘come out’
	• Could consider filtering data by high uncertainties
	  ○ Would want uncertainty value per observation
	• Require worked examples to help use the data
	• Systematic uncertainties could be more important for time series analysis
	• Could do error propagation tests with uncertainties to see if the results change

Cloud clearing	• Clear sky probabilities could be helpful • Would use a trial and error approach to find the most appropriate threshold ○ Start with a high value then lower to find trade-off between data volume and quality • Guidelines of appropriate thresholds for certain applications would be helpful • Probabilities could also be used to do weighting in the model fitting algorithm, but might be complicated

Concerns	• Generally not worried, the benefits outweigh the problems • LST is difficult to interpret for many reasons, so it is under-exploited

Ideal dataset	• High spatial and temporal resolution, no errors
	    ○ Higher resolution sensors in orbit
	• Anisotropy, particularly for urban
	    ○ Multi angle product at <1 km resolution
	    ○ Propose three sensors in parallel orbits viewing the same place at the same time, one at nadir, one east and one west, each with 4 viewing angles in flight direction
	    ○ There are significant discrepancies between MODIS and SEVIRI, e.g. in mountains where SEVIRI cannot see into some valleys

Table 0-6: Summary of all information collected during the interview with CRG members from MPI.

Name	Markus Reichstein and Jürgen Knauer
Organisation	Max Planck Institute for Biogeochemistry
Country	Germany
User Case Study	UCS #4 - Biosphere-Atmosphere Exchange
Application	Surface / Atmosphere interactions Data driven upscaling of biosphere-atmosphere fluxes • Predict ground based carbon fluxes • Locally – flux towers • Globally Drought detection • Europe / Africa
Current data use	Datasets: • MODIS Terra sinusoidal gridded L3, daytime only, full record How they are used: • Use surface data as statistical predictors for ground based carbon fluxes in order to produce 5 km / 0.05° gridded product • Land surface models are used • LST appears to be a good predictor (one of top six) • Train neural network models using 1 km data around flux towers • Then aggregate data to 5 km due to computational resource limits for full run • Gap fill data - use linear interpolation for small gaps, or climatologies for longer gaps • Run full model to get carbon fluxes and sensible heat Pros: • Continuous record • Quality flags provided with data are useful Cons: • Clouds – clear sky only and contamination
	Drought detection Datasets: • LSA SAF SEVIRI GEO data How they are used: • Co-variability of LST and e.g. NDVI to detect drought

	• Look at 'dry down' events, how NDVI changes • How drought can be detected by combining LST and vegetation information
Interest in CCI	• SSM/I interesting but resolution could be a problem, need 1 km really for training the data • Blended IR + MW – possible interest • Uncertainty data is particularly interesting for generating ensemble products • GEO data could be useful for diurnal cycle, but only just starting to look at this, using for drought detection • 0.05° would be acceptable, some flux towers have a large enough, consistent area around them to be able to work with this, but not all sites. The higher the resolution the better. The spatial resolution is at least for the second application (dry down events) probably more important than the temporal one. For the spatial resolution 0.05° seems to be the absolute limit for applications including eddy covariance sites. • Concerning the temporal resolution, it would be fine to have e.g. 8-daily information on the emissivity, which could be used together with the measured (half-hourly or hourly) longwave radiation at the flux sites. • Data set length: The longer the better
CCI data use plan	As above
Improvements you hope / need to see from CCI for it to be better than other products	• Longer time series – ideally to match up with flux towers • Better consistency • Higher quality data – this is more important than improved resolution • Uncertainty data
Uncertainties	• Do not currently use but would be very interesting • Could generate ensembles with characteristics fitting the uncertainties • Spatial correlations will be very interesting – avoids assuming everything is independent • Random errors less important on global scale
Cloud clearing	• More info could be useful • Needs to be very clear what the probability represents • Would try different thresholds to see how it affects the data • Clouds themselves provide useful information, but there are better, more specific products for this
Concerns	• Inconsistencies in datasets between instruments • Inconsistencies between products • Quality of the data – bias, accuracy, precision • Less concerned about biases, more concerned about consistency from day to day
Ideal dataset	• 250m, hourly, no gaps

Table 0-7: Summary of all information collected during the interview with CRG member from MeteoRomania.

Name	Alexandru Dumitrescu
Organisation	MeteoRomania
Country	Romania
User Case Study	UCS #5 – Inter-comparison and Integrated use of LST in Urban Climate Studies
Application	Climate Variability Regional climate (Romania) Urban climate

Current data use	Datasets:
	• Combined use of:
	    ○ MODIS Aqua + Terra L3, sinusoidal grid, 1 km
	    ○ LandSAF SEVIRI, 15 min LST
	    ○ Air temperature from station data
	• CORINE Land Cover Dataset
	• Tested some land cover data from MODIS
	How they are used:
	• Statistical QC carried out on LST data to remove outliers (due to cloud)
	• Produce monthly average for day and night, during summer, 1 km resolution, 2000 - 2013
	• Convert this data to air temp to gap fill station air temp data
	• This is done for city areas using MODIS data
	• Identify hot spots in the city
	• Experimental downscaling of data using the climate scenario, LST and air temp to look at how the urban heat island will look in the future
	• Statistical downscaling using satellite air temperatures
	• LandSAF data used to look at spatial distribution over whole country
	Pros:
	• Information between stations
	Cons:
	• Not continuous in time and space
	• SEVIRI not high enough spatial resolution for application

Interest in CCI	• 1 km data products preferable for urban studies • 5 km useful enough for national studies • 3 hourly would help with diurnal cycle • Global merged LEO + GEO would be interesting for looking at diurnal cycle and min / max • Gridded datasets are preferred • Information on how data are produced required in the user guide e.g. interpolated or nearest neighbour, information on sampling etc. • Interested in looking at LST_cci SEVIRI, but need to look at it to see if it is useful / better than LandSAF data • MW data (twice per day) would be interesting especially for cold season as there is so much cloud, low resolution is still much better than anything else available • Merged IR + MW sounds like the perfect product
CCI data use plan	As above

Improvements you hope / need to see from CCI for it to be better than other products	• Long term, stable data required • Homogeneous in time • Easy access to data • Would like to download time series data for a point in space • Data in near real time
Uncertainties	• Uncertainties are not currently used • May be interested in future • Discrepancies between LST and air temp are so large that it is not felt that uncertainties would help at present • Would need guidelines on how to use the data – make it easy to use
Cloud clearing	• Clear sky probabilities might be helpful to cloud clear data as using statistical methods already
Concerns	• Missing data because of cloud for IR
Ideal dataset	• IR + MW, 3 hourly, 1 km resolution

Table 0-8: Summary of all information collected during the interview with CRG member from LIST.

Name	Kaniska Mallick
Organisation	Luxembourg Institute of Science and Technology (LIST)
Country	Luxembourg
User Case Study	UCS #6 – Integration of LST into a physically-based surface energy balance model
Application	Surface-atmosphere interactions Eco-hydrology (evapotranspiration?) Modelling Arid / semi-arid environments

Current data use	Datasets:
	• MODIS Aqua + Terra, 1 km resolution
	  ○ 8 day time series with cloud filtering
	  ○ Daily LST used more recently
	• GlobTemp (A)ATSR 5 km CDR
	• CM-SAF upwelling longwave radiation
	  ○ Estimate emissivity from MODIS and combine to get LST
	• GlobTemp MTSAT LST, 3 hourly?
	  ○ Compare 1 km to 5 km, prefer 1 km
	Data use:
	• MODIS daily 1 km LST, reject those flagged with e.g. aerosol as these have been shown to provide poor results in previous studies
	• Gap fill LST using NWP modelling - the results using daily gap filled data are better than using the 8 day version
	• Developed a fully analytical calibration-free model to bypass resistance parameterisation in the SEB models
	• SEB model requires many input variables, so use MODIS LST as lower boundary condition with upper atmospheric variables e.g. humidity and air temp estimated from MODIS atmospheric product to extract real values of conductance to feed into the physically based model

	• SEB model outputs latent and sensible heat fluxes, evapotranspiration, evaporation, transpiration and surface to root zone wetness / water availability • Produces aerodynamic temp, aerodynamic conductance and canopy / stomatal conductance as by-products – could be linked with UCS #4 • Product maps are produced from the model output to give information on vegetation stress / water requirements • Kaniska develops model and studies how it behaves in different scenarios • Works with Uni. Of Michigan who have developed an ensemble ET mapping framework with 7 SEB models over India to see the effects of climate variability on agricultural systems Pros: • Calibration-free surface energy balance modelling Cons: • Cloud! o Particularly interested in situations where it is hot, but cloudy as there will be both heat and water stress under these conditions
Interest in CCI	• CDR in 1 km resolution, L3 • Interested in IR + MW because of all sky • Also interested in MW only for this purpose • Need 10 years of data, from which extract a normal, anomalously dry, and anomalously wet year to validate model • Ideally like 25-30 years of data to study the impact of LST in the SEB model in the context of eco-hydrological extremes
CCI data use plan	• Propose to study north Australian tropical transect as it provides a very interesting aridity gradient and flux data are well maintained for Australia • 5 eddy covariance sites in this region • Look at a 10x10 pixel area around each site to understand model behaviour • Also interested in tropical sites in the Amazon and Congo regions • Would be interested in comparing merged IR + MW product with Kaniska's own gap filling products

Improvements you hope / need to see from CCI for it to be better than other products	• Improved data quality in arid / semi-arid regions
	• Blended IR + MW will be interesting to see if this is a viable gap filling method
	  o Particularly for tropical regions where there is persistent cloud
	• Would like air temperature and relative humidity / dew point temperature alongside LST data – would avoid needing to source this data from elsewhere
	• Include raw brightness temperatures in the product
	  o For day and night might be able to eliminate emissivity uncertainties
	  o BT could still benefit model initialisation when there is no LST due to cloud

Uncertainties	• Total uncertainty per pixel particularly useful • Look at residual ET retrieval compared with the LST uncertainties • Use uncertainties in a diagnostic manner to link daily ET uncertainties to daily uncertainties of LST to show how sensitive the retrievals are to the LST uncertainty
Cloud clearing	• Probabilistic cloud mask could be very useful

	• Could do statistical evaluation of errors in model output
Concerns	• Quality of LST data, particularly in arid / semi-arid environments – model retrieved hydrological variables are very sensitive to the LST, so it needs to be accurate • Would like LST under cloud • Better cloud detection at night
Ideal dataset	• 25 years of high quality LST data

Table 0-9: Summary of all information collected during the interview with CRG member from MeteoSwiss.

Name	Anke Duguay-Tetzlaff
Organisation	MeteoSwiss
Country	Switzerland
User Case Study	N/A
Application	• Climate monitoring • Regional – Switzerland • Drought and frost monitoring, heat / urban heat

Current data use	Datasets:
	• Produces and uses CM-SAF LST (Meteosat SEVIRI / MVIRI)
	    ○ Evaluated with MODIS
	• AVHRR vegetation maps
	• Hope to use (A)ATSR – high resolution data and long time series is useful for calculating anomalies
	How the data are used:
	• LEO LST is used for its spatial resolution
	    ○ Data is aggregated into a weekly 1 km dataset to reduce gaps
	    ○ Heat and drought indices are calculated
	• GEO LST is used for its diurnal cycle resolution and soil moisture
	• Feasibility study planned: Extent standard drought index (VHI, TCI) with temperature difference morning to noon
	• Feasibility study for soil moisture is ongoing: Can indirect information on soil moisture (via LST diurnal cycle) be used to map soil moisture distributions during drought events (complement station soil moisture data with spatial information)
	• LEO and GEO indices will then merged
	Other ideas:
	• Feasibility studies on using Meteosat for urban heat monitoring
	    ○ Higher resolution might be required
	• Have trialled using Meteosat for frost monitoring
	    ○ Only for flat land so far as mountainous regions probably require higher resolution data. May be difficult to characterise uncertainties in mountainous regions.
	• Looking at merging high resolution LEO LST with Meteosat data
	• Sentinel and Landsat LST, mapping temperatures in urban areas (Uni. Basel)
	• Some people developing UHI models using LST as starting point, with topography, then modelling 2m air temperature
	Pros:

	• LST useful to get coverage over all land types – stations are often only in rural areas
	Cons:
	• More support needed understanding the data
	  ○ What it represents – it provides complementary information to other datasets, not a replacement
	  ○ The physics behind it
	• Uncertainties, but we don't have these for other datasets either, and as a small met service, MeteoSwiss cannot always handle everything, although other institutions have done this
	• Need historical data
	• Meteosat has jumps between sensors, particularly in the day, night is more stable; work is ongoing to improve homogeneity

Interest in CCI	• High resolution 1 km LEO CDR
	• Anke happy using L2, but colleagues may prefer L3
	• Microwave data too low resolution
	  ○ Could try gap filling with modelling
	• Desire LEO and GEO LST separately to enable merging of indices
	• Also interested in looking at merged LST + GEO product
	• Threshold resolution 0.05 deg, higher the better
	  ○ This resolution is an issue in mountainous areas, but still better than station data
	• Min temp resolution 24 hour
	  ○ (A)ATSR datasets still useful at 3 days though, because of long, stable time series
	  ○ Also useful for anomalies

CCI data use plan	• Similar to the above, but hopes to utilise the clear sky probabilities and uncertainty information provided with the data • Interested in doing own merging of LEO and GEO data, so is interested in the technical process used in LST_cci • Also interested in the interactions with the project and the user case studies

Improvements you hope / need to see from CCI for it to be better than other products	• Continuity of 1 km resolution LST data provided in the CDR
	• Global products
	• Thoroughly validated products
	• Interaction with the project
	  ○ Exchange with user case studies
	  ○ Technical knowledge on how to merge data
	• Using data for evaluation e.g. stable (A)ATSR / MODIS to compare with other LST time series such as Meteosat
	• Clear sky probabilities
	  ○ In CM-SAF, probabilities were used to create binary mask, would have been better to provide probabilities to users

Uncertainties	• Hope to use in temperature anomaly analysis
	  ○ Propagate uncertainties
	  ○ Put uncertainties on anomalies
	• Require separate uncertainty components, but need to be wary of making things too complicated for users
	• Also concerned about data volumes, especially for smaller institutions
	• Do not know exactly how the uncertainties will be used yet

Cloud clearing	• Welcome these data
	• In CM-SAF LST product, rejected anything more than 10% chance of having cloud
	  ○ This is very conservative but there are essentially no contaminated pixels
	  ○ Threshold required strongly depends on probability method used

Concerns	• LST Observations so different from what is produced by models • Promoting of LST required, convincing users of its benefits • Complimentary to 2m air temp, not a replacement for a local weather services
Ideal dataset	• 1 km, hourly, all sky • High resolution more important for mountainous regions, for flat areas Meteosat resolution is acceptable

Table 0-10: Summary of all information collected during the interview with CRG/CMUG members from the Met Office Hadley Centre.

Name	Rob King and Debbie Hemming
Organisation	Met Office
Country	UK
User Case Study	N/A
Application	• Evapotranspiration / vegetation or crop monitoring • Soil moisture stress on vegetation • Global • Local areas of interest e.g. North Brazil, UK (Cardington) • Comparing different vegetation types • Using LST in combination with air temperature to get a measure of soil moisture and vegetation stress • Linking vegetation stress observed to future climate change scenarios

Current data use	Datasets:
	• MODIS LST
	  ○ V6, daily 0.05° climate model grid (CMG) from Aqua
	  ○ Chosen because overpass time is at the warmest part of the day – currently use only daytime values
	• MODIS land cover
	Data use:
	• Data QC'd using viewing angle <55° and QC flags that come with the data, accuracy within 1/2K
	• Re-grid data to match other data, for example air temp / satellite soil moisture
	• When comparing data to ground sites, just need to select the appropriate pixel
	• When working with other data, MODIS is binned to the 0.5° grid used for WATCH forcing data
	• Thinking of looking with 1 km data due to higher resolution
	• Look at time series
	• Compare satellite LST data with data from ground stations and flux towers

	• Want to use LST as a top of canopy temperature as a starting point then improve the canopy temperature down through the canopy
	Pros:
	• Coverage
	• LST is the closest you can get to actual observed data when using remote sensing, other values require more modelling to get the desired quantity
	• MODIS CMG really easy to work with – grid fits the 0.5° grid used for WATCH forcing data that land surface researchers use, meaning no interpolation is required, just binning
	• LST is sensitive to the top of canopy temperatures, which is useful for comparing / verifying JULES, as it also produces values for the top of canopy
	• MODIS files contain everything needed
	Cons:
	• Temporal data gaps due to swath coverage makes it hard to get a time series
	  o Looking at the tropics which there is not necessarily daily coverage
	  o Need daily coverage to monitor evolution of vegetation stress
	• Cloud causes problems for time series analysis
	• Need to fully understand what LST data and JULES skin temp represents, they are not the same so this needs to be taken into account when doing analysis
	• Some people just use the data blindly without really understanding exactly what it is
	• When comparing to ground stations you need the selected pixel to be representative of the area encompassing the ground station, but sometimes this can be heterogeneous, or it can be in a small area
	• Concerns about heterogeneity within pixels
	  o Sometimes flux towers are only in a 1 km area which is hard / impossible to match to a pixel
	• Concern about homogeneity in datasets using multiple sensors

Interest in CCI	• Long time series are of interest, especially if they are global
	  o Flux towers introduces ~1995
	  o Cardington has easy to use data from 2003
	  o Concern about homogeneity when multiple sensors used
	• Higher temporal resolution could be interesting to give info about the diurnal cycle as a lot of assumptions are made at present
	  o Most interested in peak daytime temperatures
	  o Diurnal information more useful when looking at specific sites
	• MW could be interesting where there are extended cloud gaps, but it needs to be understood as it's possible the values given do not represent the same thing as IR LST
	• 3 hourly merged product could be useful especially for model evaluation
	• Want datasets to be available on matching grids (e.g. land cover and LST) as want to avoid doing interpolation as it could add errors – consistent grid / underlying coordinate system across CCI products would be really useful

CCI data use plan	• Continuation of above • Global data re-gridded to match other datasets (air temps, satellite soil moisture)

	• For individual sites no re-gridding or interpolation done, just look at an individual grid box, or averaging of nearest neighbour • Screen out high view angles • Screen out based on accuracy • Look at differences / time series etc.

Improvements you hope / need to see from CCI for it to be better than other products	• Easy to use data – but not too easy…
	  ○ Assumptions made need to be really clear
	  ○ If data is too easy to use, it can be used blindly without really understanding what it means – open to misuse
	• Homogeneity, especially with merged products, changes in instrument need to be made really clear in the file
	• Long time series
	• File consistency between products, e.g. variable names

Uncertainties	• Currently only use QC flags • Would like to propagate errors but currently don't fully understand it or feel comfortable doing it • If the right information is provided this could be really powerful • Uncertainties could inform how reliable the skin-air temp difference is in indicating vegetation stress • If the wrong or limited information is provided then would only use QC flags • Examples would be useful
Cloud clearing	• Would need to think about how to use percentages • It would need to be very clear what the probabilities mean as it could be interpreted many ways • Concern that a certain probability could be obtained from multiple situations, for example 50% could be a thin layer of stratus, or patchy cumulus, which have very different implications for the accuracy / usefulness of the data • MODIS data has info on cloud type?
Concerns	• Is not providing the actual leaf temp which is what this study is concerned with – but neither does the model, and both provide slightly different values • People blindly use data, assuming it is what they want it to be without fully understanding what it means / represents – better understanding is needed • Comparisons can't be made in heterogeneous areas • Underlying assumptions made when calculating LST

Ideal dataset	• High spatial resolution, hundreds of metres instead of kilometres
	  ○ Not specifically to work at higher resolution, but because land use would be better resolved and hence the errors on surface type and emissivity would be less, making the LST more useful, especially for vegetation monitoring
	• High temporal resolution interesting but less important
	  ○ Would be interesting to look at diurnal cycle but realistically the research in this area isn't there yet
	• No data gaps
	• More important to improve understanding of dataset than work at higher resolutions

Appendix C - LST_cci 2020 User Workshop Organisation

The LST_cci User Workshop 2020 was held as a virtual event owing to the global Covid-19 pandemic. As the event had originally been planned as a conventional workshop with oral presentations, posters and breakout discussion groups, the format had to be redesigned to work as a virtual event. The following aspects were considered in making the event a success.

General:

- To hold one-hour 'live' sessions to avoid 'online fatigue'
- To have breaks of at least 30 minutes between live sessions to enable participants in different time zones to have meal breaks at the appropriate times.
- To keep very strictly to time to prevent live sessions overrunning into (meal) breaks and to ensure participants can join at the right time if they are logging on to hear a specific talk, for example. This was considered vital to avoid online fatigue and to keep everyone engaged.
- To give participants clear warnings when they are nearing the end of their oral slot and to use the 'stop sharing' and 'mute' option to terminate a presentation if the presenter goes over time after several warnings.
- To have multiple co-hosts on Zoom, who are able to mute participants, share presentations (if a presenter is unable to do so for technical reasons), monitor chat in case of technical difficulties, etc, as co-hosts were also session chairs and presenters, and there were multiple jobs to do.
- To ask participants to post comments in the chat facility and for the session chair to call on them to ask their question, rather than using the 'raise hand' facility, which is not available via the web version of Zoom.
- To use 'welcome' and 'we are on a break' slides before sessions and during breaks, reminding participants to mute unless presenting or called on to ask a question.
- To record all the live sessions and to indicate this clearly on the welcome and break slides.
- To provide a comprehensive workshop booklet detailing workshop etiquette, how the workshop would work, how to use Zoom and Padlet, the meeting agenda, and providing the Zoom and Padlet links (see later in this Appendix).
- To hold practice/trial sessions with the project team before the workshop to familiarise everyone with the technology and its features.

Padlet

- To set up a different Padlet for each live session topic (a single Padlet was used for all three 'Using LST in land-atmosphere interaction studies' sessions, but with a separate column on the Padlet for each live session time).
- To use a separate Padlet for the 'welcome and Padlet orientation' area, the posters, and for each discussion session.
- To use Padlet as a forum for discussion during the workshop, allowing participants to comment under each poster/presentation.
- To ask presenters to upload their presentations to the appropriate Padlet in advance of the workshop to ensure that all presentations could be downloaded by the workshop team before the live sessions and share presentations if the presenter was unable to do so. This would avoid

wasting time by getting the presenter to email their presentation during the workshop to be shown by someone else.

Breakout sessions

- To hold breakout sessions with around 6-8 members per group; any more people than this would make conversation difficult.
- To have at least one member in each breakout group from the project team, who could take notes and produce a summary of the discussion, and to ask the project team in advance who would/would not be happy to take on this role.
- To ask workshop participants to indicate in their name 'NB' if they did not wish to be allocated to a breakout group. This enabled the host to allocate participants to breakout groups appropriately and achieve a balance in the number of people per group.
- To have the host remain in the main workshop session during the breakout groups in case there were any issues with participants being unassigned, assigning late participants to breakout groups, etc. The host could also broadcast a message across all rooms to indicate when the discussion session was ending.
- To keep the discussion sessions to 40 minutes as this was thought to be about the right length.

Following the workshop, the project team noted the following that could be considered for future events of this type:

- The strict timekeeping was considered very positive. The ability to terminate presentations if necessary (this did not actually happen) is an advantage of a virtual meeting.
- One of the missing elements of this meeting (and other virtual meetings) was the networking and informal discussions that usually happen over coffee breaks. It was suggested that the breakout rooms could be used to host some sort of social event, e.g. bring your own drink.
- A virtual event could provide the ideal forum to hold some more 'hands on' sessions, e.g. demonstrating practical examples of how to use uncertainties, holding tutorials, etc.
- It was difficult to follow the discussion on Padlet because Padlet did not enable 'threaded' discussions (i.e. responses could not be added to a specific comment but appeared in order of time added). It would be better to use software that enabled threaded discussions for future events. [This was noted before the meeting, but the choice of software was limited by what was accessible at low cost and also available in e.g. China, where there were several known meeting delegates.]
- Inviting participants to ask their questions themselves was viewed as positive. This enabled more discussion and clarification, and also made the event feel more personal and less sterile.
- Running virtual breakout groups was very effective, perhaps more so than in-person breakout groups. A further positive was that participants went straight to the breakout groups and did not get distracted on route. Some people felt that participants were more willing to talk in the virtual breakout groups, perhaps because it was more of a 'level playing field' and more difficult to pick out more senior people, the presenters, etc, which may lead to some people speaking less.
- The number of participants and length of the breakout sessions worked well.
- The breakout group seed questions worked very well. The number of seed questions/points was about right for the length of the session.
- Probably the weakest aspect of the workshop was the poster session. It was suggested that perhaps a live session would work well at a future event. However, some of the project team also liked having the posters available at all times. It was suggested that a lightening round could work

well, where presenters had e.g. 5 minutes per poster. A poster session could then follow, where each poster had its own breakout session so that people could join the discussions 'around a poster', which is more similar to an in-person poster session.

- Virtual clapping was a good idea.

<u>Workshop Information Booklet</u>

A comprehensive workshop booklet was provided to all registered delegates at the workshop. This booklet detailed workshop etiquette, how the workshop would work, how to use Zoom and Padlet, the meeting agenda, and provided the Zoom and Padlet links. This workshop booklet is shown on the next few pages of this appendix.

land surface temperature cci | esa

LST_cci User Workshop 2020 Agenda

Virtual Workshop

24 - 26 June 2020

Draft Agenda v2.6 – 26 June 2020

Met Office Hadley Centre

University of Leicester · National Centre for Earth Observation · University of Reading · IPMA · KIT · ACRI-ST · Met Office Hadley Centre · Universitat de València · Estellus · Met Office Hadley Centre · DMI · UH · LIST · Meteo Romania

Contents

1. Welcome 1
2. ORGANISATION 2
   2.1 General Information 2
   2.2 Presentations 2
   2.3 Session Chairs 3
   2.4 Further information 3
3. Live Workshop Joining Instructions 4
   3.1 Accessing the meeting via the browser: 4
   3.1 Accessing the meeting via telephone: 5
4. Live Workshop Management & Etiquette 6
   4.1 Microphones & Video 6
   4.2 Asking Questions 6
   4.3 Presenting 6
   4.4 Zoom Chat 6
5. Using Zoom - Quick Guide 7
6. Using Padlet - Quick Guide 9
   6.1 Getting Started 9
   6.2 Uploading a poster or presentation (for presenters) 9
   6.3 General use 11
   6.4 Padlet Links 12
7. Agenda 14
   7.1 Time zones 14
   7.2 Wednesday 24 June 2020 14
   7.3 Thursday 25 June 2020 15
   7.4 Friday 26 June 2020 16
   7.5 Posters 17

land surface temperature cci

Met Office Hadley Centre

1. WELCOME

The LST_cci project would like to extend a warm welcome to participants of the 2020 User Workshop 2020. This booklet provides information about the workshop for presenters, session chairs, and other meeting participants. Information about the workshop can also be found on the meeting webpages https://ws2020-lst-cci.acri-cwa.fr/.

Due to the Covid-19 global pandemic, the LST_cci User Workshop 2020 will be held via remote participation. The meeting is being hosted by the Met Office Hadley Centre with the support of several of the LST_cci core project team and ESA.

2. ORGANISATION

2.1 General Information

The LST_cci 2020 User Workshop organising committee includes:

- Lizzie Good (LST_cci Climate Research Group lead, Met Office Hadley Centre)
- Freya Aldred (LST_cci Project Team, Met Office Hadley Centre)
- Darren Ghent (LST_cci Principle Investigator, University of Leicester)
- Claire Bulgin (LST_cci Project Team, University of Reading)
- Simon Pinnock (LST_cci ESA Technical Officer)

The workshop comprises of two components: a 'live' component and an 'offline' component. The live component will be conducted through Zoom (https://zoom.us/) over four 1-hour sessions between 11:30 and 17:30 CEST on 24-26 June and will include oral *presentations and dis*cussions. The offline component will take place on Padlet (https://padlet.com/) and will include the poster presentations, links to recordings of the live workshop sessions, and some discussion, where each poster and oral presentation will have a dedicated discussion thread. The timings of the live workshop and availability of the offline workshop component is to enable as many delegates as possible to participate from across different time zones.

The full agenda for the workshop is available in the Agenda section of this information booklet. **Please note that all times in this document are in CEST.**

If you require any help or information related to the workshop, please email info.lst-cci@acri-st.fr.

2.2 Presentations

The abstract deadline for oral and poster presentations for the workshop has now closed.

To ensure the workshop runs smoothly, **please upload your oral and poster presentations to Padlet by 09:00 CEST on Monday 22 June 2019**, see the Using Padlet - Quick Guide section of this information booklet on how to do this.

Presenters are asked to pay particular attention to their allotted time in the Agenda, which includes both time for the presentation and for questions. Most oral presentation slots are 20 minutes, which should include about 5 minutes for questions. When putting together presentation slides, please bear in mind some participants may have limited bandwidth and video content/animations may cause issues for them.

The workshop organising committee would like to record all presentations through Zoom. This is to enable oral presentations to be made available to those participating in the workshop 'offline'. The committee would also like to make slides and posters available to the public via the meeting webpages after the event. **If you would prefer that your presentation is not recorded and/or made publicly available, please email info.lst-cci@acri-st.fr to let the project team know.**

Posters will only be presented through Padlet, which will be available throughout the workshop. Participants are encouraged to view the posters outside of the live workshop sessions, post comments and questions, and participate in the offline discussions.

2.3 Session Chairs

Each live session will be chaired by one of the LST_cci project team. Session chairs are asked to:

- Introduce each speaker briefly
- Keep the presentations to the allotted time
- Monitor the Zoom chat facility
- Lead/moderate discussion

It is particularly important that the live sessions keep to time as the workshop is being held virtually with people joining from different time zones. The scheduled breaks are also important to maintain participant engagement. Chairs are therefore asked to pay particular attention to keeping time during presentations and should make every effort to ensure sessions do not overrun into breaks.

Oral presentation slots in the agenda include both time for the presentation and questions. Most slots are 20 minutes in length, which should include about 5 minutes for questions.

In general, talks should be chaired as follows:

1) The chair should introduce the speaker.
2) The session chair should give a verbal notification to the speaker two minutes before the presentation is due to finish (e.g. after 13 minutes in a 20-minute presentation slot) in order to allow time for questions.
3) The session chair should give further verbal reminders every 1-2 minutes as appropriate to encourage the speaker to keep to time.
4) If a presenter overruns, the time for questions should be reduced such that the slot finishes approximately on time.
5) Session chairs are asked not to allow questions if the speaker has used up their entire time slot in the agenda (e.g. 20 minutes).
6) If the speaker has received verbal reminders from the session chair but has still not completed their presentation within one minute after the end of their allotted slot (e.g. within 21 minutes), the meeting hosts will cease screen-sharing and mute the presenter.

As a session chair, you will not usually be made a co-host on Zoom.

2.4 Further information

Please send all correspondence regarding the workshop to info.lst-cci@acri-st.fr. For further information about the workshop, please visit the workshop webpages at https://ws2020-lst-cci.acri-cwa.fr/ and the Padlet workshop introduction pages.

3. LIVE WORKSHOP JOINING INSTRUCTIONS

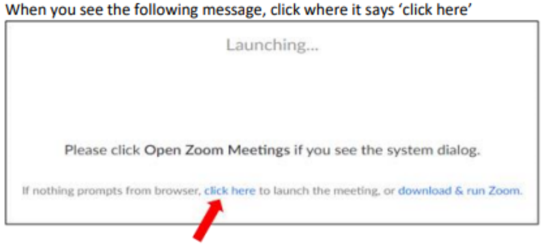
The live component of the workshop will take place using the Zoom video conferencing platform. On the day, please use the following URL and password, Chrome is the recommended browser for the best experience of Zoom.

URL: https://us02web.zoom.us/j/88950692366?pwd=NXBOcm91ZmZwUDJ3WXZ0M0pFd0JJUT09
Password: 867868

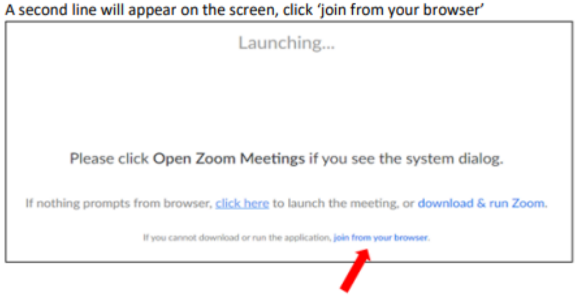
Some institutional IT systems do not permit downloading Zoom. In this case, you should be able to access the meeting via the browser option as per the instructions below. You may not see the option to 'join from the browser' unless you are using Chrome. If you encounter problems, you may need to use a different device if you have one, or dial in by telephone for audio participation only (note all presentations should be available to view on Padlet).

3.1 Accessing the meeting via the browser:

When you see the following message, click where it says 'click here'



A second line will appear on the screen, click 'join from your browser'



When prompted to enter your name, **please type your first name and surname** so it is easy to identify everyone when it comes to the discussion.

3.2 Accessing the meeting via telephone:

If you are unable to join the meeting through the Zoom app or web browser, you can join the meeting through the following toll-free telephone numbers and Meeting ID, and view the presentation slides through Padlet (see section Using Padlet - Quick Guide).

Meeting ID: 889 5069 2366
Password: 867868

Country	Toll-free number	Toll-free number	Toll-free number
Australia	1800 945 157	1800 317 562	1800 893 423
Austria	800 104 430	0 800 102 309	
Belgium	0 800 294 51	0 800 293 46	
Brazil	0 800 878 3108	0 800 761 4138	0 800 282 5751
Bulgaria	00 800 111 3251		
Denmark	80 71 12 56	80 71 12 51	
Canada	855 703 8985		
Croatia	0 800 200 588		
China	*No number available*		
France	0 800 944 049	0 800 940 415	
Germany	0 800 1800 150	0 800 000 1590	0 800 000 6954
India	000 800 050 5050	000 800 040 1530	
Italy	800 790 654	800 088 202	800 125 671
Nigeria			
Netherlands	0 800 220 0040	0 800 022 1954	
New Zealand	0 800 527 544	0 800 307 929	
Portugal	800 780 072	800 780 052	
Romania	0 800 890 203	0 80 672 631	
S. Korea	0 808 220 250		
Spain	900 053 647	800 654 404	800 906 063
Sweden	0 200 123 720	0 200 123 514	
Switzerland	0 800 561 252	0 800 002 622	
UK	0 800 358 2817	0 800 031 5717	0 800 260 5801
USA	888 788 0099	877 853 5247	

For the full list of telephone numbers you can use for this meeting, please see https://us02web.zoom.us/u/kc4wSHePKW.

4. LIVE WORKSHOP MANAGEMENT & ETIQUETTE

Please join the meeting from 11:15 CEST in advance of the 11:30 CEST start, allowing time to complete the login process. Once you have joined, please wait with your microphone muted for the host to start the meeting.

4.1 Microphones & Video

All microphones must be muted except when presenting or when called upon to ask a question. Video feed should be switched off except when speaking, this is to minimise the bandwidth usage for those with limited connectivity.

4.2 Asking Questions

If you would like to ask a question, please indicate this by using the Zoom Chat feature. Type a brief message indicating you would like to ask a question or enter your question directly if short. The session chair will monitor the Chat feature and call on you to ask a question as appropriate. Please note that there may not be time for all questions during the live sessions but questions can be posted at any time on the dedicated Padlet pages for each session.

4.3 Presenting

If you are presenting, you will be asked to share your screen so that you show and control your presentation from your own computer. Please have your presentation open and ready for your time slot on the agenda. Please do not share your screen until asked to by the chair of the session. In the event of technical problems preventing a presenter from sharing their own screen, one of the meeting hosts will open and control the presentation on behalf of the speaker. Once your presentation and any questions are over please stop sharing your screen so the next presenter can take over when asked.

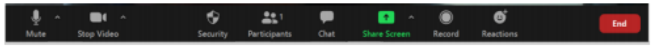
Owing to the different time zones of participants and the need to take regular breaks during this remote event, strict time keeping will be employed during the live sessions. Presenters are requested to keep to time, allowing a few minutes for questions at the end of their agenda slot. Chairs will give verbal notification when a presentation slot is nearing the end and it is almost time for questions. **Where presenters have been given several verbal warnings and have exceeded their allotted time slot, the hosting committee may terminate the presentation and mute the presenter** in order to move on to the next speaker and keep the meeting running on time.

4.4 Zoom Chat

Please do not use the Zoom chat for any scientific discussion. The Zoom chat should only be used to indicate you would like to ask a question after an oral presentation, or to highlight a technical issue during the meeting. Participants are asked to use the dedicated spaces on Padlet for each oral and poster presentation to enable all meeting delegates to view and participate in any scientific discussions, including those not dialling into the live component of the workshop.

5. USING ZOOM - QUICK GUIDE

Basic Controls
Once logged in to the Zoom meeting, move the mouse to hover over the zoom window. A tool bar like the one below will appear; all meeting options are available from there.



To share your screen click on 'Share Screen' in the tool bar and then select the application window (e.g. your presentation in PowerPoint) that you would like to share.
Displaying PowerPoint slides in 'slide show' mode will give the best experience for other participants viewing the slides, although 'slide show' mode may not work well if the connection bandwidth of the presenter is particularly limited. In this case clicking through each slide in the PowerPoint editing view may be necessary.

To stop sharing your screen click on 'Stop Share' at the top of your screen.

To ask a question click on 'Chat' in the tool bar, a group chat area will open on the right-hand side. To send a message, type in the area at the bottom where it says Type message here and click 'Enter' to send your message. We will not be monitoring the 'Reactions' feature.

To see the names of participants currently in the meeting click on 'Participants' in the tool bar. A list of names will open on the right-hand side.

To control your audio feed click on the up arrow to the right of the Mute/unmute button. This will show the options available to you for both speaker and microphone audio source.
If you hear audio echo or audio feedback during the meeting, there are three possible causes:

1. A participant has both the computer and telephone audio active
2. A participant has computer or telephone speakers that are too close to each other
3. There are multiple computers with active audio in the same room

If echoes become a problem on the day you will be asked to check your audio settings and ensure there are no other active audio devices on in the same room.

5.1 Troubleshooting

If you have trouble receiving audio in Zoom you may find these links helpful:

https://www.thewindowsclub.com/no-sound-in-chrome/

https://www.guidingtech.com/fix-google-chrome-sound-not-working-windows-10/

If you have trouble getting your microphone to work in Zoom, you may find this link helpful:

https://us02web.zoom.us/wc/support/mic

6. USING PADLET - QUICK GUIDE

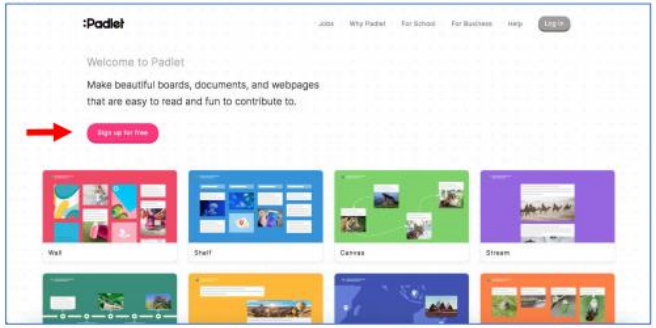
Padlet is a diverse piece of software that provides a space for gathering and sharing ideas and files. The LST_cci User workshop is using the software to provide

1) Information about the LST_cci User Workshop
2) A space where presenters can upload their oral and poster presentations
3) A space where meeting participants can view presentations and posters, and hold offline discussions and ask questions

Separate 'Padlets' have been created for each live workshop session (one Padlet is like one webpage). Each presentation within a session will have a dedicated post where the slides will be available, and related comments and discussion can take place (similar to Facebook). Information about the different workshop Padlets can be found below in the Padlet Links.

6.1 Getting Started

It is recommended that all delegates – including non-presenters – set up a free Padlet account, which can be done very quickly and easily. Note that an account is not required to participate in the workshop and you will still be able to view content and comment. However, it will help to attribute any comments and questions and keep discussions clear. You can sign up to Padlet at https://padlet.com/ by clicking on 'sign up for free' as shown below.

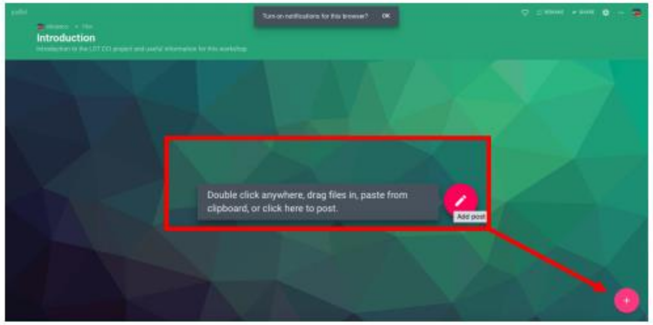


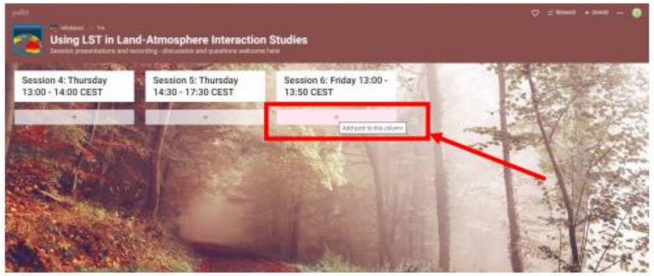
6.2 Uploading a poster or presentation (for presenters)

If you are uploading a poster, please first save it in PDF format, as this allows better viewing on this platform. It is not necessary to convert PowerPoint presentation slides to PDF.

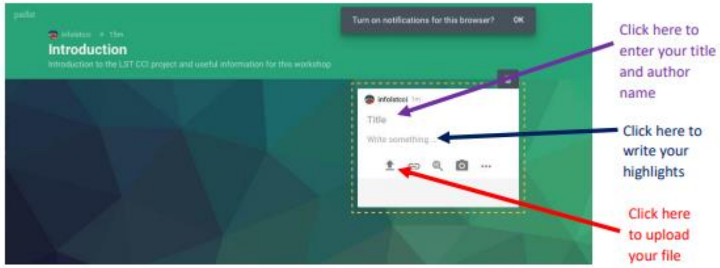
To upload your poster or presentation follow these steps:

1. Go to the Padlet board (or page) for your session - see Padlet Links section.
2. Click the '+' sign to create a new post. This will either be in the bottom right hand corner in a pink circle or in a grey box if the Padlet has columns, as shown below.

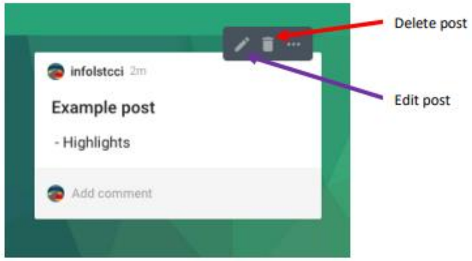




3. For the post title, please use the title of your presentation with your name in brackets (e.g. "Findings from the LST_cci User Requirements Assessment (Lizzie Good)"). We recommend you also add three highlights or bullet points in the post where it says 'write something' to aid post navigation.



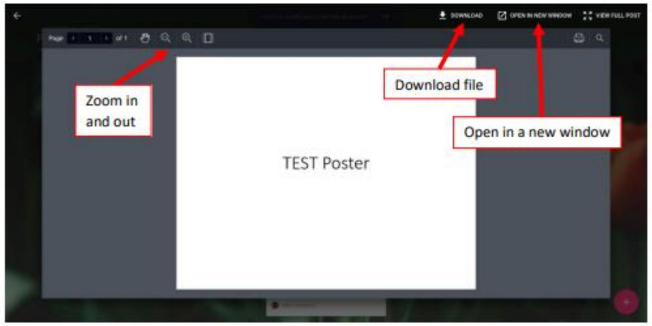
4. To upload your file, click the up arrow (highlighted in the image above with a red arrow), which will give you a panel at the side with the option to 'pick file'.
5. You can then find and upload your presentation slides or PDF poster.
6. Once your file has finished uploading, click elsewhere on the page.
7. Posts need approval by the organising committee; once approved they will be visible to all workshop participants.
8. You can edit or delete a post you have created by hovering the mouse over your post then selecting the edit or delete icon as shown below.

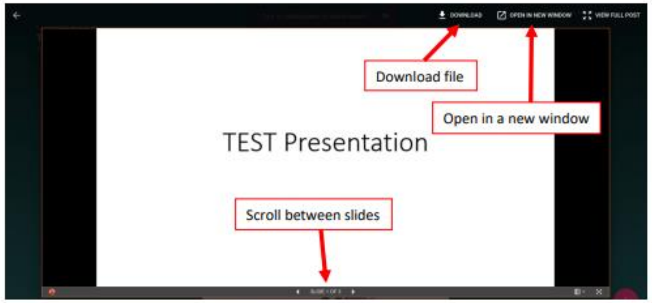


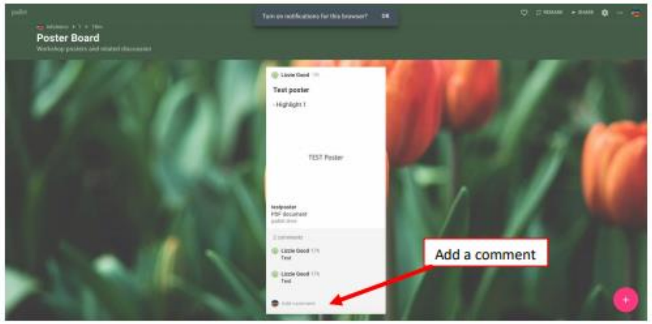
6.3 **General use**

All posters and presentations should be available from Monday 22 June 2020 and will remain on the Padlets until 3 July 2020. Links to each workshop and poster Padlet are provided below. All Padlets are linked from the main workshop Introduction Padlet. Each live session will be recorded in Zoom and the link to a session recording will be added to the relevant Padlet shortly after the session has finished.

An uploaded file in a post can be expanded by clicking on it; from here you can scroll between slides in a presentation or zoom in on a poster. There is also the option to open the uploaded file in a new window or to download it. Comments and questions can be posted below the relevant presentation or poster (these do not need to be approved like posts).







6.4 Padlet Links

General

Padlet Link	Content
Introduction	LST_cci project and workshop information (no presentations)
Poster board	All posters for the workshop.

Oral Presentation Sessions

Padlet Link	Content	Date and Time
LST_cci Project	Oral session 1 presentations, recordings and discussion	Wed 11:30-12:30 CEST
LST_cci dataset development and validation	Oral session 2 presentations, recordings and discussion	Wed 13:00-14:00 CEST
Data set development and validation	Oral Session 3 presentations, recordings and discussion	Wed 16:30-17:30 CEST
Using LST in land-atmosphere interaction studies	Oral session 4-6 presentations, recordings and discussion	Thur 13:00-14:00 CEST Thur 16:30-17:30 CEST Fri 13:00-13:50 CEST
Urban LST	Oral Session 7 presentations, recordings and discussion	Fri 14:50-15:30 CEST

Discussion Sessions

Padlet Link	Content	Date and Time
Uncertainties in LST	Discussion session 1 breakout group notes	Wed 15:00-16:00 CEST
User Requirements for Climate LST	Discussion session 2 breakout group notes	Thur 11:30-12:30 CEST
Towards climate services using LST	Discussion session 3 breakout group notes	Thur 15:00-16:00 CEST
Role of satellite LST observations in future IPCC assessments and other reports	Discussion session 4 breakout group notes	Fri 11:30-12:30 CEST
Feedback session	Recording of feedback sessions	Fri 15:30-17:20 CEST

7. AGENDA

7.1 Time zones

All times in the agenda are in Central European Summer Time (CEST). The table below provides a guide for converting between some of the time zones of registered workshop participants.

CEST	UK time	Romania	Delhi	Beijing	Melbourne	Pacific Daylight Time (e.g. Oregon)	Eastern Daylight Time (e.g. Washing. DC)
11:30	10:30	12:30	15:30	17:30	19:30	02:30	05:30
13:00	12:00	14:00	17:00	19:00	20:00	04:00	07:00
15:00	14:00	16:00	19:00	21:00	23:00	06:00	09:00
16:30	15:30	17:30	20:30	22:30	00:30	07:30	10:30

7.2 Wednesday 24 June 2020

Wednesday 24 June 2020			
11:15 CEST	Start arriving into workshop		15 mins
LST_cci Project (Link to Padlet) Chair: Claire Bulgin			
11:30 CEST	Welcome and general information	Lizzie Good (Met Office, UK)	20 mins
11:50 CEST	Overview of the LST_cci Project and Products	Darren Ghent (U. Leicester, UK)	20 mins
12:10 CEST	ESA's CCI Programme	Simon Pinnock (ESA)	20 mins
12:30-13:00	**Break**		
LST_cci Data Set Development and Validation (Link to Padlet) Chair: Darren Ghent			
13:00 CEST	LST_cci products	Darren Ghent, Sofia Ermida, Carlos Jiménez, José Sobrino	30 mins
13:30 CEST	First results of the LST_cci validation analysis	Maria Martin (KIT, Germany)	15 mins
13:45 CEST	Construction of a gap-free multisensor ice surface temperature product for the Greenland ice cap and assimilation into atmosphere and ice sheet models	Jacob Høyer (DMI, Denmark)	15 mins
14:00-15:00	**Break**		

Discussion session: Uncertainties in LST (Link to Padlet) Chair: Darren Ghent			
15:00 CEST	Recent advances in the field of satellite data uncertainties	Claire Bulgin (U. Reading, UK)	20 mins
15:20 CEST	Discussion – break out groups		40 mins
16:00-16:30	**Break**		
Data set development and validation (Link to Padlet) Chair: Sofia Ermida			
16:30 CEST	On the validation of the All-Sky Land Surface Temperature product based on MSG/SEVIRI observations	Joao Paulo Martins (IPMA, Portugal)	20 mins
16:50 CEST	Multi-decadal validation of the TIMELINE AVHRR Land Surface Temperature product with MODIS and in situ LST	Philipp Reiners (DLR, Germany)	20 mins
17:10 CEST	Developing ESA's LSTM for the next generation of High Spatial Resolution Thermal Remote Sensing	Mike Perry (U. Leicester, UK)	20 mins
17:30	**End of day 1**		

7.3 Thursday 25 June 2020

Thursday 25 June 2020			
11:15 CEST	Start arriving into workshop		15 mins
Discussion session: User Requirements for Climate LST (Link to Padlet) Chair: Claire Bulgin			
11:30 CEST	Findings from the LST_cci User Requirements Assessment	Lizzie Good (Met Office, UK)	20 mins
11:50 CEST	Discussion – break out groups		40 mins
12:30-13:00	**Break**		
Using LST in land-atmosphere interaction studies (1) (Link to Padlet) Chair: Carlos Jimenez			
13:00 CEST	Recent progress on the global ET product with the thermal energy balance method	Xuelong Chen (Institute of Tibetan Plateau Research, China)	20 mins
13:20 CEST	Evaluation of Land Surface Temperature in the EC-EARTH3-Veg climate model: Use of LSA-SAF and role of vegetation	Emanuel Dutra (IPMA, Portugal)	20 mins
13:40 CEST	The role of LST characteristics in the data-driven simulation of land-atmosphere fluxes	Sophia Walther (MPI-BGC, Germany)	20 mins
14:00-15:00	**Break**		

Discussion session: Towards Climate Services Using LST (Link to Padlet) Chair: Lizzie Good			
15:00 CEST	Underpinning science to a climate service: examples from Climate Science for Services Partnership-China (CSSP-China)	Tyrone Dunbar (Met Office, UK)	20 mins
15:20 CEST	Discussion – break out groups		40 mins
16:00-16:30	**Break**		
Using LST in land-atmosphere interaction studies (2) (Link to Padlet) Chair: Frank Goettsche			
16:30 CEST	Exploitation of a combined use of Sentinel-3 fAPAR & LST data for primary production estimates	Roel Van Hoolst (VITO, Belgium)	20 mins
16:50 CEST	Using satellite-derived surface temperatures for atmospheric boundary-layer studies	Antoni Grau Ferrer (Universitat de les Illes Balears, Spain)	20 mins
17:10 CEST	Sensitivity of diurnal cycle of LST to the soil moisture detected from combined LST, SM, precipitation observations	Yanfeng Zhao (CNRS, France)	20 mins
17:30	**End of day 2**		

7.4 Friday 26 June 2020

Friday 26 June 2020			
11:15 CEST	Start arriving into workshop		15 mins
Discussion session: Role of satellite LST observations in future IPCC Assessments and Other Reports (Link to Padlet) Chair: Lizzie Good			
11:30 CEST	Global and regional trends in LST	Freya Aldred (Met Office, UK)	20 mins
11:50 CEST	BAMS State of the Climate	Robert Dunn (Met Office, UK)	20 mins
12:10 CEST	Discussion		20 mins
12:30-13:00	**Break**		
Using LST in land-atmosphere interaction studies (3) (Link to Padlet) Chair: Emma Dodd			
13:00 CEST	Applications of an LST based diagnostic to evaluate soil moisture-surface flux relationships in land surface models.	Sonja Folwell (CEH, UK)	20 mins
13:20 CEST	Satellite applications in climate observations of LST and biomass burning	Julia Stoyanova (National	20 mins

		Institute of Meteorology and Hydrology, Bulgaria)	
13:40 CEST	Constructing seamless MODIS LST maps for Australia from swath data	Kaniska Mallick (LIST, Luxembourg)	10 mins
13:50-14:50	**Break**		
Urban LST (Link to Padlet) Chair: José Sobrino			
14:50 CEST	Country-Scale Climatology of the Surface Urban Heat Island using MODIS	Sorin Cheval (National Meteorological Administration, Romania)	20 mins
15:10 CEST	Investigating the Seasonal SUHI Intensity Hysteresis Curves in Europe	Panagotis Sismanidis (Ruhr University Bochum, Germany)	20 mins
Feedback from breakout groups (Link to Padlet) Chair: Karen Veal			
15:30 CEST	Feedback from Uncertainties break out group	Claire Bulgin (U. Reading, UK)	20 mins
15:50-16:20	**Break**		
16:20 CEST	Feedback from user requirements	Freya Aldred (Met Office, UK)	20 mins
16:40 CEST	Feedback from Climate services	Lizzie Good (Met Office, UK)	20 mins
17:00 CEST	Closing remarks	Darren Ghent Lizzie Good	20 mins
17:20	**End of day 3**		

7.5 Posters

Poster presentations will be available to view on Padlet.

Posters (Link to Padlet)		
Number	**Presenter**	**Title**
1	Emma Dodd (U. Leicester, UK)	Validation for Sentinel 3 Land Surface Temperature Products
2	Cheolhee Yoo (UNIST, S. Korea)	Estimation of All-Weather 1 km MODIS Land Surface Temperature for Humid Summer Days
3	Frank Goettsche (KIT, Germany)	Alternative and improved algorithms for estimating LST from Sentinel-3 SLSTR data [link to paper]
5	Mary Langsdale (King's College London, UK)	Airborne mapping and in situ validation of European land surface temperature using the NASA-JPL's HyTES sensor
6	Tomas Dowling (King's College London, UK)	Meteosat and MODIS land surface temperature product validation with a new environmental satellite data calibration and validation station: Kapiti, Kenya
7	Cristina Dumitrica (Institute of Geography, Romania Academy)	The influence of land use/land cover types on the surface urban heat island effect. Insights from urban areas of the Southern Romania

Appendix D - LST_cci User Workshop 2020 Padlet Content

This appendix includes a direct copy of all the comments posted on the public Padlets used during the LST_cci User Workshop 2020. The contents of this appendix is organised by Padlet: Separate Padlet 'pages' were set up for each workshop session (see workshop booklet in Appendix C). It appears exactly as it was posted on these Padlets, which were publicly unrestricted pages (i.e. open to anyone with internet access).

LST_cci Project Padlet Content

Overview of the LST_cci Project and Products (Darren Ghent)

- Objectives
- Highlights

Gregory Duveiller 2mo
Question: is there an objective of doing a single consolidated multi-sensor product? I think many users (especially non-RS specialists) will want 1 and only 1 product to use rather than a whole suite of products. Is this foreseen? (sorry if I missed it from you talk)

Anonymous 2mo
We are doing a single Merged Product combining both polar orbiting and geostationary satellites. The challenge here with this dataset rather than all the individual datasets is that there are several additional uncertainty components to include pushing up the overall total uncertainty

Gregory Duveiller 2mo
Good to know there is this Merged Product in the pipeline. Regarding the uncertainty, if there are several different sources of LST data that are combined together, in some kind of ensemble, the actual uncertainty with respect to reality should ultimately be lower than that of individual products, shouldn't it? Or otherwise, the uncertainty in the different products is actually underestimating the actual uncertainty, no? Am I missing something?

cebulgin 2mo
There are a couple of options for uncertainty information in combined products. One of these is to use the

cebulgin 2mo
There are a couple of options for uncertainty information in combined products. One of these is to use the uncertainty to inform the data combination itself - for example, if you were calculating an average from a number of different inputs you could weight these by the total uncertainty of each contributing observation and then propagate the uncertainties accordingly.

ESA's CCI Programme (Simon Pinnock)

Overview of ESA's Climate Change Initiative, including example ECVs relevant to LST.

Anonymous 2mo
Apologies, looks like my PPT is too big to view on padlet. I've got a smaller version that I can upload (also updated).

Lizzie Good 2mo
It's OK, Simon, people can download it from Padlet to view, so I don't think that is a problem.

LST_cci Dataset Development and Validation

LST_cci products (Darren Ghent, Jose Sobrino, Sofia Ermida, Carlos Jimenez)

- Overview of the CCI_lst data products and algorithms
- Thermal Infrared polar orbiting and geostationary + Microwave

Gregory Duveiller 2mo
Hi Darren. Question: when making the LEO + GEO combined dataset, how are you going to manage the effects caused by the strong differences in observation from an angular point of view?

Anonymous 2mo
We have developed an angular correction factor as shown in Sofia's slides

Lizzie Good 2mo
Carlos, will you estimate an uncertainty on the correction to the LST due to the orbital drift? Do you have a feel for what this uncertainty is at the moment, e.g. 0.5 K, 1 K?

Anonymous 2mo
Hi Carlos: maybe I missed it, how do you eliminate emissivity changes in microwave products?

Anonymous 2mo
Hi Carlos, maybe i missed it in your presentation, but how far back in time can you go to produce a stable LST CDR in the microwaves domain?

Matteo Piccardo 2mo
Hi Sofia, which parametric models do you use for angular corrections on LST?

Francesco Fusto 2mo
Hi Sofia, when is planned to complete the Seviri product for the whole period until 2020?

Sofia Ermida 2mo
Hi Matteo, we tested different models, namely the kernel model from Vinnikov et al. (2012) and the hotspot model from Lagouarde and Irvine (2008). We've also developed a combination of the two that works best in different conditions. You can get more info from these two papers: https://doi.org/10.1016/j.rse.2018.02.066 ; https://doi.org/10.3390/rs10071114

Matteo Piccardo 2mo
Thanks Sofia

Sofia Ermida 2mo
Hi Francesco, we don't have a specific date yet. We will reprocess the full data record once the algorithm calibration exercise is complete since we need the new coefficients for consistency with the other products. But we are hopping to start the reprocessing in the next 2-3 months

carlosjimenez13 2mo
Regarding how to take into account the emissivity dependence in the MW retrievals, we use a "climatological" emissivity to guide the retrieval. But if at a given moment the "real"emissivity differs considerably from the one input to the retrieval, we will be certainly making an error in the retrieved LST. This is one of the reasons for our larger uncertainties. For more details: https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2015JD024402

carlosjimenez13 2mo
Regarding how far we can go back in time, we could possible stretch down to 1992 for a coherent data record using the SSMI family of sensors. Previous to that we have another satellite with a SSM/I from 1987, but there were some technical problems. And further back in time we have the SMMR instrument, but it is not straightforward to estimate LST from it due to different reasons (see e.g. https://www.atmos-meas-tech-discuss.net/amt-2019-493/)

carlosjimenez13 2mo
Concerning the uncertainity on the correction, yes, we will try to produce the correction and an uncertainty. We just started, so I do not have any numbers yet, sorry :)

Results Of The LST_cci Validation Analysis (Maria Martin)

- First results of the validation of the LST_cci data products are shown
- Including in situ validation against several globally distributed stations and satellite satellite intercomparisons

Yuhan (Douglas) Rao 2mo
Hi Maria, it looks like from the intercomparison results that one of the major factor that LST_cci products are more consistent is the same cloud clearing procedure?

Mary Langsdale 2mo
Hi Maria, Q: How are you performing the upscaling of the in situ data to the different satellite products?

João Martins 2mo
Part of the striped differences between MODIS and SEVIRI are explained by different viewing and illumination geometries.

NikosAlexandris 2mo
What is the difference between MODIS' standard product 'MOD11A' and 'MODISA' mentioned in the presentation/ demonstrated in the slide regarding differences with SEVCCI?

Raquel Niclos 2mo
The same question: What is the difference between MODIS' standard product 'MOD11A' and 'MODISA' mentioned in the presentation/ demonstrated in the slide regarding differences with SEVCCI?

Raquel Niclos 2mo
Could be the striped differences consequence of the use of the gridded MOD11 product? Are you using MOD11A1 or MOD11L2 products?

Sofia Ermida 2mo
Over Africa there is barelly any overlap between MODIS swaths, the stripping is most likely due to the viewing geometry

Sofia Ermida 2mo
I think MOD11A is the original product and MODISA is the CCI version, but Maria should confirm

Raquel Niclos 2mo
Thanks Sofia

Maria Martin 2mo
Hello Yuhan, from what do you conclude that? If I am correct, the SEVIRI LST_cci project has a different cloud mask than the MODIS LST_cci products. Right, Sofia?

Maria Martin 2mo
Yes, MOD11A is the operational MOD11-Aqua product, and MODISA is the LST_cci MODIS Aqua prodcut

Maria Martin 2mo
So, it is MYD11_L2

Sofia Ermida 2mo
yes, SEVIRI cci uses the LSA-SAF cloud mask

Maria Martin 2mo
Hello Mary, this depends on the type of station. For the KIT station, where the land scape is not homogeneous (so EVO, DAH_T_ and KAL), there are several in situ sensors set up and the in situ LST is calculated by an weighted sum of the different measurements, depending on an assumption on how the land cover is mixed. For the SURFRAD stations, there is only a broadband sensor measuring the in situ LST, we cannot do that. However, we have looked at each station very carefully and for some we used less pixels for the LEO LST data sets to get on a more homogeneous land cover (which, of course, is not possible for the GEO and MW data sets)

Anonymous 2mo
Hi all, to confirm the MODISA product (CCI) uses the GSW algorithm, with CIMSS emissivities as input. The retrieval coefficients have been generated using a different Calibration Database to the operational MODIS11 which is significant contributor to these differences between these products.

Anonymous 2mo
Over Africa the intercomparisons are composite outputs from all 5 minute matchups between MODIS and the hourly SEVIRI CCI product. This means that matchups will only get included for certain orbits within a repeat cycle with the MODIS across track viewing geometry generating different LST differences with the disk geometry of SEVIRI

Construction of a gap-free multi-sensor ice surface temperature product for the Greenland ice cap and assimilation into atmosphere and ice sheet models (Jacob Høyer)

- Aim to use LST data to construct a multi-sensor L4 product to evaluate the performance of a regional climate model in calculating the surface energy budget over the Greenland ice sheet
- Easy to use LST CCI products
- Documented uncertainties would be helpful
- (A)ATSR observations are more challenging due to low sampling and diurnal variability
- Need documented validation and harmonization in CDRs

Simon Pinnock 2mo
Are the very large but localised biases between IceBridge and Satellite-LST due to cloud-clearing errors?

Emma Dodd 2mo
Comment: For more in situ data over Greenland there is in situ data collected by the University of Utrecht (you have to contact for access still them I think) in the ATSR time period and beyond. I can try to put you in contact if you are not already if this is useful.

Anonymous 2mo
Thanks Emma, we are actually in contact with Utrecht and the Promice/GC-net teams who run the AWS network on the ice sheet

Anonymous 2mo
(That was from Ruth Mottram btw - I will sign in so you can see it is me!)

Anonymous 2mo
Looking at the large localised differences between MODIS and IceBridge I would conclude these are cloud misses. The MODIS product uses the operational cloud mask and will be updated in the next Processing Cycle to implement the Probabilistic Mask which should hopefully address some of these issues

Anonymous 2mo
Hi Jacob, thanks for the nice presentation. The deviations of MODIS LST over Greenland are really impressive, especially compared to the better performing AVHRR (GAC) LST. Do you have any idea what the main reason for that could be? Emissivity errors of that magnitude I would rule out, since over snow ice emissivity should be quite well determined.

AlejandroDUSSAILLANT 2mo
Nice Jacob thanks! On a tangent, but have you or are you going to look at new or enlarging melt water areas i.e. lakes? Perhaps combining this data with land cover sat data?

Emma Dodd 2mo
Good to know you are in contact with Utrecht and I'm glad the data we processed was of use! Nice to see what happens to the data. (I was involved in the preliminary coding and/or processing).

Anonymous 2mo
I am not sure about the exact reason for the large Modis biases. I would suspect that they are due to emissivity differences arising from land cover misclassifications (the largest errors are at the rim of the ice sheet). The signal does not look like cloud cover effect in my opinion, as these would have a more variable nature, but this is just guessing. We will compare against radiometric observations from the Promice network. Best wishes, Jacob

Anonymous 2mo
Hi Alessandro, We are going to combine the IST with passive microwave data to determine melt extent for the Greenland ice Sheet. Best wishes, Jacob

Validation of the All-Sky Land Surface Temperature product based on MSG/SEVIRI observations (João Martins)

- A new LST product combines IR LSTs with temperature estimates from a surface energy balance model, to fill in the gaps caused by clouds
- Representativity at the pixel level of the estimates from 33 sites is maximized in the validation procedure
- Comparison with skin temperature estimates from ERA5-Land allows a more comprehensive validation.

Mary Langsdale 2mo
Great talk, thank you João! You showed that some stations are spatially heterogeneous and might not be suitable for validation. Do you account for this in your uncertainty calculation of the in situ LSTs (and how do you do it if so)?

Anonymous 2mo
Hello, Again. I am interested to know about the phase difference in ERA5, which you mentioned is ~+2 hours than the observed. I suppose it is how they calculate LST. Would like to have your thoughts on this. Another question, why did you choose ERA5 for validation?

João Martins 2mo
Thanks Mary! :) we didn't go that far, no... we didn't actually validate the uncertainties themselves, which is, I believe, where that information would go into.

annu panwar 2mo
Hello, Again. I am interested to know about the phase difference in ERA5, which you mentioned is ~+2 hours than the observed. I suppose it is how they calculate LST. Would like to have your thoughts on this. Another question, why did you choose ERA5 for validation? Annu Panwar MPI BGC

João Martins 2mo
Hi Annu! Thank you for your interest. One possible reason is the timestep used to run the HTESSEL model, which was of 1h. Running the model with a lower timestep (which we experimented offline) greatly reduced this time lag. Other possible reasons include the thermal conductivity to the ground that may need some adjustment, and also the discretization of the soil layers. Emanuel Dutra will talk about this in his talk, so be sure to watch it :)

João Martins 2mo
@carlosjimenez: I took a quick look into the ATBD describing the surface energy model, and it just assumes zero resistance to evaporation (https://landsaf.ipma.pt/GetDocument.do?id=755)

annu panwar 2mo
Hey Martins, Yes it can be due to representation of ground heat flux. If it is it should be visible when you compare different vegetations surface. Although, I think this can also be related to greater phase lag of air temperature in surface energy balance in ERA5.

João Martins 2mo
I forgot to tell you why we chose ERA5. In our feasibility paper, we compared to MW data from AMSR-E, you can check it here: https://www.mdpi.com/2072-4292/11/24/3044. But it wasn't available for 2018. Then we decided for ERA5 since it has a similar physical model behind it and it also incorporates many observational data.

Emanuel Dutra 2mo
Hi Annu, the phase lag in ERA5-Land is still under investigation, but it's mostly due to the model numerics. Reducing the model timestep reduces the phase error. Also the ground-heat flux and soil thickness of the first layer is relevant.

Multi-decadal Validation of the TIMELINE AVHRR Land Surface Temperature Product with MODIS and in situ LST (Philipp Reiners)

- Validation with in-situ LST resulted in MADs within the accuracy range of other LST studies
- Comparison with MODIS LST shows positive bias of TIMELINE LST
- Consistency across sensors
- Create the foundation for multi-decadal and climate relevant statements for decision makers, the scientific community, the UN and NGO's

Emma Dodd 2mo
Comment: For more in situ sites it might be worth looking at GBOV (https://gbov.acri.fr/), which is using many existing sites and setting up new ones, and LAW for the future (poster in the poster session gives information).

Anonymous 2mo
Nice talk Philipp. We would welcome the opportunity to intercompare our CCI datasets with your TIMELINE product - we can discuss via email

annu panwar 2mo
Maybe a basic question, I look on the differences in surface and air temperature. Usually, global warming is quantified in terms of air temperature. You show global warming in terms of LST (land surface temperature). I would like to hear your thoughts on the difference in warming of the surface and air temperature. Why do you think we should go for LST and not air temperature? MPI BGC, Jena

Anonymous 2mo
Thank you very much, Emma, I will definitely have a look into that

philippreiners 2mo
I am not sure, who to address for the second comment, but thank you. Yes I think this comparison will be very interesting. Feel free to email me at Philipp.reiners@dlr.de

philippreiners 2mo
Annu, I think there are strong links between Near Surface Air Temperature and Land Surface Temperature. I am also planning to compare TIMELINE LST to the ERA air temperature. I think there is no possibility to directly derive air temperature from multispectral EO data, so land Surface temperature is a useful Proxy.

annu panwar 2mo
Philip, Thanks for your response. Yes they are coupled. But their coupling varies with evaporative conditions and vegetation types. Air temperature also responds to boundary layer heat storage that is in feedback to turbulent heat flux, the same is not true for LST. Also, I would be interested to know why to compare your LST with ERA5 air temperature? Is your LST product near surface temperature or skin temperature?

Dataset Development and Validation

Developing ESA's LSTM for the next generation of High Spatial Resolution Thermal Remote Sensing (Mike Perry)

- Looking to the future of LST High Resolution Remote sensing.
- Developing mission requirements from a User/Science driven standpoint
- Using simulation and Campaign data to provide Trade-Off analysis concurrently with instrument development

ardye 2mo
Hi, great project and talk thanks Mike. Is there any news on ESA developing a satellite with a high spatial resolution thermal sensor? 50 to 30m would be amazing for glacial lake temperature studies!

Investigating the Seasonal SUHI Intensity Hysteresis Curves in Europe (Panagiotis Sismanidis)

- Surface Urban Heat Island Intensity (SUHII) exhibits seasonal hysteretic cycles (i.e. the looping patterns of SUHII vs. the background rural LST), whose shape and direction vary across climatic zones
- In this work we use ESACCI land surface temperature (LST) data from MODIS to investigate the SUHII hysteresis curves for numerous cities in Europe.
- Cities in wet or relatively wet climates show a concave up hysteresis.
- Cities in dry regions will show a concave down curve.
- Nighttime SUHII Curves are almost the same between Europe's biogeographic regions.

sophiawalther 2mo
Panagiotis, nice clear presentation, and appealing figures! the topic of SUHII is new to me, my background rather is the vegetation, but I just wanted to add to my question about the stronger suhii effect in spring than in autumn and if this was rather related to a different mean rural temperature than mean urban temperature, it might be due to 1) less moisture in autumn than in spring which is increasingly observed due to carry-over effects from warmer springs with higher transpiration such that later in the growing season less moisture is left and increases rural LST, 2) color change of crops when they mature, are harvested and senescene, 3) I would be curious to know whether the spring-autumn difference is as strong when forests are considered as well in the rural

Urban LST

Country-scale Climatology of the Surface Urban Heat Island using MODIS LST products (Sorin Cheval)
- LST, SUHI and high temperature hazard risk for all cities above 30,000 inhabitants in Romania
- Aim to analyse the results in combination with drivers such as land cover

Mary Langsdale 2mo
Interesting presentation - thanks. Did you find the spatial resolution satisfactory for this study?

Using LST in Land-Atmosphere Interaction Studies

Session 1

Evaluation of LST in EC-EARTH3-Veg climate model (&ECMWF model): Use of LSA-SAF and role of vegetation (Emanuel Dutra)

LST diurnal cycle fundamental for model evaluation and to guide model development

cmt4 2mo
Very nice presentation!

cmt4 2mo
Is the CCI land cover fixed over time (ie no land cover change)?

annu panwar 2mo
Hey, I am a bit alert after your presentation. I am using ERA5 for study of land atmosphere interaction. surface, air temperature and surface energy balance components are the main variables for my study. My argument for going for ERA5 is the availability of all the components of surface energy balance, which might be not correct but surely consistent. Do you have any suggestions are guidance, when choosing the right data? Thanks

cebulgin 2mo
Hi Emanuel. Very interesting presentation. I recently read the paper on your study over Iberia and was thinking of using the HTESSEL model with the CCI vegetation corrections as a means of representing the diurnal cycle in surface temperatures as input to our clear-sky simulations for cloud detection. Essentially improving the ERA-5 inputs. Do you think that there would be a global benefit to doing this given your mixed analysis or would we run the risk of potentially making things worse in some regions?

Emanuel Dutra 2mo
Hi cmt4, yes land-cover was fixed using the 2010 data. For these large-scale and spatially coarse use land-cover changes will have a small impact.

Emanuel Dutra 2mo
Hi Annu, Many thanks for the feedback. No dataset (observations, models, reanalysis, etc...) is perfect, and all have limitations. It will depend on the exact use of ERA5, but in terms of reanalysis data, it has a very good quality, and many recent papers are showing it. If you have some concerns in your application, maybe including other dataset like MERRA2 could give further support.

Emanuel Dutra 2mo
Hi cebulgin, Thanks for the feedback. We're currently evaluating the global impact of updating land-cover (and LAI) in CHTESSEL. In terms of LST, the results are mostly positive (over the MSG disk). If you're interested, I'm happy to further discuss this with you and share the global simulations data. Just get in touch (emanuel.dutra@ipma.pt)

annu panwar 2mo
Emanuel Dutra Thanks for this suggestion.

The role of LST characteristics in the data-driven simulation of fluxes of carbon, water and energy (Sophia Walther)

- LST as one of the most **important predictors** in data-driven modelling of land-atmosphere fluxes
- use **MODIS** and **Seviri** LST
- test effects of LST characteristics (**retrieval method, spatiotemporal resolution, directionality**) on simulated fluxes

AlejandroDUSSAILLANT 2mo
@Chen: bear with my ignorance - how does the method separate vegetated versus non-vegetated land cover and assign ET to actual vegetated land (Tcanopy-LST relation)? Could this explain some of the apparent deviations?

João Martins 2mo
I will just leave the link to our GPP product, it would be nice to see some comparisons :)
https://landsaf.ipma.pt/en/products/vegetation/mgpp/

sophiawalther 2mo
Thanks Joao!

Simon Pinnock 2mo
Hi Sophia, I just wondered if you were aware of the CCI Soil Moisture data record: www.esa-soilmoisture-cci.org ? Maybe this would help solve the problem with droughts?

sophiawalther 2mo
Hi Simon, yes thanks, it is already on the list of variables/ data streams to include in the new setup of simulations and definitely will be included.

Anonymous 2mo
@ Alejandro, the energy balance method used a mix-pixel scheme. It is assume that LST, LAI, canopy height etc. at each pixel could represent the mean value of the whole pixel. The apparent deviation could be that there are too many input variables, which could influence the final ET.

Recent progress on the global ET product with the thermal energy balance method

- Improements have been made to an Energy Balance (EB) model
- The thermal EB model can estimate daily ET for all weather conditions with gap-filling methods
- EB ET data has a higher potential for agriculture water resource management than most of the global ET products
- Errors in the ET could be radiation or LST gaps

sophiawalther 2mo
Could you provide more details on how you combined terra and aqua in the gapfilling? In the map over the combined overpass time it looked like they were both directly merged?

Anonymous 2mo
Sophia, you are right on the terra and aqua merging. When the Terra has a gap, it will be filled with non-gap value of Aqua. Quite simple method.

Sensitivity of diurnal cycle of LST to the soil moisture detected from combined LST, SM, precipitation observations (Yanfeng Zhao)

- When superficial soil moisture increases, nocturnal effect and daytime cooling effect are detected over some semi-arid regions
- The linear regression coefficient between LST_max and SM is negative, between LST_min and SM it is positive

annu panwar 2mo
Hey Zhao, I find your study very interesting. I was wondering to you correct for the solar radiation contribution on LST. You are using mainly dry periods, and I think mostly deserts(no vegetation) so you can obtain a straightforward relationship via linear regressions.

Yanfeng Zhao 2mo
Thanks Annu. We don't want precipitation to affect soil moisture at the first step, so we use dry spell firstly. Next step, we will take into account the precipitation to see the change from SM to LST.

annu panwar 2mo
I would like to take this opportunity to direct you to my recent work. It is a bit of different methodology, instead of dry spell or precipitative events, we segregate days with wet and dry days and then look how surface and air temperature changes with evaporative conditions (or soil moisture).
https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019GL082248
Also a paper under review shows the importance of land cover type, which might be of your interest.
https://www.hydrol-earth-syst-sci-discuss.net/hess-2020-95/#discussion

Anonymous 2mo
Hi Yanfeng, if I understood correctly, then you require 10 days of (practically) no rainfall followed by a day with 24 hours clear sky LST oberservations for establishing the regressions between LST and SM. At LSA SAF they (Joao Martins et al., 2019; doi: 10.3390/rs11243044) have developed an all-weather LST product, which would allow you to also LST obtained under cloudy conditions (after the 10 days without rain). Do you think that could be used to expand the geographical area over which the approach could be applied? (Frank Göttsche).

Anonymous 2mo
In this respect another useful satellite LST product could be LSA SAF's DLST (LSA-003) product, which provides min, max and temperature amplitude for 10 day maximum and median composites.
https://landsaf.ipma.pt/en/products/land-surface-temperature/dlst/

Yanfeng Zhao 2mo
@Annu, thanks for your suggestions, could I contact you by email if I have some questions about your papers?

Yanfeng Zhao 2mo
@Frank, thanks so much, I think LSA SAF datasets could expand the geographical area, I will try to use this.

annu panwar 2mo
@Yanfeng offcourse I will be happy to discuss. My contact: apanwar@bgc-jena.mpg.de

Antoni Grau Ferrer 2mo

Using satellite-derived surface temperatures for atmospheric boundary- layer studies (Antoni Grau Ferrer)

- Analysis of AWS and satellite surface temperatures under sea-breeze conditions show that the thermal gradient is >= 5 C
- Other mechanisms are also relevant such as large-scale winds, soil moisture and locally generated winds
- A methodolgy is proposed to compute a chilling hours map for agricultural applications
- It is possibly to determine the variability in chilling hours

João Martins 2mo
Thanks for the explanations and for the very nice presentation! I would love to show you some of our results too!

Anonymous 2mo
Of course! Maybe we could meet next week and Toni could also join us. We could use zoom as well

annu panwar 2mo
Hey, I am interested to know what is happening physically in figure of slide no 8. I assume WS max is late in the night (+7 hours). Is it wind speed associated to breeze. Because normally wind speeds are higher at nights. What is the relationship of these winds to the temperature gradient? Thanks

João Martins 2mo
OK! You may reach me by email: joao.martins@ipma.pt

Anonymous 2mo
Annu. Thanks for your comment. Maybe the figure is not clear but for the PDFs in black you have to see the bottom z-axis amb for those in blue the top x-axis. Please. Goto the paper https://owncloud.uib.es/index.php/s/af68SwXAmLwdoRx and see the explanation of this figure. The strongest winds take place about 8h after sunrise and about 2h later the maximum temperature gradient. Therefore, winds are stronger during daytime.

annu panwar 2mo
Thanks!

Using LST in Land-Atmosphere Interaction Studies

Session 2

Exploitation of a combined use of Sentinel-3 fAPAR & LST data for primary production estimates (Roel Van Hoolst)

Using LST in Land-Atmosphere Interaction Studies

SESSION 3

Folwell, Sonja S. 2mo

Applications of an LST based diagnostic to evaluate soil moisture-surface flux relationships in land surface models (Sonja Folwell)

- Evolution of daytime LST and Tair anomalies contain important soil moisture information and can represent the changing ET dynamin during a dry spell
- RWR provides information on model SM-ET during 10 day dry spells
- Some areas are difficult to resolve due to clouds or short timescales involved

annu panwar 2mo
Hey Sonja et al, I really like the concept of comparing day to day warming rate. Please have a look on my published manuscript, where instead of day to day, I compare the diurnal warming rate of surface and air temperature for different evaporative conditions. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019GL082248

annu panwar 2mo
Here we tried (very simple model) to relate heat storage to air temperature warming rate.

Folwell, Sonja S. 2mo
Thanks Annu . Here 's some links on the method and global analysis https://doi.org/10.1175/jhm-d-15-0064.1

Folwell, Sonja S. 2mo
https://doi.org/10.1029/2019GL082962

annu panwar 2mo
Sonja, I will go through them,. Thanks

Constructing seamless MODIS LST maps for Australia from swath data (Kaniska Mallick)

Daily LST, MODIS Terra, Aqua, 1 km, Australia

- Seamless mosaics of MODIS Terra and Aqua day and night LST for Australia were produced for 2001 - 2016
- These serve as input to further SEB modelling and stress index calculations allowing the analysis of LST and ET patterns along aridity gradients

AlejandroDUSSAILLANT 2mo
@Sonja: nice work! What higher resolutions are planned to be implemented?

Folwell, Sonja S. 2mo
Thank you. I would to like to apply this to convection permitting models which operate on ~4 km. More grid boxes to sample over, but typically much shorter simulations.

Satellite observations of climate relations between LST, drought and biomass burning (Julia Stoyanova)

LST, drought, fire activity

- Results indicate that MSG IR LST retrievals can be used to identify the most drought prone regions on a regional level
- A generalised linear statistical model fits the relationship between LST and the released energy from biomass burning, showing that satellite LST can be a source of information in the climatic assessments of the energy release from possible wildfires and to locate the potential 'risly spots'.

Posters

Estimation of All-Weather 1 km MODIS Land Surface Temperature for Humid Summer Days (Cheolhee Yoo)

- New approaches for all-weather LST estimation are proposed for humid summer days.
- Thermal and passive microwave satellite data are fused using machine learning.
- The proposed two-step approach effectively simulates low LSTs in cloudy skies.

carlosjimenez13 2mo
Hi Cheolhee, interesting way of fussioning MW and IR data! A couple of questions: (1) Do you know what produces the largest S1-S2 differences at daytime? It may be interesting to look at that in order to perhaps correct the schemes and come out with just one (instead of mixing S1 and S2 predictions) (2) The MAST and YAST at 1 km that you use for the downloading, where do they come from? (2) Your ASOS in situ LST, is it publicly available? It's rare to have so many insitu data in a relatively small area, it could be used as testbed to evaluate RS data if the ASOS data is of sufficient quality.

Cheolhee Yoo 2mo
Hi, Carlos. Thanks:) In case of daytime, S2 uses more input variables in terms of spatial information for the machine learning model, so the temporal pattern (i.e., variable of microwave BTs) could relatively be loosen. However, for S1, we divided the variables into two-step where first step focus more variables which represent more temporal pattern of summer daytime. And then second step, we downscaled 10 km to 1 km LSTs using spatial detailed variables. This makes S1 could catch temporal pattern of summer daytime better than S2.

Cheolhee Yoo 2mo
(2) ACPS were processed by Dr.Benjamin- one of the co-author of this research. Check this paper too:) B. Bechtel, "Robustness of Annual Cycle Parameters to Characterize the Urban Thermal Landscapes," in IEEE Geoscience and Remote Sensing Letters, vol. 9, no. 5, pp. 876-880, Sept. 2012, doi: 10.1109/LGRS.2012.2185034.

Cheolhee Yoo 2mo
(3) Yes the ASOS data were publicly available from Korea meteorological administration. But I think It would be better that I could download the data for you if you request. Because the portable is preferable for Korean.

Cheolhee Yoo 2mo
This is the paper of the research : Remote Sens. 2020, 12(9), 1398; https://doi.org/10.3390/rs12091398

Airborne mapping and in situ validation of European land surface temperature using NASA-JPL's HyTES sensor (Mary Langsdale)

- Data acquired during joint NASA-ESA Temperature Sensing Experiment in support of LSTM mission
- Airborne hyperspectral measurements of LST, emissivity and reflectance collected with accompanying in situ data
- First time HyTES flown in Europe!
- Preliminary evaluation shows HyTES LSTs slight overestimation but within GCOS target requirements
- HyTES emissivities mixed agreement with in situ values

cebulgin 2mo
Hi Mary, thanks for adding your poster here. Your preliminary validation results are interesting. Do you know why the bias is higher when you include water pixels? Are these open water or inland water? I am thinking that inland water pixels are perhaps more likely to be 'mixed pixels' making the retrieval more difficult?

Mary Langsdale 2mo
Hi Claire, thanks for the Q.The water temperature measurements included in this comparison are from contact surface temperatures (thermocouples attached to the bottom of buoys) whereas the other ones were radiometric. As such, it is likely that they were measuring the temperature of the top cm rather than the skin temperature itself which we think is the cause. We do have radiometric measurements of the lake surface temperature as well but the timestamps of these data have been a bit corrupted so we're having to manually process them (hence why not yet included in the data). The measurements themselves were made in inland lakes that were all at least 10 x 10 pixels (given the small size of the HyTES pixels).

cebulgin 2mo
Thanks Mary - yes that makes perfect sense.

Validation for Sentinel 3 Land Surface Temperature Products (Emma Dodd)

- The LAW project aims to strengthen the validation of S3 data products, including LST.
- Initial work has identified priority sites to fill gaps in validation coverage for SL_2_LST and a validation methodology, based on the current state of the art, has been proposed.
- Deployment of new instrumentation is expected in late 2020 at 6 new sites. Data and documentation for these new sites will be made available by the LAW project.

João Martins 2mo
Hi Emma! Will these new stations be available for the scientific community? When can we expect the first measurements?

Emma Dodd 2mo
From LAW I believe the data will be available publically. We were due to deploy stations this summer, but Covid got in the way. We hope to go into the field in autumn, but if you some new data now then there are two GBOV sites (https://gbov.acri.fr/) we have deployed that might interest you in Australia and Spain. Australia is currently down after a bush fire (and delayed fix due to covid), but we aim to get this back up as soon as we can. We are also adding some of our own NCEO/UOL sites to GBOV soon that are not available elsewhere.

Anonymous 2mo
Also, if you follow me on twitter I will probably tweet about fieldwork so this may help you keep an eye on what data is forthcoming. @EmmaMayAnnDodd

Emma Dodd 2mo
Sorry, the above was me, padlet went weird...

Alternative and improved algorithms for estimating LST from Sentinel-3 SLSTR data (Frank Göttsche)

- 17 SWAs were investigated for retrieving LST from Sentinel-3 SLSTR data
- 9 of 17 SWAs with superior performance were identified via comprehensive evaluations
- All 9 SWAs have better accuracy than the official SLSTR LST product in validation
- The 9 identified SWAs provide practical alternatives for retrieving SLSTR LST

Simon Pinnock 2mo
Hi Frank, what was the best performing algorithm in the end?

Anonymous 2mo
Hi Simon, there was no big difference between the 9 SWAs; BL-WD (Becker & Li - Wan & Dozier) was used in the plots for demonstrating the in-situ validation results. The corresponding (in-situ) statistics for the 9 algorithms are provided in Tables 8-10. Their good performance for globally representative situations (simulation results) is summarized by Table 7 .

Meteosat and MODIS land surface temperature product validation with a new environmental satellite data calibration and validation station: Kapiti, Kenya (Tom Dowling)

- New cal-val site established in East Africa. A network of 4 masts observing all elements of the ecosystem.
- Finds that the new LSA-SAF all weather product performs better than ERA5 and MODIS.
- Evaluation of SLSTR and ECOSTRESS coming soon!

Simon Pinnock 2mo
Hi Tom, you should talk to Emma in the poster next door!

João Martins 2mo
Hi Tom, great to see that our all-sky LST is already out there :) Just a question, in the top plots. shouldn't the bias be negative? Or am I missing something?

The influence of land use/cover types on the surface urban heat island efect. Insights from urban areas of Southern Romania (Cristina Dumitrică)

investigates the LST-LUC interactions accounting for the surface urban heat island (SUHI) effect in eight selected cities of southern Romania, during the heat waves of July 2007 and 2012

cebulgin 2mo
Hi Christina, do you know how LST relates to near surface air temperature for your study region? I would think that the air temperature has the biggest impact on human heat stress so it would be interesting to see if that is also highest where the LST is highest and whether that varies with land cover?

Recent Advances in the Field of Satellite Data Uncertainties (Claire Bulgin)

Cristina Charlton-Perez 2mo
Claire, is the uncertainty budget time invariant?

cebulgin 2mo
Hi Christina - I think I could answer that question in two ways as I'm not entirely sure which you mean. 1) In one sense no, uncertainties are provided at a per-LST basis on the basis of the information used for that retrieval so will not be the same at the same location at the same time each day.

cebulgin 2mo
2) Uncertainties may also have a time correction component. For example, in the single sensor CDR the equator overpass times vary between 1000 and 1030 for the sensors that we use so we have to correct to a single time, which has an associated uncertainty for the correction.

Discussion Session 1: Uncertainties Introductory presentation

Discussion Session 1: Uncertainties Group discussion and summary

- Most users had used uncertainty but in such a way as to filter out bad data.
- This use led to the suggestion of having quality levels per pixel for identifying bad data
- There was much
- Other suggestions included: i) level-4 combined product for users as the main product from the project, even if this means higher uncertainty than single sensor products; ii) further breakdown of the uncertainty budget by individual surface components for instance to understand what the main causes of the errors are
- General feeling that uncertainty information is inadequately documented for operational products with details missing from ATBDs
- Request that uncertainty uncertainty is well documented in the LST CCI PUG with specific easy to follow examples on recommended use including how to propagate for different cases.

- Uncertainties predominantly used to filter data where the total uncertainty is greater than a threshold
- There is a balance to be found between filtering for the highest quality data and keeping enough data to be useful for the study
- Uncertainties provided can vary between products so it can be difficult to understand
- Discussion about appropriate thresholds for filtering the data, whether there is a value that is generally accepted. This very much depends on the application and region etc. but 2K could be a reasonable starting point
- Discussion about down scaling data and how uncertainties would be propagated through this process
- Regarding documentation, how far the documentation is looked into is dependent on the study - not everyone needs to understand everything in high detail
- It is very important that documentation is as good as possible with as much detail as possible, you never know when you are going to need it. Some products have poor documentation and this can be very frustrating for users!

Q1.
- Some are not using as they are new to the field and are not quite at that stage yet, but would like to found out more. This includes how uncertainties can be used and validated.
- Some are using it for quality control or data assimilation, either themselves or within their group.
Q2.
- Most use total uncertainty for quality control or data assimilation if used.
- One person's group uses the components in upscaling.
Q3.
- All in room are either using, planning to use or new to the field and not yet at the stage of using uncertainties (but would like to).
- Might be worth providing some links and material to those participants new to LST and LST uncertainties. Some links were shared in the chat to GlobTemperature Documents from previous user meetings and the handbook.
Q4.
- Merged GEO ATBD and user manual (project unknown) is thorough and useful for one user
- Some have had issues finding CCI specific information on the LST CCI website and had to ask project team for links.
- This should be looked at and addressed and this may be a barrier to both users and potential users of data.
Q5.
- For some applications this is not seen as essential (quality control). For others this is very important (upscaling).
- But Claire's talk was very useful in providing a background, even if users only need total uncertainty.

Q1.
- Used Lst but not uncertatitnies
- CCI products in SST and LST
- CCI /globtemp products used uncertainties
- Used ASTER LST glacial lakes tricky atmospheric correction issues so atmosphere component useful. Norway and Patagonia
Q2.
- Selecting pixels to use – would use components but not in the 0.01 deg. Product. Also use LandSAF and ECOSTRESS products similarly
Q4.
- Use the attributes in the netCDF files
- Not found - needs publicising more
Q5.
- Yes need information if propagating in data assimilation system
- Important to know what components are included and that its documented.
- Geolocation uncertainties important – looking at glacial lakes. Sufficient in CCI. Suspended sediment/scum.

- Most users have not yet used the uncertainty provided with LST products, but used instead quality flags to identify "the best quality" estimates and discard "poor quality" ones.
- However, uncertainty information is recognised to be important.
- The effective use se of uncertainty estimates will depend on the application. User must also gain confidence in the uncertainty values - validation of uncertainty estimates is therefore important!
- The appropriate way to use LST uncertainty information is still under investigation in most fields – including data assimilation.

- Guidance on how to use product uncertainty or examples on the use of LST uncertainty in different applications were requested. This was considered as important as providing the uncertainty description and/or breakdown.

- The group did not have experience with current documentation on product uncertainty - so there is nothing to point out at this at the moment, but the presentation made by Claire was very much appreciated.

- Indeed, knowing the sources of LST uncertainty and how these are propagated to the final product, as well as being aware of the various components of the uncertainty budget was recognised to be important and to potentially help users to better understand what is being up-taken by their models/applications.

- It was also pointed out that "uncertainty" often appears to refer to different things: products are often stamped with a given uncertainty (in the product specifications), which corresponds to an "overall vale" and is based/checked with validation exercises; or it refers to the estimate of model/algorithm uncertainty and propagation of input uncertainties.

- Overall, users are still learning how to use the uncertainty information - the main message is that guidance is needed!

Summary

- Users have used uncertainty e.g. to limit where the data is valid when comparing with other datasets, or to explain findings when comparing datasets.
- Sometimes uncertainty just came as a flag (e.g. low/high), so data flagged as low was discarded. When coming as a number, some users seem to set a threshold just based on leaving enough data to proceed their analysis, i.e., taking a pragmatic approach.
- Users comparing with their own insitu data also generate their own idea about how uncertain the product from this comparison, and probably trust more its analyses.
- Some users questioned whether the uncertainty breakdown is useful. It may be useful, but very dependent on application (e.g., very useful on data assimilation, but not so much when comparing datasets).
- Users seem in general worried about cloud contamination, and whether the current uncertainty deviation includes that component. They report that in many occasions the only way to remove cloud contamination seems to be a posteriori treatment of the data (e.g., looking for "spikes" in time series, or by comparing with other datasets at similar location and times), but that current uncertainty estimates are not capturing this yet.
- There is a general feeling that documentation on how to understand and use the produced uncertainty is missing, or not easily available. A report on paper with clear examples on how to apply and propagate the uncertainty for different LST applications will be welcome.

Comments

Simon Pinnock 2mo
I'd just like to reinforce Carlos's last point, that it seems many people don't really understand why you need to separate the uncertainty into components. There is a need for some straightforward documentation (e.g. a cookbook) on how to use these uncertainty components. I had a quick look at the LST_cci PUG, and didn't find much help in there.

Simon Pinnock 2mo
There was also a suggestion from Joao, that perhaps we could investigate whether ensembles of retrievals could be used to estimate difficult-to-quantify errors such as from failures of cloud-masking.

Simon Pinnock 2mo
Sorry, just remembered, that Joao also suggested trying to make use of the ERA5 ensembles to characterise the uncertainty in ERA5 inputs.

Simon Pinnock 2mo
ERA5 inputs to the LST retrieval, I mean.

cebulgin 2mo
That point about using ensembles for estimating cloud detection uncertainties is similar to what is discussed in this paper: https://doi.org/10.3390/rs10040616. For this you really need an ensemble of cloud masks or lots of coincident data in space or time from multiple sensors.

Simon Pinnock 2mo
Great paper, thanks!

João Martins 2mo
Thanks Simon! I definitely think that when the retrieval model complexity is too high, the best way to estimate uncertainties is through ensembles (which is actually what most numerical weather prediction models are doing nowadays).

Discussion 2: User Requirements Introductory Presentation

Findings from the LST_cci User Requirements Assessment (Lizzie Good)

- Approach to gathering user requirements for climate LST
- Online survey results
- Discussion questions

Discussion 2: User Requirements Group Discussion

Q1.
- Daytime averaged required, normalised to a given time (e.g. 12 noon). Is this covered by the requirements?
- No-one in room involved in the gathering, so hard to comment

Q2.
- Some wouldn't mind having this globally
- One thought it might not be used except for Africa subsets
- Others would like this as a future evolution, might be useful for models or to upscale MW

Q3.
- Internally to CCI, found easy.
- One user found difficult to get pixel overpass time from the data.
- Does the documentation cover this? And how to convert to other commonly used datetime formats.
- Suggested contacting the team if a specific product is having an issue here.
- Another wants to look at it if time, would like to know where to find it.
- Suggested contacting the team for access.

Q4.
- Could use it if it exists, but not an urgent need for one user.
- Another user: Some take 2 or 3 months, which is too long. Weekly would be good.

Q5.
- Yes would be of interest to most in this room. Especially for climate and validation (identifying homogeneity).

Simon Pinnock 2mo
There was also a comment that component LSTs could be useful for model validation, as models starting to provide similar info. Also on spatial resolution, important that the spatial resolutions of all the data sets used for model validation are coherent.

- There does not seem to be many requirements missed; however, some of the user requirements combined together may be difficult to achieve (e.g. high spatial and temporal resolution because of current sensor capabilities).
- Different applications have different needs and therefore different requirements.
- Spatial resolution is always a recurrent issue: fine or coarse resolution? This could be solved by developing platforms where the user can aggregate the fine-resolution stored data as required and over the areas of interest. That would require also uncertainty aggregation, which may be complicated to do in the platform.
- We were wondering whether the CCI toolbox may facilitate this type of processing.
- Not much experience on using the LST_cci datasets, as they are not publicly available. But one team producer in the room also used other project datasets and was greatly impressed by the formatting consistency between the different datasets, which facilitates to a large degree data processing and variable interpretation.
- Timeliness of data is dependent on the final goal of the products. For LST_cci, if if ends up as a C3S product, a very short latency may not be required as the goal will be to provide climate information. But it would be different if it was part of the Global Land Services, as the focus may be more on operational systems.
- Goals and processing will impact the timeliness. E.g., for climate services you may have to use inter calibrated L1B data and a more careful processing, while for more operational things the L1B data may need to come with a shorter latency and less quality controlled, and the processing may need to be faster and perhaps less accurate.

Q1.
- it is already a large list of requirements, however the requirements vary from user to user
- we discussed about the use of the uncertainty information, which is used by one participant mainly for screening for low quality data, not for uncertainty propagation
- one particpant would like to have correction for cloudy conditions (merging with MW data?) and might be interested to use in situ LST data directly
- one participant would be interested to use LST trends rather than absolute LST, yearly trends as well as day to day trends

Q2.
- for urban areas a scale of 300 m or less would be very useful
- these urban areas might be distributed globally, but then only a small subset of the global data set is needed

Q3.
- one partipant had problems with the netCDF data format with the IRIS python package, but this had been resolved after he gave feedback about it to Lizzie

Q4.
- (near) real time data (near daily) would be good to have for vegetational purposes, hydrological use

Q5.
- one participant pointed out it would be good to have it for validation of Earth System Models, however, if that means that the component LST are modelled (and not from high resolution observation), it would be less useful

- There was a general question on advice with regards to which product(s) to use when a user requires both high spatial resolution and high temporal resolution data
- General consensus that highest resolution gridded data possible should be provided rather than prescribing a set resolution like 0.05deg. This would then allow users to aggregate the data themselves to their required resolution. A consequence of this would be very well documented examples on how to aggregate the uncertainties.
- The CCI Toolbox or equivalent should be able to facilitate such aggregation of bulk data.
- Users are very happy with all CCI datasets having the same broad structure making datasets interchangeable in their applications.
- It would be good to have an update of the CDR with a timeliness of a few days, not necessarily NRT (ie hours). The purpose would be to enable assessment of contemporary climate events in the context of a longer "consistent" CDR.
- It could be seen as useful for modellers to understand the component temperatures but could be divided into components at coarser resolution by the end user (who understands their surface types better for their application) providing we provide the gridded data at the highest spatial resolution (ie the 0.01deg questions again).

Q1.
- There was a comment about some people finding it hard to use the L3 averaged data in the presentation, could it be of benefit to have an additional field containing the best data value for that pixel rather than the average?
Q2.
- Upscaling eddy covariance fluxes: a high resolution product is useful to match well with flux towers, whilst a 0.05 degree global product is useful for model runs. In future a 0.01 degree product could be useful for model runs, but some investigation would have to be done in how to handle the data volumes. Being able to process data on JASMIN might be really helpful here
- For surface urban heat island (SUHI) studies 0.01 degrees is a minimum requirement. The large data volumes are manageable but requires knowledge how best to work with it, which probably isn't needed for the lower resolution products. High resolution is absolutely needed for urban applications!
- Question about data production and availability of this 0.01 degree product. Some have been produced for UCS.
Q3.
- Noticed discrepancy in dimension / variable naming convention in SEVIRI vs MODIS products: in MODIS they were both lat/lon and in the other dimensions were lat/lon whilst the variables were latitude/longitude
- Using MODIS data, for each day there are different bits of the orbit in the file, so data needed to be tiled first, this isn't a problem but required extra processing
- An additional variable of local solar time would be useful: had to combine the timestamp in the file name with the time difference in the variables, again this is ok but requires extra processing
- Experiencing problems around coastlines with MODIS products. Using the LCC variable to find land pixels, but getting really bad data points, ended up masking 5 pixels inside the coastline
- Still some possible cloud contaminated pixels
- QC flags are provided with MW data but not IR so processing needs to be different. Clear sky info very useful in IR data, but QC flags would also be useful
- Question about whether there is a product user guide available
Q4.
- Real time data not needed for eddy covariance UCS
- In future, the users of the produced fluxes need annual updates of the data, up to the end of the previous year, for them it could be really useful to also have LST data updated annually to match this
- Real time data not needed for SUHI work
Q5.
- Values for each land cover type within a pixel could be really useful for SUHI studies where pixels can contain multiple types
- This could also be useful where matching pixels to flux towers - if a tower is measuring fluxes in a forested area, but the resolution of the satellite means forest and grasslands are in the pixels, having a value for the forest area would be really useful to improve the match
- Questions about how this would work and how reliable it would be

Q1.
- Overall the user requirements seem quite comprehensive!
- The question of priorities is interesting - can all of these be addressed or are some prioritised?
- One requirement for high resolution LST <1km was mentioned in yesterday's discussion.
- There was significant discussion about the quality information and how this is presented to users. In some cases the use of bit encoding may be difficult to interpret. Clear examples could help with this in common programming languages.
- A per-pixel quality level might also be a useful piece of information, but the question on how to determine this is open as it may well be application specific.
- There was also mention of data selection tools for various regions and data checking via quality information.
Q2.
- For model evaluation/NWP data would immediately be aggregated to coarser resolution. Documentation on how to do this with correct uncertainty propagation would be useful.
- Need for high resolution data is very application specific. It would be needed for things like fire scar monitoring.
Q3.
- Only one user so far, L3 MODIS to generate a time series. No issues using the data. Not a previous user of GlobT data.
Q4.
- In a perfect world close to real time would be very good. Some applications need anomalies or want to look at current events and for that you need the data.
- A 1 month delay would be good. There seemed to be support for progressing to more operational funding eg. Copernicus like the originally funded set of CCI projects eg. soil moisture.
Q5.
- Some discussion was had about component LSTs and their uncertainties, and the links to spatial variability within the grid cell and how best to represent this.
- Uncertainty in the land cover classification would feed in here.
- Such data has been really valuable in projects such as ECOSTRESS.
Other points:
- Spatial aggregation of data to coarser resolution and how to deal with uncertainty correlations dependent on biome was discussed - this is a difficult question and users would like some guidance on the recommended best practice.

Q1.
- NRT (1-3 day)
- Temporal trend info
Q2.
- 1km is useful but for urban and (smaller) catchment scales, 300m or less is needed
Q4.
- NRT (1-3 days max) for vegetation management (e.g. irrigation)
Q5.
- Ideally at least separate vegetated versus non-vegetated (e.g. pavement, bare soil etc)

Discussion 3: Climate Services Introductory Presentation

Underpinning science to a climate service: Examples from CSSP China (Tyrone Dunbar)

- The process of developing a climate service
- Case studies of climate service development from a research programme in China

- Question: how well established are services within the satellite community? Quite mixed, with data producers and users, who will have varying awareness of services and what is involved in creating them.

Data availability and format
- GlobTemperature data was available through the climate data store, with a link to the project data and other related products
- The current format of data is aimed at scientists or specialists, and would realistically need some level of processing or presenting for use by non-scientists
- There is a range of scales over which the data is required - for example long term data for trends, or high resolution data for urban studies, it could be challenging to provide pre-processed data that is appropriate for all these uses

Required information and resources
- Cloud services could be used to hold the data, then a set of tools could be provided to allow users to interact with these data
- Tools have been provided in previous projects to help extract data that a user wants, returning a smaller dataset, but these havent been investigated in this project yet. These tools dont process the data though.
- Other projects have provided e.g. jupyter notebooks with tutorials on how to process data on the cloud
- This could still be too much for a non-scientist/specialist?
- Some work has been done trying to identify non-specialist users of datasets, and none have been identified so far, all users are of a technical background
- Could governments be interested?
- Discussion on who is responsible for identifying users: there are different actors in the process of providing a climate service, from the user to the data providers, often with boundary actors in between. These boundary actors often take the role of identifying users and requirements.
- Decision makers: real time data could be important for example heatwave or drought monitoring, but for these people netcdf data requiring processing with e.g. python likely wouldn't be useful, they would need the data to already be processed. A graphical web interface could be more useful with maps etc.

Documentation:
- Need to think about who is actually going to use the data and make sure it is appropriate for them. This is likely to be scientists / specialists not the final user
- Users often want examples of data which aren't often provided, these would be useful with this data
- Need to make a bridge between what a user wants and what is actually possible with the data / resources available, then can work on making a useful service. Examples of what can be done are really useful here, especially when linked to a previous scenario the user cares about. E.g. how a service would have helped make better decisions.
- Also important to think about where information is kept, for example providing a document which initially goes into great depth and detail, then ends with a couple of examples of how to use the data might mean the reader has lost interest before they get to the information they need. These sources of information could be kept in different places.
- Providing infographics with examples of how the data/product can be used can be useful
- Are workshops on specific aspects of the data / products useful, e.g. one held on uncertainties?
- Can be useful to be shown how data is used, and also the way information is conveyed is important, it doesn't need to be in depth but clear. Having different means of communicating this info could help with this

Analysis ready datasets
- Little experience of these within the group
- Looked at example of Landsat ARD
- Could see this being useful in a climate service
- Easier to then provide e.g. graphical interface on the web for a user to explore the data with if data stored in the cloud
- Would be large overhead on someone close to the data producer to put the data in this format
- Really need to understand what the user needs before this can be done
- Reduces flexibility in data processing as some is already done, but makes it easier to work with - need to find the right balance

Discussion 3: Climate Services Group Discussion

Data availability.
- LST data sets not always at the temporal or spatial scale needed for neighbourhood. Urban heat, needs both spatial and temporal but perhaps not simultaneous.
- Demonstrate usage of data, in heat waves/ droughts. Requires manual processing per project. EUMETSAT Toolbox was found to be very useful.
- There needs to be greater clarity that the LST is very different to the 2m air temperature.
- We could add this into the meta data / documentation to cater for non-specialists
- We should also promote the benefits of LST, not just point out the fact that it is not 2m air temperature.
- Format is highly important, moving away from hdf toward NetCDF.
- Many GIS packages can use NetCDF even if users are unaware that they can do so. We could try to promote this more to reduce the caution in using them.
- European Data portals need to have better ease of access to data. Sentinel 3 highlighted as a particular issue. If people cannot get the data easily they will go elsewhere.
- Data visualisation at the portal level helps the user select the data they want easily.

Additional resources
- Encourage users with tools, example software.
- Provide help to convert the data into other formats
- This could encourage new researchers to adopt cci_lst data
- Intercomparison within climate (model) studies really does need NetCDFs
- CCI standardisation across projects makes this a realistic possibility

Documentation
- Basic user guide is good for quick reference and engagement
- Avoid repeating in the documentation i.e. keep algorithm details out of validation reports.
- Provide inter-links to the relevant documents
- Product user guides are far too long and put off users reading them
- A user guide version of an executive summary would be very good.
- This also was highlighted as key in the uncertainty discussion
- Maybe a brief PowerPoint outlining this
- Maybe a short video (youtube) on how to use the data

Analysis Ready Data
- Less about the science of the algorithm, more about the usability of the data across projects/disciplines
- Done in a set projection readily accessible
- Downstream users with no science background should be able to pick up the data and use it
- Datacubes and dataset stacking is of particular interest in the urban regions.

Unfortunately there was little awareness of climate services among the participants, so we did not have much to contribute directly on the seed questions. But here are the main issues we did discuss:

- There was generally a lack of clarity over what is a climate service versus, say, a long-range forecast. Examples were suggested, including the use of future climate projections to help make decisions on selection of crop varieties to plant for different future heat stress regimes, or using LST to locate hotspots that would indicate high vulnerability to future heat extremes.
- LST has great value in developing diagnostics for model calibration and validation, and there seems to be growing interest from modellers to use LST, particularly now that models start to include vegetation. Some modellers are overwhelmed by the large variety of single-sensor satellite LST data sets, and are waiting for a quality-assured global merged data set that captures the diurnal cycle to become available.
- Assimilation of LST is rare, due to its impact on Tair in models that have never needed to worry about getting Tskin right. Also, high temporal and spatial resolution satellite LST can be large resource-consuming data sets.
- Tair is much more commonly used than LST, often for simple reasons of historical inertia, so it's important to clearly communicate the availability ad benefits of LST data sets, and the differences between LST vs. Tair. For some applications, LST has advantages over Tair, particularly for vegetation stress. We need to make stronger efforts to raise awareness of the availability of satellite LST, particularly outside the surface energy balance community. It was suggested to perhaps write an LST-focussed white paper in a journal dedicated to climate services (or BAMS, perhaps). It might be helpful to write-up illustrative examples of where LST has already been successfully employed in different applications/services.
- On Analysis Ready Data: Focussed efforts are needed to provide large satellite data sets to users in a way that makes them easy to use. E.g. by providing server-side pre-processing facilities to subset or quality-control data in advance of download. It was suggested that the CCI Toolbox could play a role here.

- Regarding data format and accessibility, online tools which do not require users to be experts on the data, could prove to be highly useful. This is especially the case if they allow choosing the area of interest, or extract/analyse time-series/ doing most of the processing online without downloading large amounts of data.
CCI data portal provides some of these functionalities (widowing, time-series, extracting pixels/windows) – further improvement is encouraged.
- Tutorials on how to handle the data/plot the data (e.g., in a python notebook, other languages such as R) would definitely be useful.
- Cloud infrastructures where the LST would be available together with other variables/ data sources (satellite observations and products, ground observations, model fields) would also be highly beneficial, especially if these have enough computing resources to allow most of the heavy data analysis to be done without downloading the data.
- Engaging with users will be the best way of ensuring that documentation is useful. Unified/standardized documentation among different variables or datasets is welcome (e.g., as in LPDAAC, https://lpdaacsvc.cr.usgs.gov/appeears/)
- Examples of applications on how to use the data would also help.
- The group is ware of ARDs prepared/under preparation for specific areas (continental or local scale), e.g. Landsat ARD (https://www.usgs.gov/land-resources/nli/landsat/us-landsat-analysis-ready-data?qt-science_support_page_related_con=0#qt-science_support_page_related_con)
- User's perception that (ground/in situ) observations are "the ones to be trusted" seems to apply to models and also to satellite estimates, including LST. Users disregard the fact that ground observations may not always be representative of the area they are interested in.

Trends in LST: A Stability Assessment of the LST_cci Products (Freya Aldred)

- Generally good correlation between LST and T2m data
- Initial stability analysis of multi-sensor beta products shows non-climatic discontinuities
- Initial trend analysis of trends in MODIS products look promising

AlejandroDUSSAILLANT 2mo
nice work and presentation! As I mentioned, would be nice to select areas with negligible land use & other changes, to study trends ((I have seen papers based on the argument that as LST are increasing that is a proof of CC, without controlling for LU and other changes...)

Francesco Fusto 2mo
Hi Freya, regarding your presentation I would like to ask why you don't use also GEO data (Seviri in ex. over Europe). Also in the station comparison (Aqua Modis) you downscale to match point location ?

cebulgin 2mo
Hi Freya. Thanks for a very interesting talk. On the point of assessing uncertainties in trends this recent paper looking at trends in SST might be of interest: https://doi.org/10.1038/s41598-020-64785-9

infolstcci 2mo
Alejandro, yes I agree it would be really interesting to look at the trends for separate land cover, and since the data are provided with the land cover class this should be easy to do. I'm not certain I will have time to include it in this study but perhaps in the future!

infolstcci 2mo
Hi Francesco, I haven't included the GEO datasets as at present they only cover a short time period, which generally isn't enough for trend analysis. I don't do any downscaling, I simply match the closest pixel to the station location

infolstcci 2mo
Thanks Claire, I'll take a look!

philippreiners 2mo
Thank you for this very interesting presentation. I am also planning to do similar comparisons with our AVHRR LST product, someday. I would be very happy to be kept updated about your work and findings, but unfortunately I cannot find you on researchgate. Is there another possibility to follow your work?

Discussion 4: Future Climate Assessments Introduction Presentations

BAMS State of the Climate Overview of "Global Climate" Chapter (Robert Dunn)

- What is State of the Climate
- Key results from 2018 report

Discussion 4: Future Climate Assessments Group Discussion

- Using LST in something like the BAMS state of the climate requires it to be a bit more operation or near real time.
- C3S could be a route through to operational development as with other ECVs.
- We need to convince the community of the value of LST as compared to other products such as T2M which more directly relate to the temperatures felt by the population.
- It is challenging to provide both LST and T2M datasets of an appropriate length.
- A good starting point would be to provide monthly anomalies of LST on a regular basis, and close to real time. This would help users to grasp how to interpret these data, but they would need to be produced in a manner consistent with Climate Data Record production.
- There is an need to educate the wider community on the difference between LST and T2M.
- LST is closely linked to the surface energy balance - making this connection could put us in a good position to relate this directly to climate.
- There are some challenges for sparsely observed regions - both high and low latitudes including deserts and the Arctic.
- There is a wealth of satellite observations over the polar regions but cloud detection is particularly challenging here.
- Absence of observations in the IR over cloudy regions was mentioned, but all-sky microwave observations could be helpful here.

Anonymous 2mo
- LST over the Arctic region would complement the T2m record which is sparse over this region. With this region experiencing fast change it is critical to confront knowledge gaps with high quality LST over permafrost, ice sheets, and sea-ice. Cloud masking is a big challenge which needs improvement and currently there is no sea-ice surface temperature from CCI.

Anonymous 2mo
- For transitioning to C3S we need to evidence the climate quality of the LST CDRs and then lobby C3S

ardye 2mo
Hi all, I think that there is a very strong case for using LST for assessing the Arctic Amplification of Climate Change, although it would require a lot of work to be done. As mentioned there is a serious paucity of current observational data, so LST could provide a big advance in assessing spatial patterns of 'temperature trends' and give a pan-Arctic view. Including assessment of sea ice temperatures as Emma mentioned (onset and spatial pattern of melt dates etc). Obviously there are a lot of challenges with this, cloud masking as Darren mentioned and I imagine atmospheric correction could be tricky in maritime areas, as well as other issues. But I think having reliable LST dataset for a large remote area that is undergoing substantial and rapid changes is of high priority. Ideally I guess this would require a longer lower spatial resolution dataset for overall trends but also higher spatial resolution dataset for looking at extreme events.

ardye 2mo
Also think LST could be valuable in relation to snow cover trends/anomalies over Siberia and influence on atmospheric circulation.

The comments on the right were posted below the discussion seed questions on the Padlet.

Appendix E - LST_cci User Workshop 2020 Zoom Chat

The following table presents the contents of the Zoom 'Live Chat' facility. Participants were discouraged from holding scientific discussions using this facility and were instead encouraged to use the Padlets. Comments considered scientifically irrelevant (e.g. indicating a technical issue, thanking a presenter for their presentation, someone indicating they had a question but not specifying the question, etc) have not been included. The name of the postee and the time of the post have not been included. However, the comments are grouped according to the relevant presentation or session. Some comments have been edited with a 'light touch' to improve readability. Most of the comments below are questions that have been posed to the presenters and are included here for reference.

Overview of the LST_cci Project and Products (Darren Ghent) • Great summary Darren - what are the main challenges to go below 5km to 1 km or less?
First results of the LST_cci validation analysis (Maria Martin) • Maria: to compare in-situ data with MW, do you interpolate point data so as to compare similar area-averaged values to MW? • Maria: what is producing the bands changing sign of bias over Africa? • Maria: Similar to Alejandro's question, how are you conducting the upscaling of the in situ data to the different satellite products? • Maria: what is the difference between MOD11A (standard MODIS LST product) and MODISA? • this is likely the view angle [*believed to be in response to the question above 'what is producing the bands…..'*]
On the validation of the All-Sky Land Surface Temperature product based on MSG/SEVIRI observations (Joao Paulo) • Joao: The EB model is a land surface model, how do you apply it for inland water? • Do you see spatial inconsistencies where you transition from the traditional clear-sky to the cloudy-sky LSTs? • Hey, very nice talk. What can be the reason for the phase difference in ERA5 LST? Is it because of their different way of obtaining LST than your products?
Multi-decadal validation of the TIMELINE AVHRR Land Surface Temperature product with MODIS and in situ LST (Philipp Reiners) • What are your plans to fully assess the stability/homogeneity of the TIMELINE data? This is needed before any correction can be derived, I think. • Can I ask a question about the sensor consistency? • Nice results and presentation! Do you have any explanation for the very good results over DRA Station (compared to other satellite LST)? • We would welcome the opportunity to intercompare our [CCI] datasets with your TIMELINE product - we should discuss offline • How is orbital drift between the NOAA satellites accounted for? • Maybe a basic question, I look on the differences in surface and air temperature. Usually, global warming is quantified in terms of air temperature. You show global warming in terms of LST (land surface temperature). I would like to hear your thoughts on the difference in warming of the surface and air temperature. Why do you think we should go for LST and not air temperature?
Developing ESA's LSTM for the next generation of High Spatial Resolution Thermal Remote Sensing (Mike Perry)

- What is the 'OE' algorithm?
- Nice presentation Mike - what about accuracy & precision on Trends as opposed to absolute LST values (i.e. increase/decrease in LST)?

Recent progress on the global ET product with the thermal energy balance method (Xuelong Chen)

- bear with my ignorance: how does the method separate vegetated versus non-vegetated land cover and assign ET to actual vegetated land (Tcanopy-LST relation)? Could this explain some of the apparent deviations?
- How do you gap fill in places like Amazonia during rainy seasons where the vast majority of overpasses are cloud-affected?
- I'd have a question: Could you provide more details on how you combined terra and aqua in the gapfilling?

The role of LST characteristics in the data-driven simulation of land-atmosphere fluxes (Sophia Walther)

- Hi! Have you looked into our (LSA-SAF) GPP product?
- https://landsaf.ipma.pt/en/products/vegetation/mgpp/
- @Sophia: Any comment on validating the corrected LST after applying the Kernel hotspot normalisation?

Underpinning science to a climate service: examples from Climate Science for Services Partnership-China (CSSP-China) (Tyrone Dunbar)

- Nice work Tyrone, the climate service loop is great conceptual model

Exploitation of a combined use of Sentinel-3 FAPAR & LST data for primary production estimates (Roel Van Hoolst)

- @Roel: what air temperature do you compare with LST? How near the surface and how do you measure it (sampling "control volume" and how do you account for interference from sensor temperature)?
- @Roel: on the GPP for the cropland site, is it harvesting you see in the in-situ measurements but not in the retrieval? Or did I miss something?

Using satellite-derived surface temperatures for atmospheric boundary layer studies (Antoni Grau Ferrer)

- Very interesting study, especially the use of LST and SST to better understand land-sea breeze. I would like to know what explains the phase differences you showed for wind, temperature gradient diurnal cycles. Is it something standard (~5 degrees Celsius of thermal gradient) or it may vary ecosystem to ecosystem?
- Interesting sea breeze characterisation. Did you see reduced LST and sea breezes in the days after heavy rain, when evaporation is more important?

Sensitivity of diurnal cycle of LST to the soil moisture detected from combined LST, SM, precipitation observations (Yanfeng Zhao)

- how can you compare your result with other literature with different season?
- Are the night-time LSTs in the Sahel sensitive to the presence of high water vapour in the atmosphere modulating down-welling LW at the surface? I know that this effect is important for air temperature variability during MAM in the Sahel
- Can you quantify, by how much temperature decreases with an increase in unit soil moisture? Why not look at air temperature. Also, how do you correct for the contribution of solar radiation on LST, which varies with latitudes. I work on similar objectives. I find vegetation very important to consider.

Global and regional trends in LST (Freya Aldred)

- Re: use LST for trend analysis - what if select area where there has not been land use (& other changes)?
- Nice work... have you compared trends from Aqua and Terra? Are the trends consistent?

- How will you complement LST for T2m analysis? Is it driving T2m data using LST?
- Congratulations for the work Freya. In case you're interested, we just published the paper "Surface Temperature of the Planet Earth from Satellite Data over the Period 2003–2019" in Remote Sensing and is available online: https://www.mdpi.com/2072-4292/12/12/2036
- Are we expecting the same trends from LST and T2m?
- (I have seen papers based on the argument that as LST are increasing that is a proof of CC, without controlling for LU and other changes...)

BAMS State of the Climate (Robert Dunn)

- I would like to raise a basic point. First, we need to convince scientific community why not T2m and why LST. Of course data availability and all. But I find people relate more to T2m than LST. Also, LST is complicated, (is it skin temp, radiative temp).
- Also limited air temperature observation data set across the Arctic.
- Global temperature trends obtained from air temperature data can be replicated with surface temperature obtained from satellite data.
- Directly use current LST would be hard since if we want to have a consistent assessment based on LST similar with T2, the data length, accuracy, and stability can be challenges. At NCEI, we are currently updating climate normal, which is based on thirty year observations between 1980 and 2010. We don't really have an operational climate quality LST product last that long. When we are looking at extending with AVHRR data, the orbital drift made it rather difficult to get the stable dataset. Last, the accuracy of the current LST data is likely larger than the signal we can see in the data itself. LST CCI is a great step forward, but moving to operational climate quality LST data is important. Maybe some lessons can be learn from SST community such as the development of OISST data.
- Totally agree with [*what was said*], if we could produce up to date monthly anomalies which are critically underpinned by the long-term CDR
- The Arctic is a specific area which is experiencing large changes, and T2m observations are sparse but satellite observations are very plentiful. Consistency with Permafrost CCI is crucial. A big challenge over the Arctic is to improve the cloud masking for LST.
- Comment on Arctic: consistency with snow cover CCI is also needed as this influences the accuracy of the LST.
- Also, could LST potentially be useful for assessing the spatial extent of Arctic Amplification of Climate Change? Obviously would ideally require a 30yr+ dataset.
- To follow up on Arctic: we don't have sea ice surface temperature in CCI yet. For the Arctic as a whole, this must be included.
- And atmospheric correction over the maritime areas of the Arctic would be tricky.

Applications of an LST based diagnostic to evaluate soil moisture-surface flux relationships in land surface models (Sonja Folwell)

- Very interesting! Your relative warming rate index is similar to my diurnal warming rate, maybe you want to have a look at it. How do you account for the heat storage in the atmosphere for the air temperature's relative warming rate?

Construction seamless MODIS LST maps for Australia from swath data (Kaniska Mallick)

- The challenges Kaniska mentions again raises the question of resolution and processing level actually required by the users
- Yes, but we cannot cover all specific needs :)

Country-scale climatology of the Surface Urban Heat Island using MODIS (Sorin Cheval)

- I have a question on the comparison between MODIS LST and TAIR from stations.

Investigating the Seasonal SUHI Intensity Hysteresis Curves in Europe (Panagiotis Sismanidis)

- Is the difference in SUHII [Surface Urban Heat Island Intensity] strength between spring and autumn rather due to urban temp or rural temp?
- I have a question too related to methodology
- I would guess that given in autumn vegetation is senescent, rural temp is similar to urban temp
- I have a question related with the vegetation
- Is there a reason to exclude forest land cover from the rural?
- Hi all, In case you're interested, we just published the paper "A Methodology for Comparing the Surface Urban Heat Island in Selected Urban Agglomerations Around the World from Sentinel-3 SLSTR Data" in Remote Sensing and is available online: https://www.mdpi.com/2072-4292/12/12/2052

Feedback from Uncertainties break out group (Claire Bulgin)

- The ILSTE group could be a forum for a "community" standard
- Quality Level flags was an idea we first discussed in GlobTemperature days and it would be informative to know whether this is something that would be really helpful for the users
- Users frequently need to upscale data. I think the propagation of uncertainties when upscaling is a major barrier to using them as this process is non-trivial. To encourage users to use uncertainties (and the data properly), it would be very helpful if tools are provided to e.g. re-grid data that propagates the uncertainty components.
- I think the current PUG contains only half a page on the uncertainties. Perhaps we need to be more complete in this sense, and have more information also there.
- Already asked, but noting here for the record: the requirement for pixel and file quality information was identified in the user requirements document, e.g. 'worst quality', 'best quality', etc.

Feedback from user requirements (Freya Aldred)

- We all want high resolution data, but we should not forget our current sensor capabilities.
- Overall question is whether gridded products should be at the highest resolution possible for the given sensor, and the highest common spatial resolution for merged products ?
- Not everyone wants high-res data! For some global or even regional climate analysis, 0.05 deg is too high. 0.5 deg or even coarser is fine.
- Therefore perhaps the need of having platforms where the highest resolution possible is stored, and the user does his/her required aggregation.
- Yes, but note my point earlier: users will struggle to aggregate uncertainties. Need something where users can output the data set at the temporal/spatial resolution they need, produced centrally with consistent processing.
- Yes, I was going to suggest the same as Carlos. Maybe we should a consider an online tool where users can aggregate data prior to download
- that handles all the uncertainty propagation
- Agree, the tool should be clever enough to also do a proper aggregation of uncertainties.
- I think there are already a few cloud computing tools for Copernicus and sentinel
- maybe we can use those
- https://www.wekeo.eu/
- This would be complicated by the fact that the tool needs to offer options for quality checks and filters (application dependent) before aggregation
- in the case of this tool, the processing is done through Jupyter which means that users can edit if they want. The code would be fully available

Feedback from Climate Services (Lizzie Good)

- Another good one: https://gfcs.wmo.int/what-are-climate-services
- For info, a journal dedicated to climate services: https://www.journals.elsevier.com/climate-services/

- ARD [*Analysis Ready Data]* is a very active discussion in CEOS but some debate still on the specifications
- Example of a tutorial video: https://www.youtube.com/watch?v=Ze1PC9Y-FZo
- maybe make the workshops more "hands on"
- I think there is need to bring another group of participants into the discussion of data format/accessibility/usability, which are the data engineers / curators. NOAA and NASA have invested in the past twenty years to engage users and engineers via Earth Science Information Partners (ESIP) and other international groups to improve the usability of the data. I think CCI could also benefit from similar engagement.
- I think I can comment on non-specialist users
- Our current PUG goes over 30 pages I think, something to think about?
- LP DAAC has a data processing (e-learning) website with materials, jupyter notebooks etc : https://lpdaac.usgs.gov/resources/e-learning/
- maybe have examples in a different document
- Some training resources: https://dmtclearinghouse.esipfed.org/browse
- and more here: https://dmtclearinghouse.esipfed.org/search/dmt?mefibs-form-dmt-search-fulltext-homepage-search_api_views_fulltext=&mefibs-form-dmt-search-fulltext-homepage-search_api_views_fulltext_1=&mefibs-form-dmt-search-fulltext-homepage-mefibs_block_id=dmt_search_fulltext_homepage
- Within the SST community we did have a hands-on workshop on uncertainties. We have also done hand-on activities within GlobT on uncertainties.
- yeah, Data Management Clearing House provided by Monika is a great effort from ESIP with the support from NASA and NOAA to create a hub of how-to resources for using Earth science data in general. There are also regular webinar training with recordings for specific sensor data / products for users as well.

Appendix F - LST_cci User Workshop 2020 Feedback Survey

The following pages present the results of the workshop feedback survey. A total of 53 responses were received. However, respondents were not obliged to answer every question. Respondents could provide multiple answers to some of the questions (2, 3, 5, 7, 8). However, from the results it is clear that several respondents only provided one answer for questions where multiple answers could be selected so the results should be interpreted with care for these questions.

The number of respondents that selected each option is provided in each table of results in the column 'n'.

Where respondents free text answers have been included in the sections below, these have been edited for spelling and grammar, but without changing the overall meaning of what has been stated.

---

1. Please select the response that most closely matches your attendance of the twelve live Zoom sessions 24-26 June.

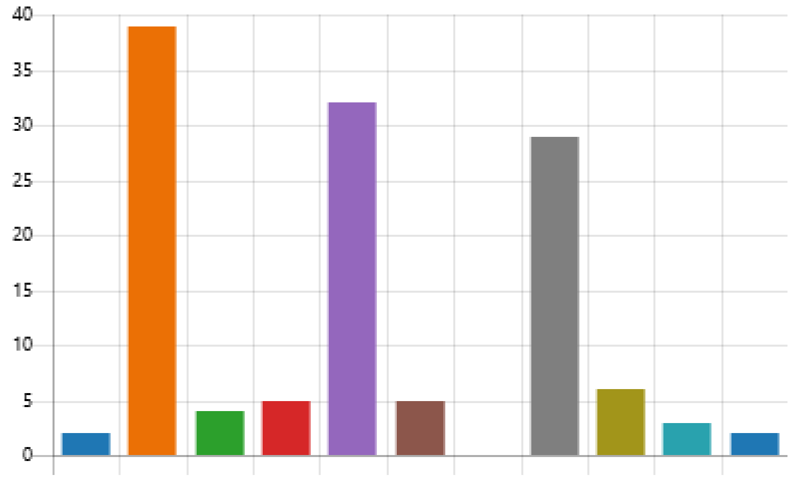
	Question 1	n
🔵	I did not attend any of the live sessions	0
🟠	I attended most or all of the live sessions	32
🟢	I attended some of the live sessions	15
🔴	I attended one or two of the live sessions	6

Key points:

- The survey was only answered by people that attended at least one or two of the live sessions.

2. What was your experience of the live sessions? Please select all that apply.

	Question 2	
●	I did not attend any of the live sessions	2
●	The 1-hour length of the live sessions was about right	39
●	I would have liked longer live sessions	4
●	I would have liked shorter live sessions	5
●	The breaks between each live session (30 or 60 minutes) were about right	32
●	The breaks between each live session (30 or 60 minutes) were too long	5
●	The breaks between each live session (30 or 60 minutes) were too short	0
●	The number of live sessions was about right	29
●	I would have liked more live sessions	6
●	I would have liked fewer live sessions	3
●	Other (see free text comments below)	2



Free text answers for 'Other':

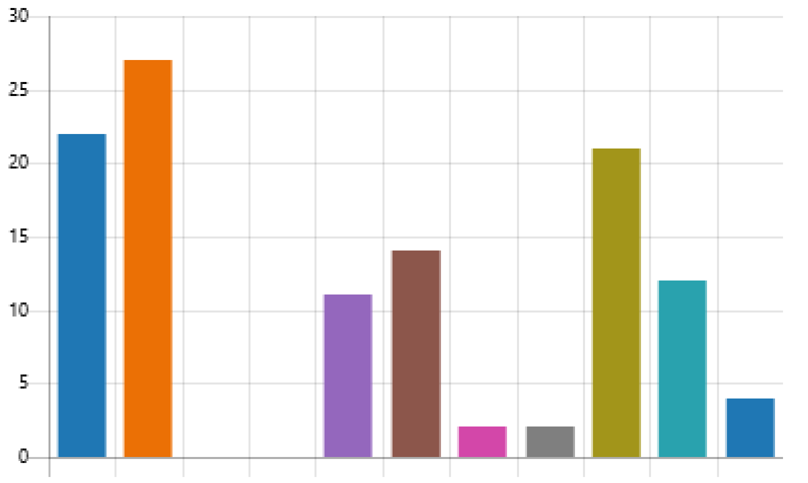
- I initially thought the 30min coffee breaks were a bit too long, but in fact it provided a useful opportunity to look at the posters on padlet.
- I would have liked a live poster session
-

Key points (caveat: not every respondent selected multiple answers):

- The majority of respondents thought that the 1-hour length of the live sessions, the 30-60 minute breaks between live sessions and the number of live sessions was about right.
- A few respondents felt that they would have liked longer or shorter sessions and more or fewer live sessions.
- A few respondents felt that the breaks between each session were too long. No respondents felt the breaks were too short.
- On respondent suggested a live poster session.

3. What was your experience in the break-out discussions during the live Zoom sessions? There were three break-out sessions of 40-minutes in length, with approximately 7 people per break-out group. Please select all that apply.

Question 3	
I did not attend any of the break-out discussions	22
I enjoyed the break-out discussions and would like to see similar break-out discussions at future events (face-to-face or virtual meetings)	27
I did not enjoy the break-out discussions and would prefer not to attend similar sessions at future events (face-to-face or virtual meetings)	0
There were too many people in each break-out group	0
There were not enough people in each break-out group	11
The number of people in each break-out group was about right	14
The break-out discussion was too short	2
The break-out discussion was too long	2
The length of the break-out discussion was about right	21
The value of structured break-out sessions, e.g. to the project team, is clear to me	12
Other (see free text comments below)	4



Free text answers to 'Other':

- It turned out difficult to start a real discussion in situations/ groups when too many people did not have comments to give or experience or where hesitant to participate in the discussion, but the other way around, in situations with active people the discussion can become very fruitful, I experienced both during the workshop and do not see anything that you as organizer could do about it.

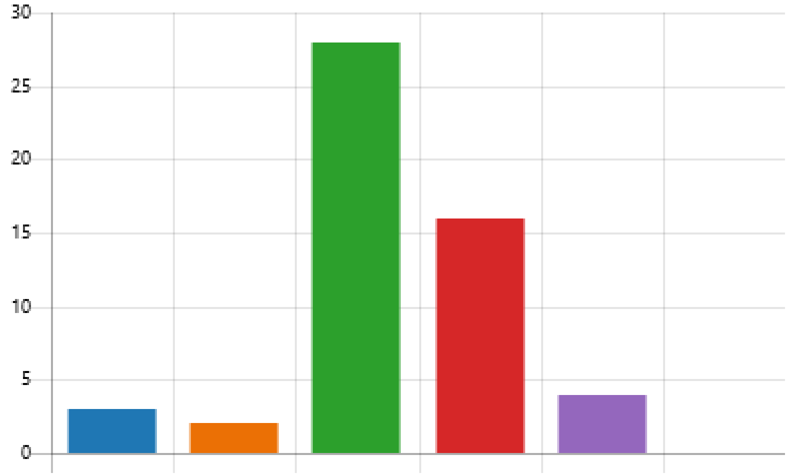
- Perhaps face to face video could work during the smaller breakout sessions and make dialogue less awkward?
- Break out session were very well organised. Although, being alien to most of the people in breakout session, I could not participate my 100%. I attended 2 or 3 breakout session. At some point I felt scientists are discussing their work to other possible contributors. Maybe I felt a little bit left out. But maybe I am very early career scientist and need to learn more to enjoy the breakout session.
- In some break-out groups the participants did not contribute to the discussion

Key points (caveat: not every respondent selected multiple answers):

- About 40 % of the survey respondents did not attend any of the breakout sessions
- At least 50 % of respondents reported enjoyed the breakout sessions and would like to see similar breakout discussions at future events. No respondents reported not enjoying the breakout sessions.
- There was a fairly even split of respondents that felt there were either not enough people in each group (11 respondents) or that the number of people was about right in each group (14).
- Of the respondents that commented on the breakout session length, 84% felt the length of the breakout sessions was about right. The remaining 16 % were equally divided between the sessions being too long or too short.
- Only 12 respondents confirmed the value of the breakout sessions was clear to them.
- One respondent commented that perhaps using face-to-face videos during the breakout sessions would have helped the discussion
- A couple of respondents commented that some of the discussion sessions were difficult and they felt they and others could not fully participate.

4. Please select the response that most closely matches your use of Padlet during the workshop

Question 4		
● (blue)	I could not access Padlet	3
● (orange)	I chose not to participate in the offline workshop component on Padlet	2
● (green)	I only used Padlet on a few occasions during the workshop	28
● (red)	I used Padlet many times during the workshop	16
● (purple)	I used Padlet almost constantly throughout the workshop	4
● (brown)	My primary participation in the workshop was through Padlet as I could not attend the live sessions on Zoom	0

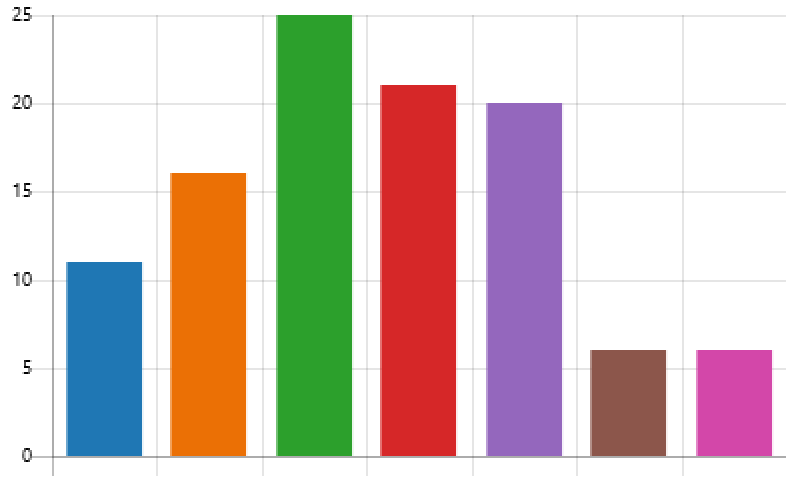


Key points:

- 3 survey respondents could not access Padlet during the workshop, while 2 respondents chose not to participate in the Padlets.
- However, Padlet was generally quite well used by the survey respondents: The majority of respondents (28) only used Padlet on a few occasions, but 16 respondents used Padlet many times during the event, while 4 respondents used Padlet almost constantly through the workshop.

5. What was your experience of the 'offline' component of the workshop? This includes viewing presentations and participating in discussions on Padlet, and watching the recordings of the live Zoom sessions. Please select all that apply.

Question 5	
I only participated in the workshop via the live Zoom sessions	11
I looked at Padlet but did not comment or post	16
I thought the Padlet was well organised and found it easy to navigate	25
I thought Padlet was a very valuable component of this workshop and would like to see this (or something similar) used at future virtual events	21
I think something like Padlet would be a good addition to future face-to-face events, as well as virtual events	20
I was not able to attend some/any of the live sessions but have been viewing/listening to the recordings of the live Zoom sessions	6
Other (see free text comments below)	6



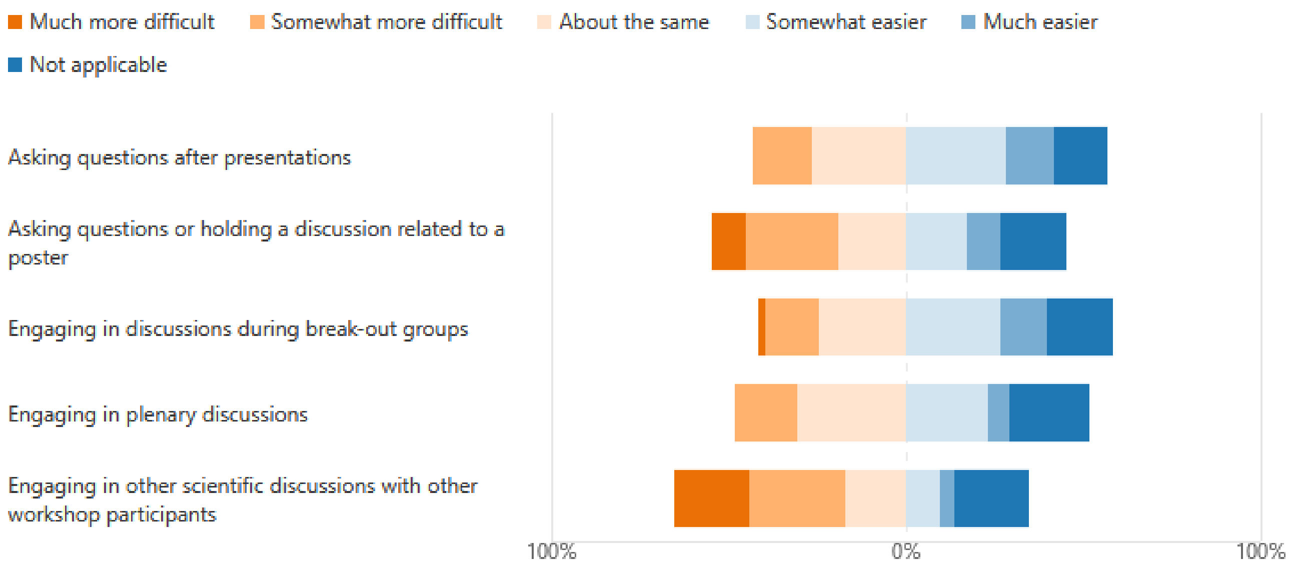
Free text answers to 'other':

- I found it a bit complicated to have separate Padlet links for each session, maybe one central link would be simpler.
- I found the Padlet well organised, but navigation was a bit difficult with checking the links from the program and then navigate there from the Padlet starting page. But I have to add that I did not explore Padlet options, so maybe there was an easy way to customize the Padlet or have all sessions as an overview on the Padlet start page that I am just not aware of. Another advantage of the recordings is the opportunity for self-reflection on one's own presentation, to get another impression of how one speaks and the chance to learn and improve in the future.
- Posters available in Padlet did not get much attention - a dedicated session should have been organised.
- It would be good also to publicise the Padlet 'home' page from which to navigate to all the workshop pages.
- I did comment on tablet and found it partially useful, but not all that great. Partly, the fact that many were labelled as 'anonymous' did not help.
- I am looking forward to following up on some presentations and discussions in the term break.

Key points (caveat: not all respondents provided multiple answers):

- Respondents generally felt that Padlet was well organised (n=25), a valuable component of the workshop (n=21) and that something like Padlet would be a good addition to future events (n=20).
- However, a large number of respondents (n=16) looked at Padlet but did not comment or post.
- There were three individual comments that suggested navigation around the different Padlets was a bit complicated. It was suggested that a 'homepage' or similar should be used in future to make this easier.
- One respondent commented that many comments on Padlet were labelled 'anoymous', which was not helpful (names only appear if a user creates an account on Padlet, which was optional at this event, but this could be enforced at a future event.).
- One respondent commented that the poster Padlet did not get much attention.

6. How did you find the following types of interaction with other participants at this virtual workshop compared with a face-to-face event?

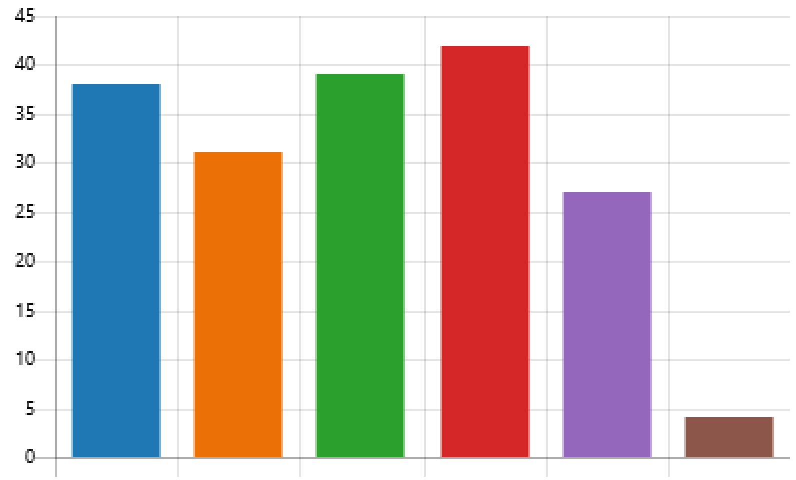


Key points:

- 15-23% of respondents answered 'not applicable' to each component of this question (dark blue on the bars above). These are excluded below.
- In general, nearly half of the respondents who did not answer 'not applicable' to this question found asking questions after presentations (48.9%) and engaging in discussions during break-out groups (48.8%) easier during this virtual workshop. About 20% of the respondents found it more difficult and about 30% found it about the same for each of these question components.
- About 44 % of the respondents who did not answer 'not applicable' found that discussion or questions related to a poster was more difficult.
- Of the respondents who did not answer 'not applicable' to the question on engaging in plenary discussions, ~23% found it harder, ~40% found it about the same and ~38% found it easier than at a face-to-face event.
- Of the respondents who did not answer 'not applicable' to the question on engaging with other scientific discussions, 61% found this harder, 22% about the same, and 17% easier than at a face-to-face event.

7. What has been your experience of the organisation and communication related to the workshop? Please select all that apply.

Question 7		
● (blue)	I felt fully informed about the workshop at all times	38
● (orange)	All the emails I have received about the workshop have been useful	31
● (green)	The information booklet was very helpful and the level of detail was appropriate	39
● (red)	The workshop was very well organised	42
● (purple)	I appreciated the emphasis on keeping to time during the live sessions of the workshop so the sessions did not 'run over'	27
● (brown)	Other (see free text comments below)	4



Free text answers to 'other':

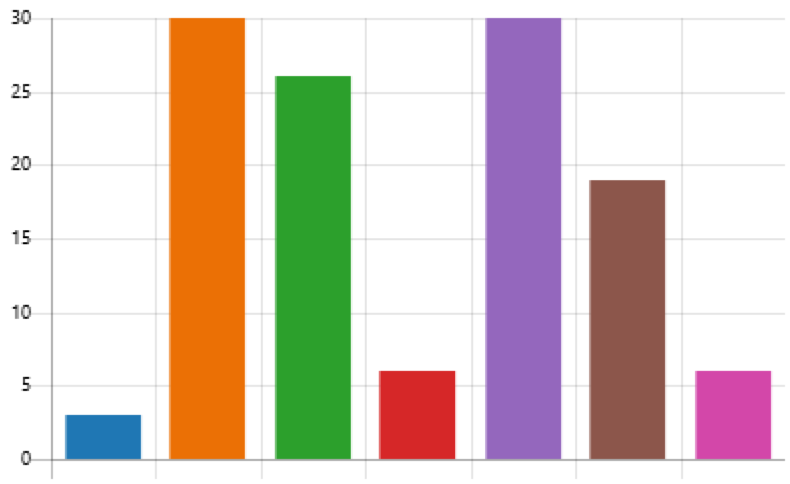
- Spot on Zooming
- I did not receive good information about the workshop in the months/weeks ahead. Rather short notice of confirmation of details.
- Well done! Low number of participants ~50 also helped. People were maintaining the discipline needed
- well done!

Key points (caveat: not all respondents provided multiple selections for this question):

- The majority of respondents were very positive about the workshop organisation and communication.
- A large number of respondents felt fully informed at all times (n=38), appreciated the email communications (n=31) and the information booklet (n=39).
- The most positive response was to confirm the workshop was very well organised (n=42).
- A large number of respondents (n=27) appreciated that the live sessions were kept strictly to time.
- One respondent commented that information about the workshop in the preceding weeks could have been better. (This was because the timing of the decisions concerning the workshop occurred during the early part of the Covid crisis (April) and it was unclear whether the workshop could take place 'live' or not at that time. Consequently, the final decision was made rather close to the event. Nevertheless, improving advanced communication should be considered for future events.)

8. What statements best match your overall views on this virtual event? Please select all that apply.

Question 8		
● (blue)	I think I would have got significantly more out of a face-to-face LST_cci User Workshop compared with this virtual event	3
● (orange)	I was surprised how effective this virtual event was compared to an equivalent face-to-face event	30
● (green)	I would be open to attending virtual events like this in the future rather than face-to-face events	26
● (red)	I have a strong preference that future workshops are held face-to-face	6
● (purple)	Attending more virtual events suits me as I am trying to reduce the amount I travel for work for environmental reasons	30
● (brown)	I don't think virtual events like this can fully replace face-to-face events	19
● (pink)	Other (see free text comments below):	6



Free text answers to 'other':

- In my opinion the future lies in a healthy balance between virtual and face-to-face events
- However, face to face events allow more interaction. But an online workshop prevents any grouping of scientists (which usually happens in EGU, or face to face conference). Online workshop helps better participation of early career scientist. It is also free and I do not need to apply for VISA.
- I think a hybrid format with both fact-to-face and virtual components can increase the engagement with users and partners.
- I had not been able to spend the time for the face-to-face workshop. Thanks for the opportunity to listen to some selected presentations!
- Virtual events cannot fully compensate for the social aspect that one has in a face-to-face event.
- I wouldn't be able to attend if it was face to face.

Key points (caveat: not all respondents provided multiple answers):

- Only 3 respondents felt they would have got significantly more out of a face-to-face workshop compared with this virtual event.

- Only 6 respondents indicated a strong preference for future events being held face-to-face. However, 19 respondents did feel that a virtual event like this workshop could never fully replace face-to-face events.
- Overall, respondents were very positive about this virtual event: 30 respondents were surprised how effective it was and 26 respondents indicated they are open to attending future virtual events rather than face-to-face events.
- A large number of respondents (n=30, ~57% of total respondents) indicated they were happy to attend more virtual events for environmental reasons.
- Two respondents commented that it was easier to attend a virtual workshop than a face-to-face event.
- Two other respondents commented that the future should be a balance between virtual and face-to-face events.

9. Question 9: Do you have any further comments to make about the LST_cci User Workshop 2020?

Congrats everyone for the extraordinary organization! Especially taking into account this was relatively new everyone involved. It was not the same as a face-to-face event, and I think we must keep doing those as well. Maybe alternate between online and face-to-face would be a good compromise.
congratulations
Congratulations, very well done indeed!
Great job! Unfortunately, there is still no good solution for having a virtual 'social event' or after work socialising ...
Great organization. Thanks for the work. This Padlet utility was really useful.
I am very happy with the workshop and wish I could have attended all sessions but the time difference was too big for me. Of course, it is not the organizers' fault, and I appreciate you set the timing to fit as many locations as possible. Just one comment about break-out group discussion results. They were put on the Padlet as separate comments. If someone, by the end of the day, could put them into one presentation, therefore the total number of extra *ppt would be equal to the number of discussions, (I do not talk about a general summary as it was done on the last day), then it would be easier for a future review. Thanks again for a great event! All the best!:)
I thought breakouts worked better online because there was no time (and participants) lost due to the move to/from the breakout rooms.
I was truly impressed by how well organized everything was, no detail left without consideration, and also appreciated the technical descriptions/ instructions of accessing zoom (despite already familiar with it) and padlet. I really enjoyed it! I wondered why primarily the chat was used to indicate questions instead of the raise-hand button, but I guess this would have led to confusion when people forget to unraise. For me, the length of the session was perfect, if it would have been 1.5hours, it would have been already straining I think. A comment on virtual events in general, not specifically for this workshop, is that I was also impressed by how the format of just having slides and a voice help focus on the content of the work without visual distractions of how the speaker behaves/moves. So, despite the technical advantage of lower bandwidth, I appreciated also this side effect of having the videos shut-off.
It was a good workshop.
It was an excellent event, amazingly well organised and has really made me open to the idea that virtual conferences could be my preferred option moving forward. My thanks all involved in setting this event up.
It was excellent. Thanks.
It was very well-organised! I had work commitments that kept me out of some of the meeting, unfortunately. I would have been happy to attend more of the workshop live. I am grateful that recordings will be provided. I will probably contact other scientists who I met virtually at the meeting in the near future. I think that virtual meetings and "chats" on Padlet or similar are VERY effective and would like to see this used in face to face meetings in future to supplement the plenary or break out sessions. Thank you! Cristina Charlton-Perez

My only concern was about lack of information in the months beforehand/ I wasn't sure if it was going ahead and the information on the webpage seemed always out of date. I thought the workshop itself was really well run.
Overall it was an exceptional experience as the workshop was virtual!!
Padlet was only accessible through a personal device at my institution, which wasn't ideal. I felt much more able to ask questions (had I had any) than in a face-to-face meeting. The virtual nature made it easy to attend this workshop - I suspect I wouldn't have come in person had I needed to travel.
Thank for all effort you did for the success of the workshop.
The workshop was very well organized. Congratulations. Just a note on the use of Padlet. When someone would post a comment to a presentation the author did not received an alert. Also, when replying to a comment, we cannot "mention" someone so that the person that made the question would receive an alert of the reply. Or maybe I missed that functionality? Without this functionality, it makes the discussion in Padlet difficult, as we need to double check frequently if there are question or replies. It's just a small detail.
Very well organized!! Especially when considering the required changes due to COVID-19. I had preferred not to use Zoom (privacy). Besides the audio quality made it difficult to listen/understand.
Very well run and I'm glad it was kept to time as this is one of my pet peeves about conferences. The only thing missing is coffee discussions and networking which is nearly impossible to replicate virtually.

Key points:

- Many respondents commented on the very good organisation and generally their very positive experiences at the workshop.
- Several respondents commented that virtual events could not replace face-to-face events. In particular, replicating the social and networking aspects of ‘in-person’ workshop or conference.
- One respondent commented that it would be useful to consolidate the discussion feedback each day before putting on Padlet as there was a lot of material to review.
- One respondent commented that the breakout sessions actually worked better online than face-to-face.
- Several respondents commented that Padlet was an extremely useful addition and something like this should be used for future events (even face-to-face). However, it was noted that the lack of ‘threaded’ discussions and the ability to cite another user made it quite difficult to follow/participate in the discussion. Padlet was also unavailable to some attendees.
- One respondent commented that there was a lack of information provided in advance of the workshop and the workshop webpages being out of date (due to the uncertainty around the Covid situation).
- The availability of the live session recordings was praised, allowing people to catch up with sessions they had missed.

Key 'lessons learned' from the delegate Survey Results

Overall the feedback from the delegates was extremely positive, and the following list summarises the key lessons learned from the survey that should be considered for future virtual and face-to-face events:

- Respondents were very positive about the live workshop format (session duration, timing), including the breakout sessions. In general, respondents liked the four, 1-hour sessions and the 30-60 minute breaks between them. Some respondents (and some members of the project team) were very supportive of the strict time keeping during the workshop, so this should be considered for future events.

- Respondents were generally very positive about the Padlets and these should be considered for future events, both virtual and in-person. However, the following issues were noted:

    - A lack of 'threaded' discussion (replies being pinned to associated comments), and not being able to 'tag' other users made following the discussion quite difficult.

    - Not everyone created a Padlet account so many posts had an 'anonymous' identification, which was also problematic. In future, delegates could be encouraged more strongly to create an account, or this should be compulsory.

    - Navigation around the different Padlets was also quite difficult so a 'home' page should be created and advertised clearly (there was a 'Welcome and Padlet orientation' Padlet, but this was perhaps not advertised clearly enough).

- A large proportion of survey respondents had a positive experience in their interactions with other workshop delegates and many found it easier to ask questions and participate in discussions virtually compared with a face-to-face event. However, respondents typically felt general networking and the social interaction with other workshop participants was more difficult. For future virtual events, holding some social sessions such as 'bring your own drink', perhaps through hosting different virtual rooms, could be considered.

- Respondents were generally extremely positive about the workshop organisation and communication, although it was noted that the communication in the period leading up to the workshop could have been better (this was due to uncertainty related to the global Covid pandemic, but in future, even 'holding' information emails could be issued).

- One of the main weaknesses of the virtual workshop was the poster 'session'. This was mentioned by several participants and some of the project team. More focus should be dedicated to posters at future virtual events, perhaps having a 'live' poster session, or considering some other more interactive way of presenting the posters. For example, each poster could have a different virtual room so delegates could move between the rooms for discussions.

- The value of the breakout sessions was perhaps not clear to all participants, so this could be highlighted more clearly at future events. Use of 'face-to-face' video could be considered at future virtual break-out discussions to make it more personal.

- In general, the survey respondents were extremely positive about holding more virtual events in future as many are trying to reduce travel for environmental reasons. Holding more virtual workshops also enables more people to participate, as indicated by the number of registered participants at this event. However, the value of in-person workshops was also evident in the survey responses, so the future should probably include a balance of both types of events.

End of document