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Climate Modelling User Group

Deliverable 7.1

Climate Service Interface – Requirements and Roadmap

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Climate Service Interface – Requirements and Roadmap

Contents

Climate Service Interface – Requirements and Roadmap

Executive Summary

The uptake of CCI data by the scientific community in support of Climate Services has been remarkable, both thanks to the established connection with C3S and other climate services involved in CMUG such as the Met Office, SMHI and BSC as well as the development of tools such as the CMF and ESMValTool. The latter has come to constitute a unique bridge between the scientific community (climate model users and developers) and the data providers thanks to the availability of CCI data within a robust tool that can be easily used for model evaluation on different platforms. Likewise, the inclusion of the CMF in the C3S Toolbox means that C3S climate data users will be able to access CCI data and reanalysis data from the same platform which should facilitate data uptake.

CMUG propose a new approach to understanding climate data user requirements taking advantage of the User Requirement Database built by C3S. At the moment, direct uptake of the CCI ECVs data which are made available through the CDS represents a small portion of the user uptake (approximately 3%), mainly from academic institutions. Not surprisingly, most of the data downloads and user requests are for climate model data or for reanalysis data. However, it would be useful to reach out to the existing users of the satellite products and understand better their needs while at the same time receiving feedback on the usefulness of the product as well as any improvements that can be made. CMUG would be granted access to the URDB which would allow it to achieve this unique connection with the users. The analysis of the URDB from the perspective of the satellite data would be summarised in a new version of this document.

1. Introduction

The purpose of this document is to explore the use of ESA CCI ECV[1] products by climate services and identify how this can be improved and extended. At the time of writing the main path by which Climate Service providers can access CCI data is the Copernicus Climate Change Service (C3S) which extends and operationalizes the CCI ECV datasets when they reach a suitable state of maturity. The present

[1] See Section 6 for a list of acronyms.

status of use of CCI ECVs among the CMUG partner institutes is summarised, and recommendations made on how it can be improved within those institutes and promoted to others.

Climate services require climate data for their operational provision, the CCI can be an important source of such datasets and CMUG is in an ideal position to provide an interface between the CCI projects and climate service providers. The CMUG partners are located in institutions across Europe and have a wide network in the global climate community, providing the contacts needed to set up and maintain relationships which will be beneficial to CCI and the climate service providers. This document investigates what might be required of an interface between CCI and climate service providers and suggests a path by which CMUG can fill this role.

Section 2 of this report outlines the Climate Services activities carried out by a subset of CMUG partner institutions, section 3 describes the scientific and technical features of CCI products. More detailed analysis for each ECV can be found in the Phase 2 version of this report (CMUG, 2017) and the previous version of this phase (CMUG, 2021b) and the four previously published Quality Assessment Reports (QARs) (CMUG, 2016; CMUG, 2017a; CMUG, 2017b; CMUG, 2020) and will not be repeated here.

Section 4 summarises priorities for future use of CCI data by C3S.

2. Climate Services

The Copernicus Climate Change Service (C3S) (see previous version of this report, CMUG (2021b)) operationalizes mature CCI datasets and makes them available free of charge, alongside many other climate quality datasets, allowing climate service providers to utilise them.[2]

Climate service providers within the CMUG consortium include the BSC, Met Office, Météo France and SMHI, whose activities are discussed below. These summaries demonstrate that there is potential for further uptake of the CCI data in all of these agencies. This would be best approached through C3S provision of operational datasets, which CMUG could facilitate.

[2] https://cds.climate.copernicus.eu/cdsapp#!/home

2.1 Climate services at BSC

The BSC has built over the years a strong expertise on the development of Climate Services, becoming one of the European reference centres in the field. These activities have been led by the Earth System Services (ESS) group, a consolidated and specialised research unit with long-lasting and ongoing links with national and international companies in the energy (e.g., Iberdrola, Nnergix), agriculture (e.g., DCOOP), retail (e.g., Decathlon), wine production (e.g., Codorniu) and insurance sectors (e.g., AXA XL). Through the years, they have worked to understand the industry's needs and their knowledge integration team has specialised in tailoring climate prediction (e.g. from C3S) and observational (e.g. satellite data and reanalyses) information in a way that is both useful and usable to the business sector. Because of the challenges that these companies face due to climate change both in Spain and worldwide, their interest in what climate services (and the ESS group in particular) can offer has increased over time. In this context, the long-established successful collaboration between the ESS group and the other departmental more fundamental research groups involved in CMUG – the Atmospheric Composition (AC) and Climate Prediction (CP) groups – opens an excellent communication channel that could be leveraged in the current and future CMUG phases to understand the potential of different CCI products – including their strengths and limitations – for the development of different sectoral applications, as well as to propose future CMUG activities with a more applied and/or user-oriented focus.

In addition, complementary climate prediction research activities in CMUG and C3S have been undertaken by the BSC. These CMUG contributions had a more scientific focus and included an exploration of the benefits of assimilating sea ice data on the forecast skill, as well as a forecast evaluation of the latest decadal prediction system with EC-Earth, using the longest ESA CCI products available. Direct BSC contributions to C3S have been made through the C3S_34c contract which has developed a prototype service for decadal climate predictions. This involved the production of single-model and multi-model forecast probabilistic products, which included the same EC-Earth decadal prediction system developed and evaluated in CMUG, an example of how the research-driven forecast improvements enabled by CMUG research had a positive impact on the final products developed and delivered in C3S_34c.

2.2 Climate services at UK Met Office

Climate services are provided by several groups across the Met Office, including the Applied Science teams, International Business and Knowledge Integration. These teams draw upon Met Office weather and climate science to develop and deliver customer focused products and services, often working with customers and expert partners in a trans-disciplinary approach which reflects the complex interaction

between climate variability and change and socio-economic factors. Topics such as food security, climate extremes, climate trends, water management, urban development, international development and transport are addressed.

Met Office customers include UK Government, other national hydro-meteorological services (NMHS), UN organisations, NGOs, research institutes and commercial businesses. The Met Office provides policy-relevant advice, produces a range of effective communication tools, delivers training and capacity building, and develops new research and analysis to help understand the implications of climate change on a range of climate-sensitive sectors.

Examples of Met Office climate services are included in the Newton Fund Weather and Climate Science to Services Programmes (WCSSP)[3], FCDO funded ARRCC[4] and WISER projects[5].

The Met Office also plays a leading role in the climate service community, in the UK, across Europe, e.g. through coordinating the H2020 Climateurope Network, and globally, e,g, through significant involvement in the development of the WMO-led Global Framework for Climate Services (GFCS) and the Climate Services Partnership (CSP).

Currently ESA CCI data are underutilised at the Met Office, and while they are used through the Copernicus Climate Change Service (C3S) for climate monitoring, they are rarely used for downstream climate service applications. There is potential for much better uptake which CMUG is well placed to facilitate.

2.3 Climate services at Météo France

Meteo-France develops its own climate models and offers three kinds of climate services: climate warming diagnosis, adaptation to climate change, education and training. Diagnosis services include a description of atmospheric variables over a region of interest in past, present and future conditions. Extreme events such as intense precipitation or severe droughts can be included in the analysis. Regions of interest can be in metropolitan France, French overseas territories, or anywhere in the world. Adaptation services are designed to anticipate and manage climate risks, e.g., forest fires, adverse effects

[3] https://www.metoffice.gov.uk/research/approach/collaboration/newton
[4] https://www.metoffice.gov.uk/services/government/international-development/arrcc
[5] https://www.metoffice.gov.uk/about-us/what/working-with-other-organisations/international/projects/wiser

on energy production and distribution, urban heat island, etc. They also include indicators relevant to agricultural and forest productivity, to tourism in mountainous areas. Education and training services are provided by Ecole Nationale de la Météorologie (ENM) in Toulouse. Customized solutions can also be proposed. On-line resources are available (http://www.drias-climat.fr/, https://meteofrance.com/climathd).

ESA-CCI data have the potential to make contributions to all of these activities at Meteo France, reaching out to the scientist involved in developing these products and demonstrating the utility of the CCI datasets would go a long way to encouraging uptake.

2.4 Climate services at SMHI

SMHI, the Swedish Meteorological and Hydrological Institute, is an expert authority for knowledge, research and services. The Rossby Centre is SMHI's climate modelling research unit. The Rossby Centre pursues research on climate processes and the behaviour of the climate system and have leading roles in developing the regional climate model HCLIM and the global climate model EC-Earth. Results from the climate model simulations are supplied via SMHI climate change scenario services. The CCI ECVs are used at the Rossby Centre and at the hydrological, ocean and remote sensing units at the research department. The ECVs are used for process studies, evaluation of models and as part of ESMValTool. SMHI is involved in a number of climate service activities where the CCI data could be used as described below.

SMHI is the host institute for the International Project Office (IPOC) for CORDEX (Coordinated Regional Downscaling). The IPOC is responsible for providing strong global coordination, together with the appropriate administrative, scientific and technical support, to CORDEX's worldwide activities. The CCI data could be promoted at CORDEX meetings and conferences.

SMHI Core services supply climate indicators for Sweden calculated from surface based observations from 1860 up to today for e.g. temperature, Baltic Sea maximum sea-ice extent and sea-level. The indicators can be analysed and put into a broader context of analyses of covariance of indicators and compared with the results from climate models. Satellite climate indicators from ESA-CCI could be provided via SMHI and other CMUG institutes indicator websites.

SMHI organizes international training programme on Climate Change - Mitigation and Adaptation designed for decision makers in developing countries who hold positions in their home organisations with mandate to initiate change on local to national level. Participants access the latest research and development in their areas of work, supervised by skilled Swedish colleagues and experts, develop a network of colleagues from other countries and enhance knowledge in new working methods. The CCI data and tools could be used at these courses.

The Swedish National Knowledge Centre for Climate Change Adaptation is based at SMHI. The centre provides tools and information to help society cope with a changing climate, now and in the future. Science, policy and practice, is brought together to the decision makers, businesses, research providers and organisations that make climate change adaptation happen. The Centre collects, develops and shares research, information from authorities and learning examples to facilitate sound decision making. The CCI satellite data, education resources and stories could be shared here.

To improve and extend the use of ESA-CCI data at SMHI, nationally and in internationally, a first step would be to contact responsible persons for the listed activities above to inform about what is available. That could include how to obtain the CCI data and demonstrate the educational resources and the stories. For the international training courses, the CCI Toolbox could be used for exploring the CCI data for different regions around the globe. The CCI data could also be useful for the SMHI Professional services in e.g. air quality, environment and energy.

3. Scientific and Technical features of CCI data relevant to Climate Services

3.1 General scientific features of CCI data

The current set of 23 CCI ECVs have achieved, or are, with a few exceptions, working towards achieving the following specifications:

- decadal or longer time scale datasets
- good global and regional coverage
- high temporal resolution (sub-daily to monthly) [not applicable to LC and HRLC – yearly data at most]
- comprehensive characterisation of uncertainties (including estimates of random errors)
- accurate and realistic climate variability

- reliable estimates of long-term climate trends
- validated (often against *in situ* data) homogenous, high quality climate data
- excellent provenance to source
- already well linked to user communities (mostly research but includes others)

3.2 Specific features of CCI data

A number of specific features characterize the CCI ECVs that are desirable in any dataset which an operational, user-driven climate service would provide. These include:

- **User requirement-based datasets:** The user requirements set by GCOS were considered as starting goal requirements for the ECVs. In addition, potential CCI ECV users are periodically engaged to provide application-specific user requirements for each ECV. These requirements are independently collected by CMUG and each CCI team from as many users and sectors as possible, they are documented and periodically revised. Many of these user requirements have now been met.
- **Algorithm Maturity:** Most CCI teams have reached a good algorithm maturity resulting from i) objective algorithm selection through Round-Robin inter-comparisons of available European models, ii) identification in the selected algorithm(s) of areas in need of improvements to meet the user requirements, iii) fully documented ATBDs, iv) fast turn-around with typically one-year cycle required to go from updating the algorithm to releasing validated datasets to users for most CCI ECVs. Some CCI+ teams are still working on achieving some of these goals.
- **Data Maturity:** Each dataset is fully characterized. Metadata are included with each product and fully documented uncertainty characterization with quantitative estimates at pixel level for Level 2 data in most cases. User-friendly flags are routinely included in ECV product format and specification with datasets validated by each ECV Climate Research Group and independently by CMUG. Details on data format, data compliancy, levels of processing, and data access are given in chapter 3. Many CCI ECVs were both self-assessed and assessed by the Core-CLIMAX[6] consortium using the Core-CLIMAX Data Maturity Matrix before and during the 2014 Core-CLIMAX Workshop[7].

[6] https://www.ecmwf.int/en/research/projects/core-climax
[7] https://cordis.europa.eu/project/id/313085/reporting

- **Temporal coverage:** An important element of CCI was to create long, consistent time series of ECVs exploiting a number of available satellite instruments. This was achieved by applying the ECV state-of-the-art algorithm selected through the round-robin exercise to different sensors. Whenever applicable, the single-sensor datasets were merged together to produce longer time series. Attention was paid to inter-instrumental biases to avoid sudden, unphysical jumps in the obtained records.
- **Consistency:** This aspect is considered at many levels. In Phase 1, all CCI teams were encouraged to use the same source of a priori information, namely the ERA-Interim reanalysis. This aspect was achieved throughout the CCI. A Land-Sea Mask (LSM) and a Freshwater Mask have been produced by the Land Cover project and other CCI teams and independent researchers are encouraged to use these masks for consistency. (see also section 3.5). Examples of improved internal consistency with other model variables and/or non-CCI observations used in the user models has been already documented (e.g. the assimilation of the CCI GOME-2 ozone profiles improved the fit to the assimilated AIRS ozone-sensitive radiances, CMUG QAR 2015). Activities are also on-going to improve across-ECV consistency. For instance, Aerosol-CCI and Cloud-CCI collaborate to ensure a consistent interpretation in their own algorithms of the same measurements when they are found to be either cloud-affected or aerosol-affected pixels.
- **Added value:** Many of the assessments performed to date confirm the quality of most CCI ECVs and their potential added value to several applications. This is corroborated by the wide use of many CCI datasets in international assessments like the IPCC AR5 and the 2014 WMO Ozone Assessment, as well as by the usa of, for instance, many O3-CCI products in the C3S ERA5 reanalysis.
- **Documentation:** For each CCI ECV, the following documents are publicly available and periodically updated: i) Algorithm Theoretical Basis Document; ii) Uncertainty Characterization Report; iii) Product User Guide**;** iv) Product Validation Plan; v) Product Validation Inter-comparison Report; vi) Climate Assessment Report (CAR); vii) System Specification Document. Results are also documented in peer reviewed papers (an excess of 700 papers have already been published by the CCI). All the above documents are reviewed by CMUG. In addition to the ECV CAR, periodic assessments are independently carried out by CMUG (CMUG QAR 2015, see also section 2.3).

In addition to the value of each single ECV, it is worth mentioning and should not be underestimated that the CCI programme has brought together scientists from very diverse backgrounds dedicated to tackle specific scientific questions, creating a closely-linked community. This community has

blossomed with time and has promoted a number of cross-ECV studies to improve their products (as discussed above between Aerosol and Cloud-CCI), and to address and explain some of today's climate change signatures. An example of the latter is represented for instance by the CCI project set up to investigate Sea Level Budget Closure (SLBC). Phase one of this project concluded in 2019 and a second phase is currently under preparation. The SLBC project involves all CCI teams that work with ECVs relevant, or could be related, to Sea Level changes, for instance Glacier-CCI, and might also provide information relevant to climate change services and their users.

3.3 Potential applications for CCI data in Climate Services

Climate services are concerned with a variety of users and sectors, including:

- Climate monitoring and attribution
- Reanalyses
- Seasonal forecasts
- Climate data applications
- Adaptation community (including EEA)
- Mitigation community (including national governments and the EC)
- System users (for instance town planner, governments, Climate services at a national level, (for example the UK Climate Change Risk Assessment defines user requirements with respect to addressing climate change in different systems and sectors)
- Sectoral users in the following sectors: water, agriculture, forestry, fisheries, energy, health, insurance, tourism, transport, infrastructure, natural environment, and others

All CCI ECVs are potentially useful in several of these applications and sectors.

CMUG has contributed to the development of **ESMValTool**[8] and the **CMF**[9], two tools relevant to assessments of climate products through the use of diagnostics to provide statistical analysis on the quality of the datasets. ESMValTool is used to evaluate CMIP climate models through the definition of model evaluation diagnostics which include CCI ECV data; the CMF allows rapid investigation of the homogeneity and consistency of climate data sets by comparing pre-defined products. The CMF is now being integrated in the C3S Toolbox and will display ECV datasets which were produced by CCI in its

[8] https://www.esmvaltool.org/
[9] https://apps.ecmwf.int/climate-monitoring/

initial phase and operationalized by C3S. It is expected that the development of the tool will continue as part of C3S while CCI+ and its future evolution will contribute new ECVs to the database.

Given the central role that the ESMValTool has taken in providing a platform for the exploitation of CCI ECVs for model evaluation, a separate subsection has been added to this report (see 3.3.1).

3.3.1 Earth System Model Evaluation Tool (ESMValTool)

The Earth System Model Evaluation Tool (Righi et al. (2020); Eyring et al. (2020); Lauer et al. (2020); Weigel et al. (2021)) has been developed to take model evaluation to the next level by facilitating analysis of many different earth system model components, providing well-documented source code and scientific background of implemented diagnostics and metrics and allowing for traceability and reproducibility of results (provenance). It is developed by a lively and growing community continuously improving the tool supported by multiple national and European projects. Within CMUG, several ESA CCI datasets alongside with new diagnostics capable of taking advantage of these datasets have been implemented. Recent examples include column-average methane, sea surface salinity, land surface temperature, water vapour and ocean chlorophyll. The ESA CCI datasets include consistent, long-term time series of a number of essential climate variables obtained from harmonized, reprocessed products from different satellite instruments. The data allow including new variables in the calculation of performance metrics as summary statistics and add an important alternative data set in other cases where observations are already available. Through implementation into the ESMValTool, these datasets are made available to the community in an easy-to-use way for model evaluation, which opens up new possibilities for evaluation of earth system models (ESMs) to the climate modeling community.

The latest version (v2) of the ESMValTool has been developed to specifically target the increased data volume of output from the Coupled Model Intercomparison Project Phase 6 (CMIP6) and the related challenges posed by analysis and evaluation of results from multiple high-resolution and complex earth system models. For this, the core functionalities have been completely rewritten in order to take advantage of state-of-the-art computational libraries and methods to allow for efficient and user-friendly data processing. This new software engineering approach as well as the availability of a detailed software documentation and a tutorial made the tool much more versatile and attractive for new users. This unique framework available to the climate community already resulted in several institutes involved in climate modeling such as Met Office, BSC and DLR to include the ESMValTool in their workflows as an important tool for model evaluation and analysis. Interaction with the ESMValTool users through the

newly established user engagement team allows for regular exchange and feedback between users and developers helping to identify possible improvements including the need for new features, datasets and diagnostics that can then become available to the whole community.

4. Priorities for future use of CCI data by C3S

Fifteen CCI ECVs are currently extended by C3S: Aerosol, Cloud, Fire, GHG, Glaciers, Ice Sheets, Land Cover, Lakes, Ocean Colour, Ozone, Sea Ice and Sea Level, Soil Moisture, SST and Sea Level. These projects should be encouraged to read the gap analysis provided by C3S and take into account this analysis when planning future phases.

Six of the CCI ECVs are not extended by C3S: Biomass, HRLC, Permafrost, Salinity, Sea State and Snow. These are all CCI+ projects and as such will only now be reaching a level of maturity suitable for operationalisation. For future planning they should be considering climate service requirements as listed in previous versions of this report.

Six ECVs extended by C3S are not yet provided by CCI: Albedo, Earth Radiation budget, FAPAR, LAI, Precipitation and Surface Radiation Budget. FAPAR and LAI will be included in the next phase of CCI+ and the remaining four might be considered by the CCI for future phases.

5. Lessons learned/Future outlook

The uptake of CCI data by the scientific community in support of Climate Services has been remarkable, both thanks to the established connection with C3S and other climate services involved in CMUG such as the Met Office, SMHI and BSC as well as the development of tools such as the CMF and ESMValTool. The latter has come to constitute a unique bridge between the scientific community (climate model users and developers) and the data providers thanks to the availability of CCI data within a robust tool that can be easily used for model evaluation on different platforms. Likewise, the inclusion

of the CMF in the C3S Toolbox means that C3S climate data users will be able to access CCI data and reanalysis data from the same platform which should facilitate data uptake.

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6. Acronyms

AAI	Absorbing Aerosol Depth
AATSR	Advanced Along-Track Scanning Radiometer
AE	Stratospheric Extinction Profile
ADV	AATSR Dual-View
AGB	Above Ground Biomass
AOD	Aerosol Optical Depth
AERONET	AErosol RObotic NETwork
ATBD	Algorithm Theoretical Baseline Document
AVISO	Archiving, Validation and Interpretation of Satellite Oceanographic data
BSC	Barcelona Supercomputing Centre
C3S	Copernicus Climate Change Service
CAR	Climate Assessment Report
CC	Cloud Cover
CCI	Climate Change Initiative
CCIAV	Climate Change Impacts, Adaption and Vulnerability
CF	Climate and Forecast
CDO	Climate Data Operator

CDR	Climate Data Record
CDS	Climate Data Store
COT	Cloud Optical Thickness
CMA	China Meteorological Administration
CMC	Climate Modelling Community
CMF	Climate Monitoring Facility
CMIP	Coupled Model Inter-comparison Project
CMUG	Climate Science Working Group
CRDP	Climate Record Data Package
CSS	Climate Safeguards System
CTH	Cloud Top Height
CTP	Cloud Top Pressure
CTT	Cloud Top Temperature
DLR	German Aerospace Centre
EC	European Commission
ECV	Essential Climate Variable
EEA	European Environment Agency
ECMWF	European Centre for Medium Range Weather Forecasting
ENSO	El Niño–Southern Oscillation
EO	European Earth Observation
ESMValTool	Earth System Model eValuation Tool
EQC	Evaluation and Quality Control (of the C3S)
EU	European Union
GCOS	Global Climate Observing System
GHGs	Greenhouse Gases
GRADS	The Grid Analysis Display System
HRLC	High Resolution Land Cover
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardisation
ITT	Invitation To Tender
IWP	Ice Water Path
JMA	Japan Meteorological Agency

JRA	Japanese Reanalysis Project
JRC	Joint Research Centre
KPIs	Key Performance Indicators
LC	Land Cover
LP	Limb Profile
LSM	Land-Sea Mask
LST	Land Surface Temperature
LWP	Liquid Water Path
MACC	Monitoring Atmospheric Composition and Climate
MERRA	Modern-Era Retrospective Analysis for Research and Applications
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NCEP	National Centres for Environmental Prediction
NMS	National Meteorological Services
NP	Nadir Profile
NRT	Near-Real-Time
NSIDC	National Snow and Ice Data Centre
O3	Ozone
OC	Ocean Colour
OGC	Open Geospatial Consortium
ORA-S4	ECMWF Ocean Reanalysis – System 4
PSD	Product Specification Document
PUG	Product User Guide
QWGs	Quality Working Groups
REF	Cloud Effectiveness Radius
RCA	Rossby Centre Regional Climate model
SI	Sea Ice
SIC	Sea-Ice Concentration
SICCI	Sea-Ice Climate Change Inituative
SIE	Sea-Ice Extent
SIT	Sea-Ice Thickness
SLBC	Sea Level Budget Closure

SM	Soil Moisture
SMR	Sub-Millimetre Radiometer
SRD	Systems Requirements Document
SSH	Regional Sea Level
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
SU	Swansea University
TO	Total Column
UERRA	Uncertainties in Ensembles of Regional ReAnalysis (ECMWF)
URD	User Requirements Document
URDB	User Requirement Data Base
WMO	World Metrological Organisation
WV	Water Vapour
XCH4	Methane
XCO2	Carbon Dioxide

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