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Product Validation and Algorithm Selection Report

snow cci

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ESA STUDY CONTRACT REPORT

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Abstract:

The European Space Agency (ESA) Climate Change Initiative aims to generate high quality Essential Climate Variables (ECVs) derived from long-term satellite data records to meet the needs of climate research and monitoring activities.

This document describes the baseline algorithms selected for the generation of the daily global *snow_cci* prototype snow cover fraction (SCF) and snow water equivalent (SWE) climate research data package. Additionally, this document provides results of a cloud screening round robin exercise performed with focus on cloud detection over snow covered areas. Based on the results of this round robin exercise, the baseline cloud product or algorithm used for SCF product generation from MODIS and AVHRR data is selected.

The work described in this report was done under ESA Contract. Responsibility for the contents resides in the author or organisation that prepared it.

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3.0	09 / 09 / 2021	Update of Section 3.2.4	G. Schwaizer
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1. INTRODUCTION

1.1. Scope of the Document

This document provides information on the baseline algorithms selected for the generation of the *snow_cci* ECVs snow cover fraction (SCF) and snow water equivalent (SWE) from satellite data. The baseline algorithms were selected based on the validation and intercomparison results from the ESA QA4EO project SnowPEx.

For cloud screening required for analysing the SCF from optical satellite data, a round robin exercise (RRE) of currently available cloud products and algorithms with focus on cloud screening over snow covered areas was carried out. Results of the cloud screening RRE are presented in this document. The baseline cloud product and algorithm to be used for the prototype product generation in the first year of the *snow_cci* project was selected based on these results.

1.2. Document Structure

The baseline algorithms selected for the generation of snow cover fraction and snow water equivalent prototype products based on intercomparison and validation results of the ESA QA4EO project SnowPEx are provided in Section 2. The cloud screening round robin exercise and the cloud algorithm and products selected based on the results are described in Section 3.

1.3. Applicable and Reference Documents

[AD-1] Climate Change Initiative Extension (CCI+) Phase 1 – New Essential Climate Variables (2017). Statement of Work (Sow) v1.3, ESA-CCI-PRGM-EOPS-SW-17-0032.

[RD-1] Nagler, T., G. Bippus, C. Derksen, N. Di Girolamo, R. Fernandes, D. Hall, M. Hori, R. Kelly, K. Luojus, S. Metsämäki, T. Mote, C. Notarnicola, G. Riggs, E. Ripper, D. Robinson, P. Romanov, R. Solberg, M. Tedesco, B. Ventura, and F. Zhou (2015). Review of Algorithms and Products. *SnowPEx Report D3, Issue 1, Revision 0*. http://snowpex.enveo.at/Documents/D03_ReviewOfAlg_v1.0_20151218.pdf

[RD-2] Schwaizer, G., Ripper, E., Nagler, T., Fernandes, R., Metsämäki, S., Solberg, R., Luojus, K., Derksen, C., Mudryk, L., and R. Brown (2016). Snow Product Intercomparison and Validation Report – FINAL. *SnowPEx Report D13, Issue 1, Revision 0*.

[RD-3] Wunderle, S., Naegeli, K., Schwaizer, G., Nagler, T., Marin, C., Notarnicola, C., Derksen, C., Luojus, K., Metsämäki, S., Solberg, R. (2018). ESA CCI+ Snow ECV: Data Access Requirements Document, version 1.0, February 2019.

1.4. List of Acronyms

AATSR	Advanced Along-Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
CLARA-A2	CM SAF cLouds, Albedo RAdiation data record, AVHRR-based, Edition 2
CM-SAF	Climate Monitoring Satellite Application Facility
ECV	Essential Climate Variable
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
MODIS	Moderate Resolution Imaging Spectroradiometer
NTS	Northern Test Site
QA4EO	Quality Assurance framework for Earth Observation
RRE	Round Robin Exercise
SCDA	Simple Cloud Detection Algorithm
SCF	Snow Cover Fraction
SLSTR	Sea and Land Surface Temperature Radiometer
STS	Southern Test Site
SWE	Snow Water Equivalent

2. ALGORITHM SELECTION

2.1. Baseline Snow Cover Fraction algorithms

Snow cover extent (SCE) can be obtained from optical satellite imagery. Multiple retrieval methods for detecting binary or fractional snow are available. Within the ESA QA4EO SnowPEx project, 12 currently available snow products with continental to global coverage were intercompared. Many of them are only detecting binary snow. For the *snow_cci* climate data record, the snow cover fraction (SCF) per pixel is requested by users. Additionally, for forested areas information on snow on top of the forest canopy as well as canopy corrected snow cover fraction is desired. Based on the ESA QA4EO SnowPEx validation results, the following approaches are selected as baseline methods for generating SCF climate research data packages from medium resolution optical satellite data:

- NDSI based approach adapted from Salomonson and Appel (2004, 2006), providing in forested areas information on snow on the top of the forest canopy
- SCAmod approach (Metsämäki et al., 2012, 2015), applying a canopy correction in forested areas

2.1.1. NDSI based approach

The NDSI based snow cover fraction retrieval approach was developed by Salomonson and Appel (2006) for Terra / Aqua MODIS data. The method was used by NASA for the generation of the fractional snow cover products collection 5 from MODIS data (Riggs et al., 2006; Hall et al., 2006).

The approach is a linear regression of the normalized difference snow index to detect the fraction of snow per pixel, and has been applied on Terra / Aqua MODIS, Suomi-NPP VIIRS and Landsat data. The method is very robust and can be applied on data of any optical sensor with spectral bands working in the visible spectral range (about 550 nm) and in the shortwave infrared spectral range, around 1.6 µm.

The algorithm was used for generating the Terra MODIS based snow cover products Collection 5 (MOD10_L2), available globally for the period 24th February 2000 till 3rd January 2017 via the NSIDC (https://nsidc.org/data/MOD10_L2/versions/5). These snow products were evaluated by NASA with selected reference data assessing the absolute product accuracy in general >93 % (Hall and Riggs, 2007). Additionally, the Terra MODIS Collection 5 fractional snow cover products participated in the QA4EO SnowPEx intercomparison and evaluation exercises [RD-1]. It was one of the highly rated snow cover extent products for viewable snow products [RD-2].

All further details including information about known strengths, weaknesses and limitations of the algorithm are described in [RD-1], Section 3.

The NDSI based approach will be extended with a pre-classification module to avoid known issues of snow misclassifications along shore lines and in regions with warm surfaces.

2.1.2. SCAmod approach

The SCAmod based snow cover fraction retrieval approach was originally developed by Metsämäki et al (2012) for the sensors ATSR-2 and AATSR in the frame of the ESA GlobSnow project, and was further adapted and tested with the sensors MODIS (EU FP7 projects CryoLand and SEN3APP, Metsämäki et al (2015)) AVHRR (H-SAF, experimental products at UBE), VIIRS and SLSTR (Copernicus Land Monitoring Service GlobLand). It is a physically based approach requiring only one spectral band and applies a canopy correction for snow cover fraction in forested areas. The algorithm is computationally efficient and allows the processing of large data sets. SCF products generated with the SCAmod approach participated in the QA4EO SnowPEx intercomparison and evaluation exercises [RD-1]. The SCAmod based products were highly rated compared to other snow products [RD-2], [AD-1], with average RMSE values of about 15% compared to reference data.

All further details including information about known strengths, weaknesses and limitations of the algorithm are described in [RD-1], Sections 5 and 13.

2.2. Baseline Snow Water Equivalent algorithm

The retrieval of snow water equivalent from satellite-based observations, on temporally and spatially relevant scales for an ECV (global and multi-decadal scale) is feasible only by using the measurements obtained from passive microwave (PMW) radiometer data.

There are a few existing approaches to derive SWE estimates using PMW data and the key methodologies were assessed in the ESA SnowPEx project. Based on the SnowPEx results, SWE retrievals based purely on satellite-data are unable to fully distinguish the effects of snow mass from the complicating influence of snow grain size. A significantly more accurate approach is to combine PMW data with external sources that allow independent assessment of snow microstructure through derivation of an effective snow grain size. In the case of the "ESA GlobSnow" retrieval approach, the analysis of snow grain size is informed by synoptic weather station observations of snow depth combined with snow emission model simulations.

The SnowPEx project concluded that the GlobSnow approach was significantly better performing, compared to other existing approaches. Since the assessment carried out in the ESA SnowPEx project, there have been very few new developments to improve SWE retrieval over hemispheric scale, and no new algorithms/methodologies have yet been published and made available that would be applicable for the construction of the Snow CCI SWE ECV. Therefore, the ESA GlobSnow SWE methodology serves as the basis for the Snow CCI SWE development. The "GlobSnow SWE" approach will be further improved in the ESA CCI Snow project.

2.3. Baseline auxiliary data

Auxiliary data for the prototype production include Land / water areas and permanent snow and ice areas derived from the Land Cover CCI map for the year 2000, and a global digital elevation model (DEM) using combined data from SRTM v4.1 DEM, ASTER GDEM v2 and TerraSAR-X DEM ([RD-3]).

Further auxiliary data will be prepared as needed for future improvements and will be described in detail in the updated *snow_cci* [RD-3] and Algorithm Theoretical Basis Document as needed.

3. CLOUD SCREENING ROUND ROBIN EXERCISES

This section describes the cloud screening round robin (RR) exercises with focus on cloud masking over snow. It includes the satellite database used for the RR experiment, the used cloud screening algorithms and cloud products, and the results of the cloud screening RR exercises. Based on these results, the baseline cloud screening approach to be used for the generation of the ECV snow cover extent from MODIS and AVHRR data in the first project year is selected. Also, SLSTR data to be used only at a later phase of the project are considered in the cloud screening RR exercises.

3.1. Data base

The database includes 3 swaths in North America, Europe and Asia (Figure 3.1). Regions were selected based on the AATSR swath acquisition for the year 2003, and in 20017 based on SLSTR. Table 3.1 presents available dates for the selected regions for each sensor that will be further used for the investigation.

The datasets are imported separately for each sensor. The software used for the importing is:

- SLSTR: reading and geolocation module of ENVEO's software package
- MODIS: reading, geolocation and radiometric calibration modules of ENVEO's software package
- AVHRR: *cloud_cci* pre-processing

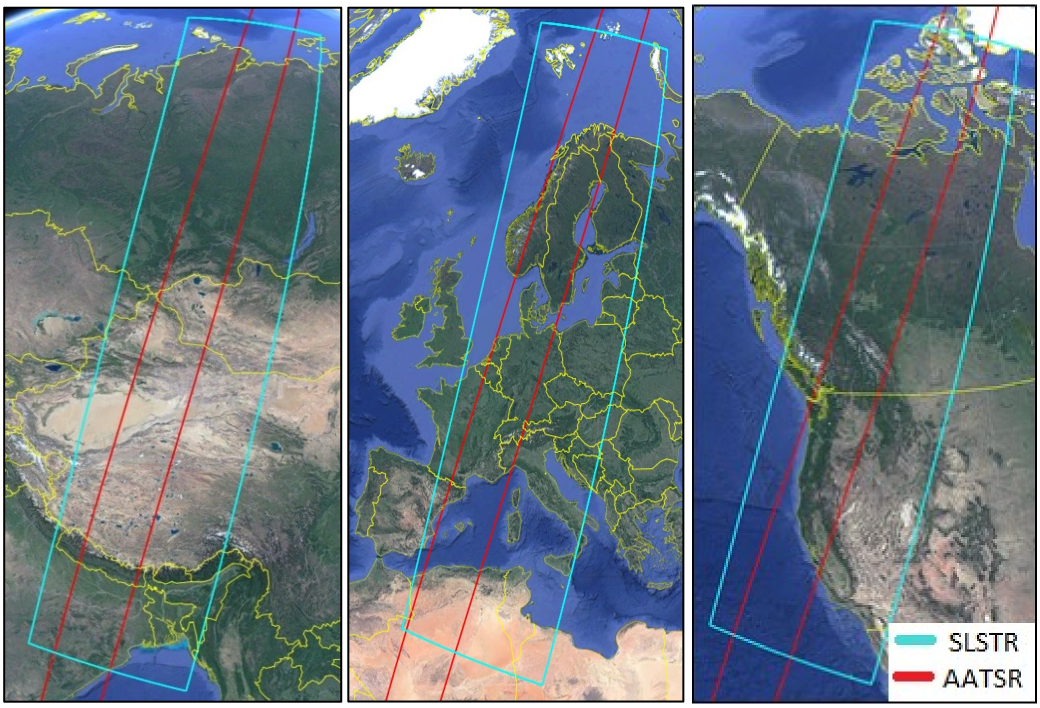


Figure 3.1: Selected Round Robin datasets a) SLSTR - 28.02.2017 and AATSR - 06.03.2003 b) SLSTR – 12.03.2017 and AATSR – 03.03.2003 c) SLSTR – 13.03.2017 and AATSR – 01.03.2003.

Table 3.1: Acquisition dates in 2003 and 2017 per selected satellite data and region used for cloud screening round robin exercises.

	SLSTR	MODIS	AVHRR	AATSR*)
North America	-- 28 / 02 / 2017	06 / 03 / 2003 28 / 02 / 2017	06 / 03 / 2003 28 / 02 / 2017	06 / 03 / 2003 --
Europe	-- 12 / 03 / 2017	03 / 03 / 2003 12 / 03 / 2017	03 / 03 / 2003 12 / 03 / 2017	03 / 03 / 2003 --
Asia	-- 13 / 03 / 2017	-- 13 / 03 / 2017	-- 13 / 03 / 2017	01 / 03 / 2003 --

*) AATSR swath data are only selected to enable a repeat of the cloud screening tests with this sensor when the newly calibrated data become available and will be used for the generation of CRDP in *snow_cci*.

3.2. Cloud screening algorithms

For cloud screening we tested and intercompared the following algorithms:

- SCDA v2.0 (draft)
- SCDA v2.1
- *Cloud_cci* cloud mask v2.0
- *Cloud_cci* cloud mask v3.0
- CLARA-A2 cloud mask
- PATMOS-x Bayesian cloud mask
- MODIS Cloud Product MOD35
- SLSTR Cloud Product

An overview which algorithm and cloud products are applied on which sensors is shown in Table 3.2. In the following sub-sections, we provide an overview and references to the applied algorithms.

Table 3.2: Overview on cloud screening method and products applied per sensor for the RR exercises.

	YEAR	AVHRR	MODIS	SLSTR
Cloud algorithms	2003	--	SCDA v2.0, SCDA v2.1	--
	2017	SCDA v2.0, SCDA v2.1	SCDA v2.0, SCDA v2.1	SCDA v2.0, SCDA v2.1
Cloud masks from third parties	2003	Cloud_cci v2.0, Cloud_cci v3.0, CLARA-A2	--	--
	2017	Cloud_cci v2.0, Cloud_cci v3.0, CLARA-A2, PATMOS-x	--	Cloud_cci SLSTR cloud mask
Cloud masks included in satellite data	2003	--	MOD35	--
	2017	--	MOD35	S3 cloud layers

3.2.1. SCDAv2.0

The cloud screening approach SCDA v2.0 (simple cloud detection algorithm) was developed in the ESA GlobSnow project, and has been further developed since then in the projects EU FP7 CryoLand, SEN3APP and the Copernicus Land Monitoring Service GlobLand. Detailed descriptions of the SCDA v2.0 are given in Metsämäki et al. (2005, 2012, 2015).

3.2.2. SCDAv2.1

SCDA v2.1 is a cloud mask further developed by S. Metsämäki (SYKE) based on SCDA v2.0. It is not officially available and published yet. The algorithm is the same as for SCDA v2.0, the only difference are thresholds used for respective steps. The detailed screening scheme with accurate thresholds is presented in Figure 3.2.

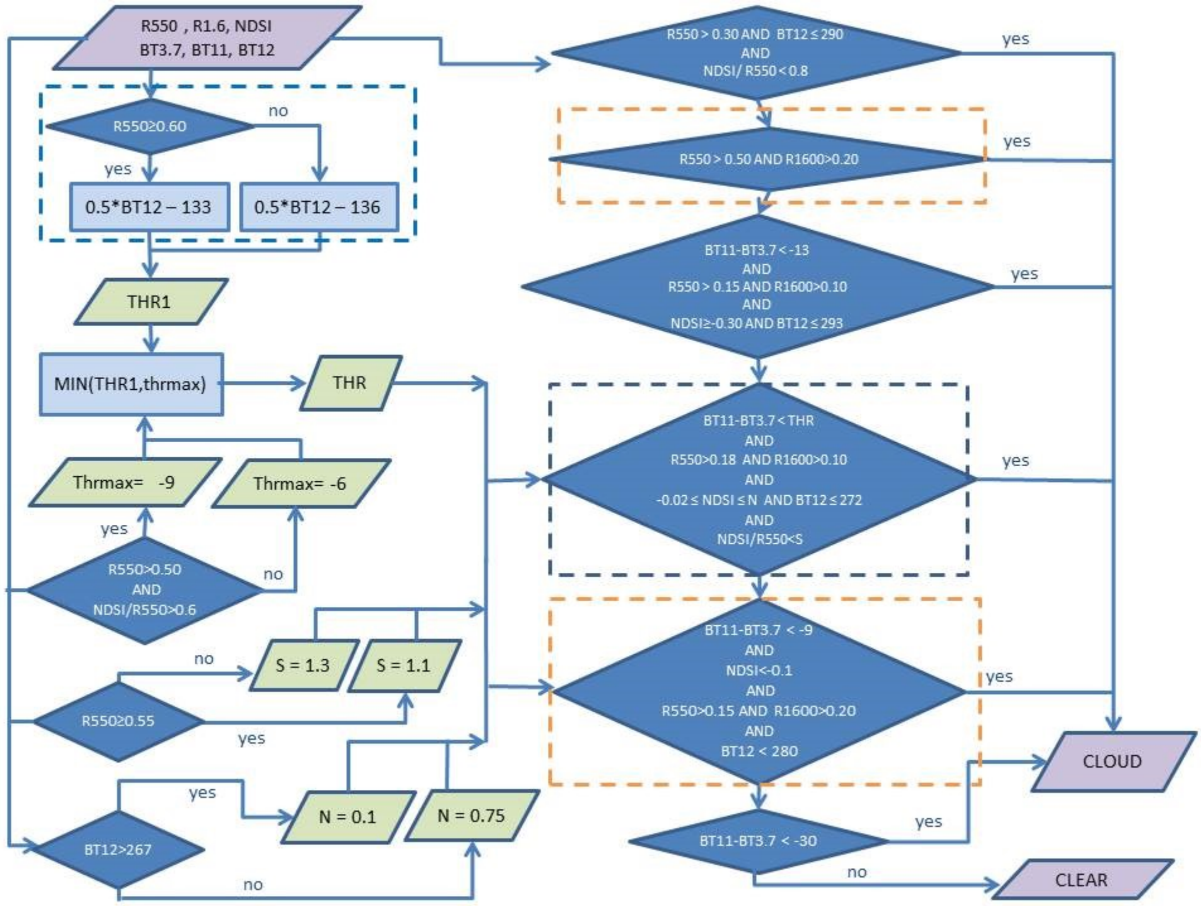


Figure 3.2: SCDAv2.1 screening scheme.

3.2.3. Cloud_cci cloud mask v2.0

Cloud_cci cloud mask version 2.0 was developed by the ESA *Cloud_cci* team. The algorithm description is provided in Poulsen et al. (2017).

3.2.4. *Cloud_cci cloud mask v3.0*

Cloud_cci cloud mask version 3.0 was officially released (https://climate.esa.int/en/projects/cloud/data/) and documented (https://climate.esa.int/en/projects/cloud/key-documents/). All the data used for the cloud screening round robin exercises within *snow_cci* were the cloud mask version 3.0 by courtesy provided by the *cloud_cci* team before the official release (personal communication M. Stengel, DWD). As the cloud mask v3.0 used for the round robin exercise is the same as the officially released cloud mask v3.0, the results presented in Section 3.3 are still valid.

3.2.5. *CLARA-A2 cloud mask*

The CLARA-A2 (CM SAF cLouds, Albedo RAdiation data record, AVHRR-based, Edition 2) cloud screening product was developed and generated in the frame of the EUMETSAT CM SAF. A detailed description of the algorithm is given in Karlsson et al (2017).

3.2.6. *PATMOS-x Bayesian cloud mask*

The Pathfinder Atmospheres Extended (PATMOS-x) is a suite of cloud products developed by NOAA and provides a climate data record of cloud properties derived from AVHRR Pathfinder Atmospheres. Further details are described in Heidinger et al. (2014).

3.2.7. *MOD35 cloud mask*

The MOD35 cloud mask is a Level 2 product generated at 1 km and 250 m spatial resolutions. The algorithm is described in detail in Ackerman et al. (2010).

3.2.8. *SLSTR cloud mask*

The SLSTR cloud mask product is a Level 1 product at 500 m resolution, which is still under development. The full description of the algorithm used for the SLSTR cloud masks participating in this RR exercise is provided in Birks & Cox (2011).

3.3. Results of round robin exercises

In this section the results of different cloud detection products and algorithms applied on different sensors are shown and cloud masks are visually intercompared. For each sensor, a preliminary baseline cloud mask was selected which seemed to work best over snow, and all other available cloud masks available for the sensor, the domain and time frame, are intercompared with this baseline cloud mask.

We selected test sites in Europe, Asia and North America (Section 3.1). The aim of this exercise was to find the cloud screening algorithm or product, that shows the best performance over fully and partially snow-covered areas. Therefore, the scenes we have chosen are located over snow areas that are partly cloud-covered.

3.3.1. AVHRR cloud screening

Cloud masks from various available AVHRR-3 based cloud products and from cloud-screening algorithms applied on AVHRR-3 data of the years 2003 and 2017 were intercompared. The AVHRR-3 sensor is on-board of different satellites with different overpass times. For the intercomparison of the cloud masks, we also considered cloud products generated from AVHRR-3 data of different satellites by the same provider for the same area and time of interest. An overview on the different satellites used for the cloud screening round robin exercise for AHVRR-3 is shown in Table 3.3. Examples of cloud masks generated by different algorithms by different cloud mask providers for test sites in Asia, Europe and North America in March 2003 are presented in Figure 3.3.

Table 3.3: NOAA and METOP satellites with AVHRR-3 sensor on-board used for the generation of the different cloud products per test site and date.

	Asia		*Europe*		*North America*
Cloud product	***2003/03/01***	***2017/03/13***	***2003/03/03***	***2017/03/12***	***2003/03/06***
Cloud_cci v2.0	NOAA-16	METOP-B	NOAA-16	METOP-B	NOAA-16
Cloud_cci v3.0	NOAA-16 NOAA-17		NOAA-16		NOAA-16
CLARA-A2	NOAA-16 NOAA-17		NOAA-16 NOAA-17		NOAA-16 NOAA-17
PATMOS-x	NOAA-15 NOAA-16 NOAA-17	METOP-A NOAA-18 NOAA-19		METOP-A NOAA-18 NOAA-19	
SCDA v2.0		METOP-B		METOP-B	
SCDA v2.1		METOP-B		METOP-B	

In the dataset for the year 2003 we tested *cloud_cci* cloud mask version 2.0 and version 3.0 and also cloud masks based on CLARA-A2 NOAA-16 and NOAA-17 data. *Cloud_cci* cloud mask v3.0 performs better over snow-covered pixels than the version 2.0. *Cloud_cci* version 2.0 detects 56.27 % of pixels identified by version 3.0 as clouds, as cloud-free (Figure 3.3).

CLARA-A2 NOAA-16 works quite well over the snow areas, where CLARA-A2 NOAA-17 misclassifies some snow pixels as clouds. In comparison with *cloud_cci* cloud mask version 3.0, CLARA-A2 NOAA-16 shows better performance over the snow, but the *cloud_cci* cloud mask version 3.0 is more conservative.

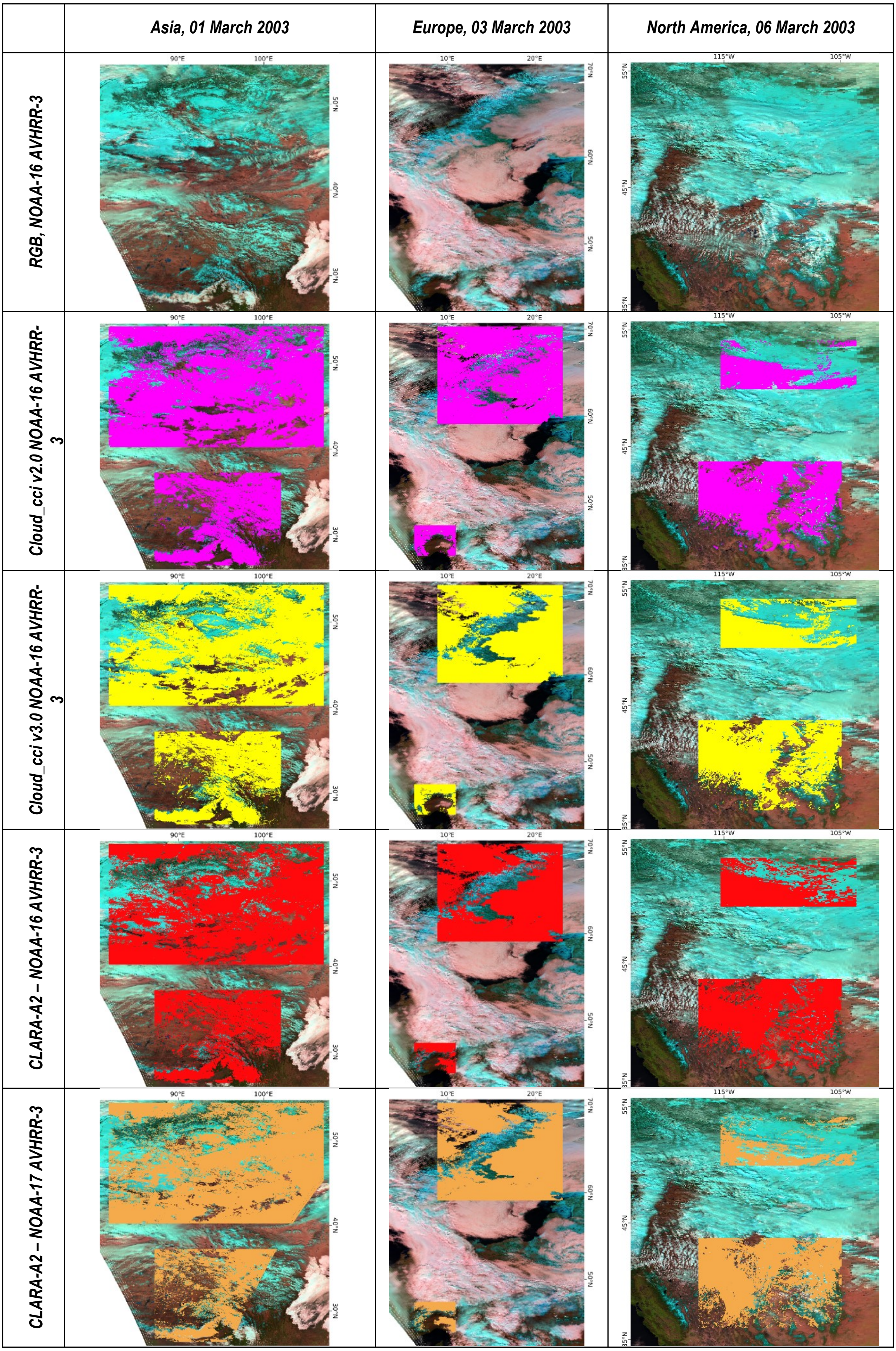
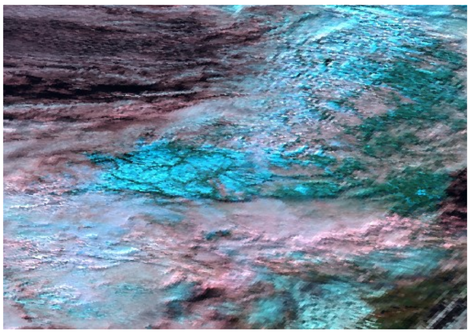
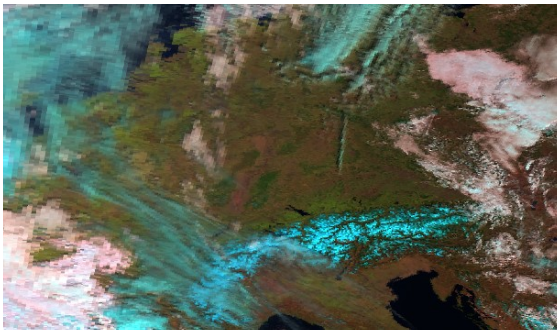
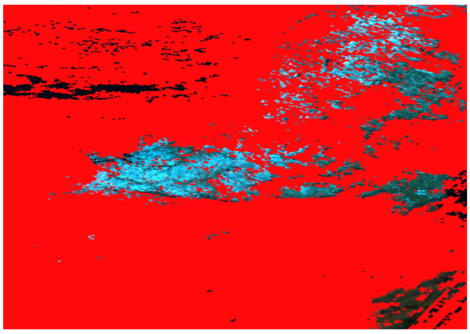
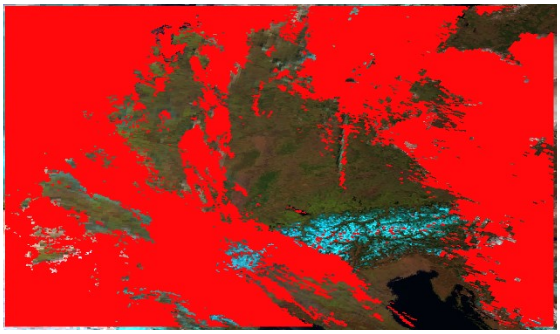
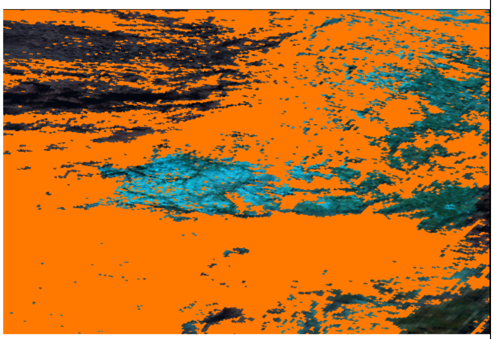
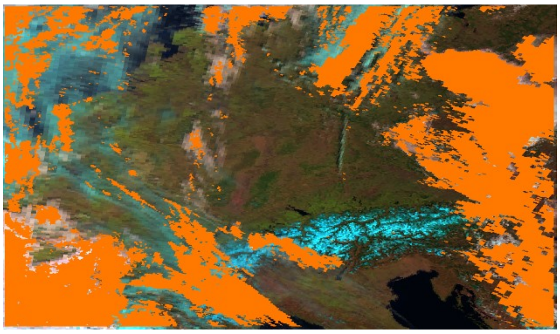


Figure 3.3: RGB false colour composites of AVHRR-3 data over Asia, Europe and North America in March 2003 and thereof derived cloud masks for selected test regions used for the intercomparison.

In the following, we present examples for two test sites in Europe for March 2017. In the cloud masks for Scandinavia based on the data acquired by Metop-A, NOAA-18 and NOAA-19 satellites (Figure 3.4) most of the snow is identified as clouds. We did not consider them in the further investigations. Both SCDA v2.0 and SCDA v2.1 agree quite well over the snow (99.8 % agreement of cloud pixels (Figure 3.4)). SCDA v2.1 misclassified small amount of snow pixels as cloud in the small area where SCDAv2.0 does not detect any clouds.

All confusion matrices including the matching accuracy of the different cloud products with the Cloud_cci v3.0 cloud mask in 2003 and the SCDA v2.0 cloud mask in 2017 are listed in Table 3.4.

	Scandinavia, 12 March 2017	*Central Europe, 12 March 2017*
RGB, METOP AVHRR-3		
Cloud_cci v2.0 – METOP-B AVHRR-3		
SCDAv2.1 METOP-B AVHRR-3		

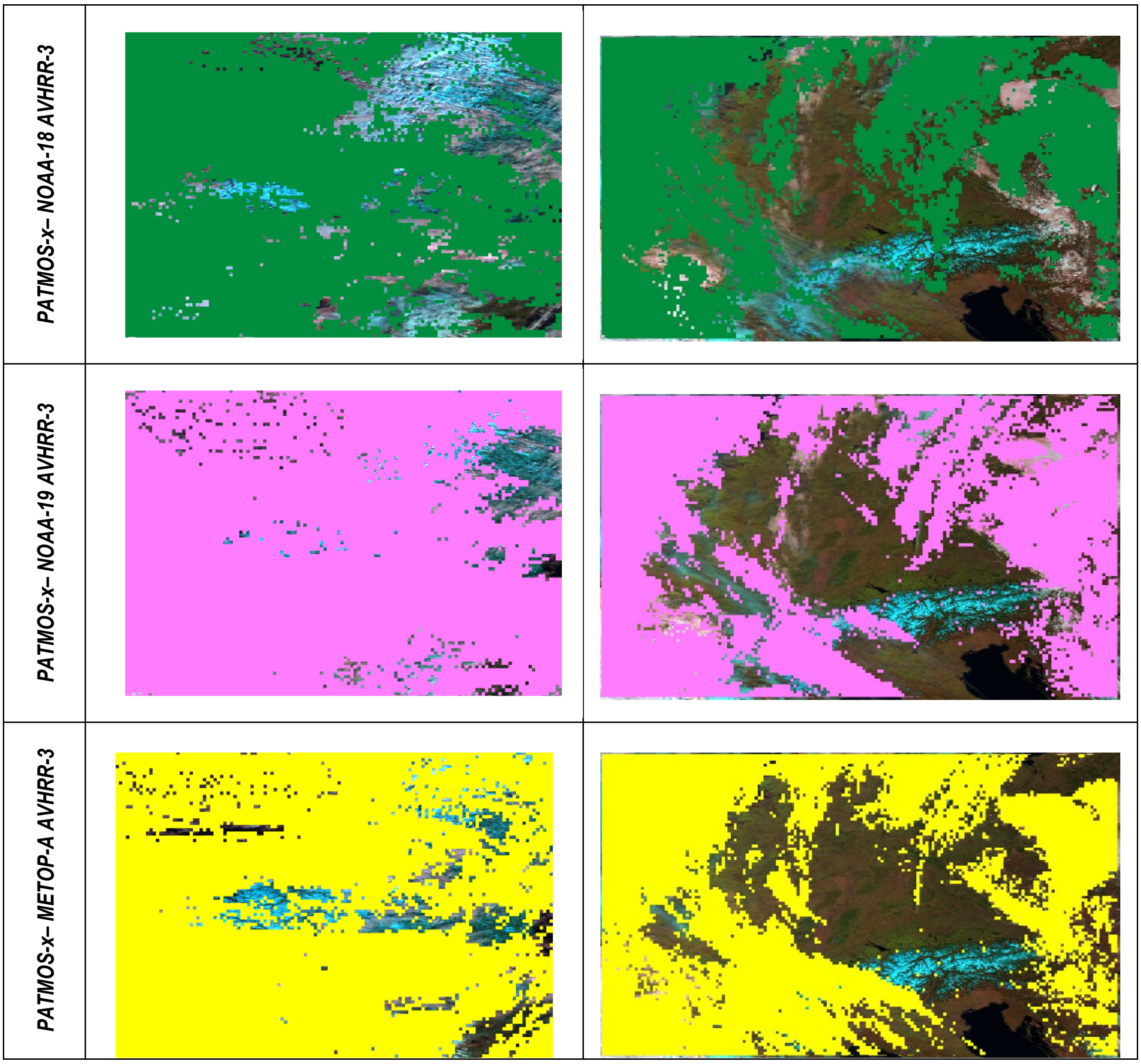


Figure 3.4: Different cloud masks generated from AVHRR data of 12 March 2017 over test sites in northern and southern Europe.

Table 3.4: Confusion matrix and matching accuracy for cloud masks from AVHRR-3 data over the different test regions in 2003 and 2017. For the intercomparisons in 2003, the *cloud_cci* v3.0 cloud mask is used as reference, for the intercomparisons in 2017, the SCDA v2.0 is used as reference, as the *cloud_cci* v3.0 cloud mask was not available at the time of the round robin exercises. Per region, two test sites are used: NTS = northern test site; STS = southern test site.

Region	Date	Cloud products used for comparison	TP	FP	FN	TN	Accuracy
Asia, NTS	01.03.2003	Cloud_cci v3.0 NOAA-16 vs CLARA-A2 NOAA-16	83.75	16.25	37.58	62.42	0.73
		Cloud_cci v3.0 NOAA-16 vs CLARA-A2 NOAA-17	79.70	20.30	53.75	46.25	0.63
		Cloud_cci v3.0 NOAA-16 vs Cloud_cci v2.0 NOAA-16	89.71	10.29	38.57	61.43	0.76
Asia, STS	01.03.2003	Cloud_cci v3.0 NOAA-16 vs CLARA-A2 NOAA-16	84.38	15.62	20.90	79.10	0.82
		Cloud_cci v3.0 NOAA-16 vs CLARA-A2 NOAA-17	54.32	45.68	24.28	75.72	0.65
		Cloud_cci v3.0 NOAA-16 vs Cloud_cci v2.0 NOAA-16	88.39	11.61	11.77	88.23	0.88
Europe, NTS	03.03.2003	Cloud_cci v3.0 NOAA-16 vs CLARA-A2 NOAA-16	91.87	8.13	26.05	73.95	0.83
		Cloud_cci v3.0 NOAA-16 vs CLARA-A2 NOAA-17	88.92	11.08	27.90	72.10	0.81
		Cloud_cci v3.0 NOAA-16 vs Cloud_cci v2.0 NOAA-16	93.49	6.51	56.27	43.73	0.69

Region	Date	Cloud products used for comparison	TP	FP	FN	TN	Accuracy
Europe, STS	03.03.2003	Cloud_cci v3.0 NOAA-16 vs CLARA-A2 NOAA-16	66.24	33.76	27.42	72.58	0.69
		Cloud_cci v3.0 NOAA-16 vs CLARA-A2 NOAA-17	65.22	34.78	27.73	72.27	0.69
		Cloud_cci v3.0 NOAA-16 vs Cloud_cci v2.0 NOAA-16	97.36	2.64	8.96	91.04	0.94
North America, STS	06.03.2003	Cloud_cci v3.0 NOAA-16 vs CLARA-A2 NOAA-16	86.36	13.64	29.12	70.88	0.79
		Cloud_cci v3.0 NOAA-16 vs CLARA-A2 NOAA-17	79.56	20.44	40.91	59.09	0.69
		Cloud_cci v3.0 NOAA-16 vs Cloud_cci v2.0 NOAA-16	93.37	6.63	10.87	89.13	0.91
North America, NTS	06.03.2003	Cloud_cci v3.0 NOAA-16 vs CLARA-A2 NOAA-16	84.47	15.53	38.12	61.88	0.73
		Cloud_cci v3.0 NOAA-16 vs CLARA-A2 NOAA-17	54.92	45.08	13.17	86.83	0.71
		Cloud_cci v3.0 NOAA-16 vs Cloud_cci v2.0 NOAA-16	73.01	26.99	8.27	91.73	0.82
Asia	01.03.2003	PATMOS-X NOAA-15 vs PATMOS-X NOAA-16	71.61	28.39	65.33	34.67	0.53
		PATMOS-X NOAA-16 vs PATMOS-X NOAA-17	80.04	19.96	48.98	51.02	0.66
Europe, STS	12.03.2017	SCDA v2.0 METOP-B vs Cloud_cci v2.0	100	0	53.75	46.25	0.73
		SCDA v2.0 METOP-B vs PATMOS-X METOP-A	86.7	13.3	49.33	50.67	0.69
		SCDA v2.0 METOP-B vs PATMOS-X NOAA-18	70.42	29.58	49.81	50.19	0.60
		SCDA v2.0 METOP-B vs PATMOS-X NOAA-19	87.64	12.36	47.95	52.05	0.70
		SCDA v2.0 METOP-B vs SCDA v2.1 METOP-B	100	0	16.1	83.9	0.92
Europe, NTS	12.03.2017	SCDA v2.0 METOP-B vs Cloud_cci v2.0 METOP-B	98.69	1.31	70.24	29.76	0.64
		SCDA v2.0 METOP-B vs PATMOS-X METOP-A	95.8	4.2	79	21	0.58
		SCDA v2.0 METOP-B vs PATMOS-X NOAA-18	80.82	19.18	73.22	26.78	0.54
		SCDA v2.0 METOP-B vs PATMOS-X NOAA-19	96.23	3.77	86.61	13.39	0.55
		SCDA v2.0 METOP-B vs SCDA v2.1 METOP-B	100	0	32.97	67.03	0.84
Asia, NTS	13.03.2017	SCDA v2.0 METOP-B vs PATMOS-X METOP-A	87.86	12.14	44.63	55.37	0.72
		SCDA v2.0 METOP-B vs PATMOS-X NOAA-18	69.38	30.62	56.27	43.73	0.57
		SCDA v2.0 METOP-B vs PATMOS-X NOAA-19	100	0	47.09	52.91	0.76
		SCDA v2.0 METOP-B vs SCDA v2.1 METOP-B	100	0	47.09	52.91	0.76
		SCDA v2.1 METOP-B vs Cloud_cci v2.0 METOP-B	78.78	21.22	38.84	61.16	0.7
Asia, STS	13.03.2017	SCDA v2.0 METOP-B vs PATMOS-X METOP-A	94.2	5.8	42.26	57.74	0.76
		SCDA v2.0 METOP-B vs PATMOS-X NOAA-18	82.11	17.89	53.26	46.74	0.64
		SCDA v2.0 METOP-B vs PATMOS-X NOAA-19	100	0	22.62	77.38	0.89
		SCDA v2.0 METOP-B vs SCDA v2.1 METOP-B	100	0	22.62	77.38	0.89
		SCDA v2.1 METOP-B vs Cloud_cci v2.0 METOP-B	98.75	1.25	43.15	56.85	0.78

3.3.2. MODIS cloud screening

The comparison of three MODIS based cloud masks (SCDA v2.0, SCDA v2.1 and MOD35) for selected dates in 2017 over test sites in Asia and North America (Figure 3.5) shows major differences in detection of clouds over the snow. SCDA v2.0 seems to work the best over snow areas in the visual comparison. In these examples, SCDA v2.1 shows overestimation of clouds over the snow and over the snow-free areas. Using SCDA v2.0 as reference for the cloud mask in Asia (Figure 3.5), SCDA v2.1 does not detect all the snow pixels; cloud-free agreement is on 62.63% rate (Table 3.6). The MOD35 is often overestimating clouds over the snow or classifies snow boundaries as clouds.

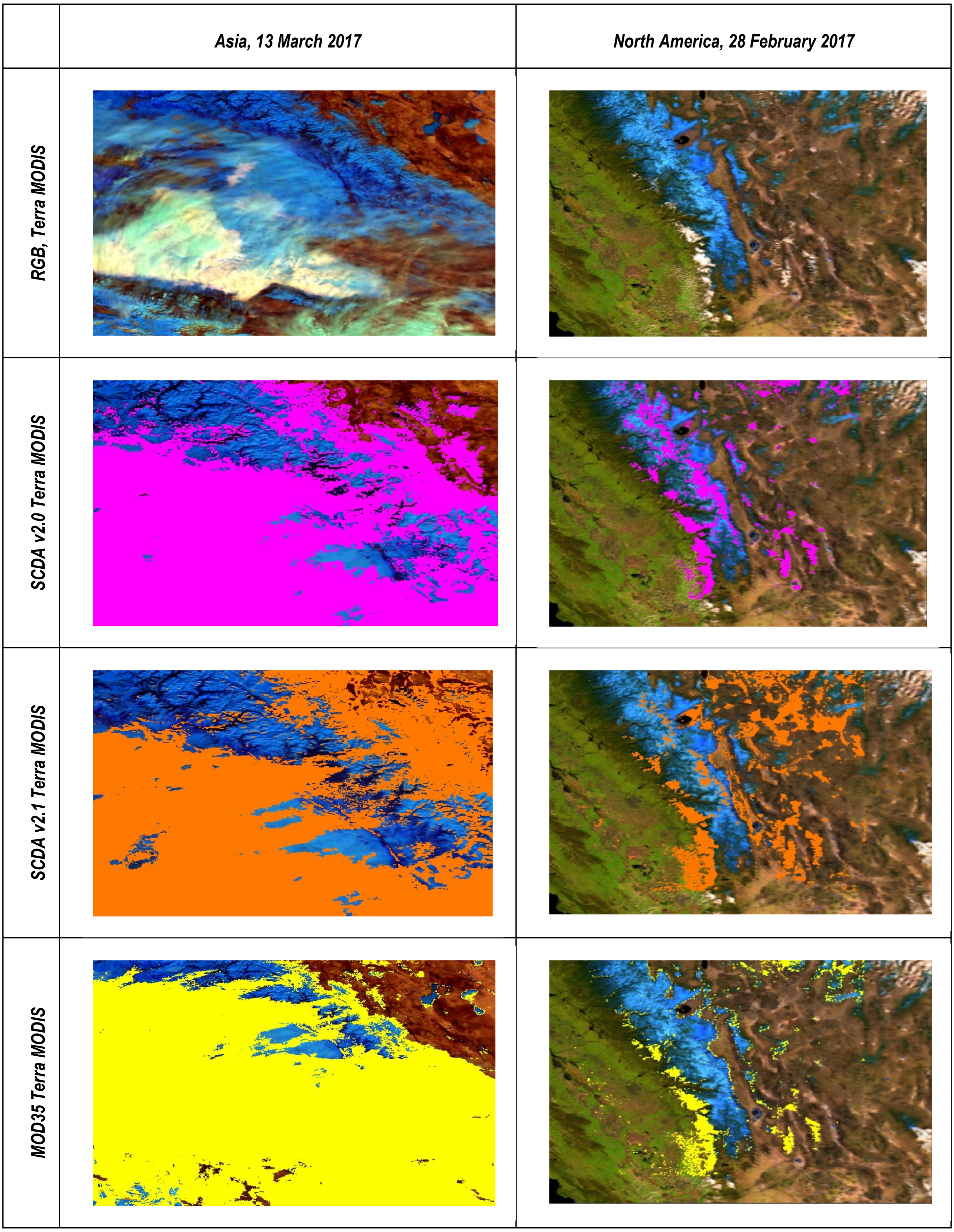


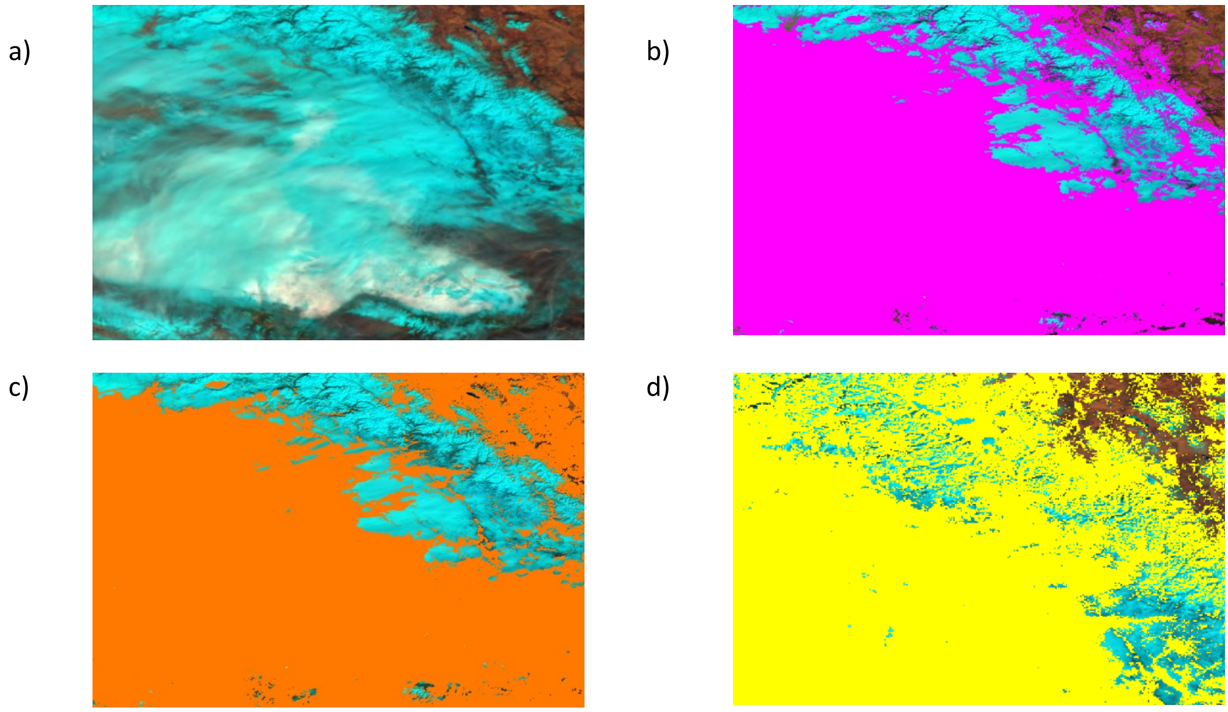
Figure 3.5: RGB composite and different cloud masks used for intercomparison over test sites in Asia and North America in 2017.

Table 3.5: Confusion matrix and matching accuracies for the comparison of cloud masks generated from Terra MODIS data of 2017 over different test sites in Asia and North America.

Region	Date	Cloud products used for comparison	TP	FP	FN	TN	Accuracy
Asia, NTS	13.03.2017	SCDA v2.0 vs SCDA v2.1	96.51	3.49	19.97	80.03	0.88
		SCDA v2.0 vs MOD35_L2	86.74	13.26	11.63	88.37	0.88
		SCDA v2.0 vs SCDA v2.1	96.95	3.05	37.37	62.63	0.80
Asia, STS	13.03.2017	SCDA v2.0 vs MOD35_L2	93.71	6.29	9.35	90.65	0.92
		SCDA v2.0 vs SCDA v2.1	96.51	3.49	19.97	80.03	0.88
		SCDA v2.0 vs MOD35_L2	86.74	13.26	11.63	88.37	0.88
North America, STS	28.02.2017	SCDA v2.0 vs SCDA v2.1	92.06	7.94	2.77	97.23	0.95
		SCDA v2.0 vs MOD35_L2	86.68	13.32	13.85	86.15	0.86
North America, NTS	28.02.2017	SCDA v2.0 vs SCDA v2.1	64.87	35.13	10.92	89.08	0.77
		SCDA v2.0 vs MOD35_L2	39.99	60.01	3.21	96.79	0.68

3.3.3. *SLSTR cloud screening*

For the Sentinel-3 SLSTR data, the cloud masks from SCDA v.20, SCDA v2.1, the SLSTR cloud mask provided as layer in the data and the *cloud_cci* cloud mask were compared. The examples presented in Figure 3.6 show the different cloud masks and the associated confusion matrices for these cloud masks from Sentinel-3 SLTSR data of 13 March 2017 over Asia are presented in Figure 3.7. The SCDA v2.0 seems to work best for SLSTR, while all other cloud masks are overestimating clouds over snow covered areas and partially also over snow free areas.



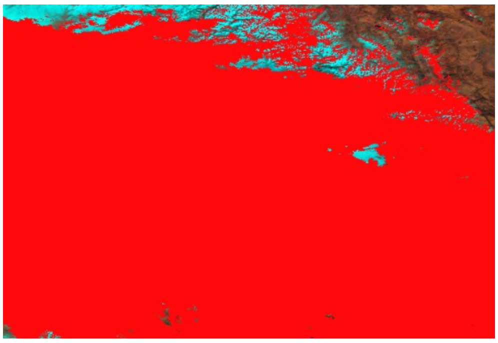
e) 

Figure 3.6: Data sets for common extent in Asia on 13 March 2017: a) RGB composite; b) SCDAv2.0; c) SCDAv2.1; d) SLSTR cloudmask; e) *Cloud_cci* cloudmask from SLSTR.

SCDAv2.1	SCDAv2.0 CLOUD	SCDAv2.0 CLOUD FREE
CLOUD	TPR 95.48	FNR 4.52
CLOUD FREE	FPR 45.92	TNR 54.08

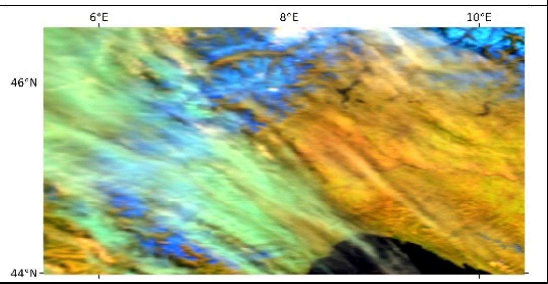
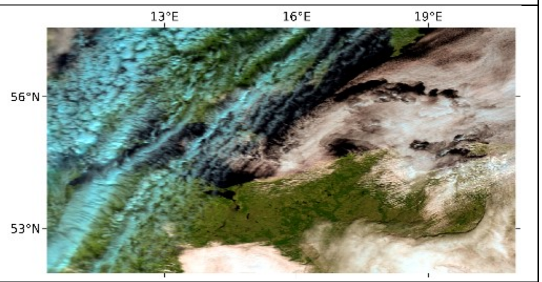
SLSTR Cloudmask	SCDAv2.0 CLOUD	SCDAv2.0 CLOUD FREE
CLOUD	TPR 94.63	FNR 5.37
CLOUD FREE	FPR 46.31	TNR 53.69

cloud_cci	SCDAv2.0 CLOUD	SCDAv2.0 CLOUD FREE
CLOUD	TPR 95.20	FNR 4.80
CLOUD FREE	FPR 41.42	TNR 58.58

Figure 3.7: Confusion matrices between SCD Av2.0 and SCDA v2.1 (left); SCDA v2.0 and SLSTR cloud mask (center); and SCDA v2.0 and *cloud_cci* cloud mask (right).

3.3.1. MODIS – SLSTR cloud mask intercomparison

The SCDA v2.0 mask has been calculated for MODIS and SLSTR for the same scene in the Alps and Central Europe. The MODIS and SLSTR scenes were each acquired on the same date with only 3 minutes delay. There is not much difference between the SCDA v2.0 mask created for both sensors. Taking into consideration that there are 3 minutes difference between acquisitions times, the accuracy of clouded pixels is very high (Figure 3.8). In both cases there are around 44 % cases of negative cloud-free pixels detection (Table 3.6).

	Alps, 12 March 2017	*Central Europe, 12 March 2017*
RGB, Terra MODIS		

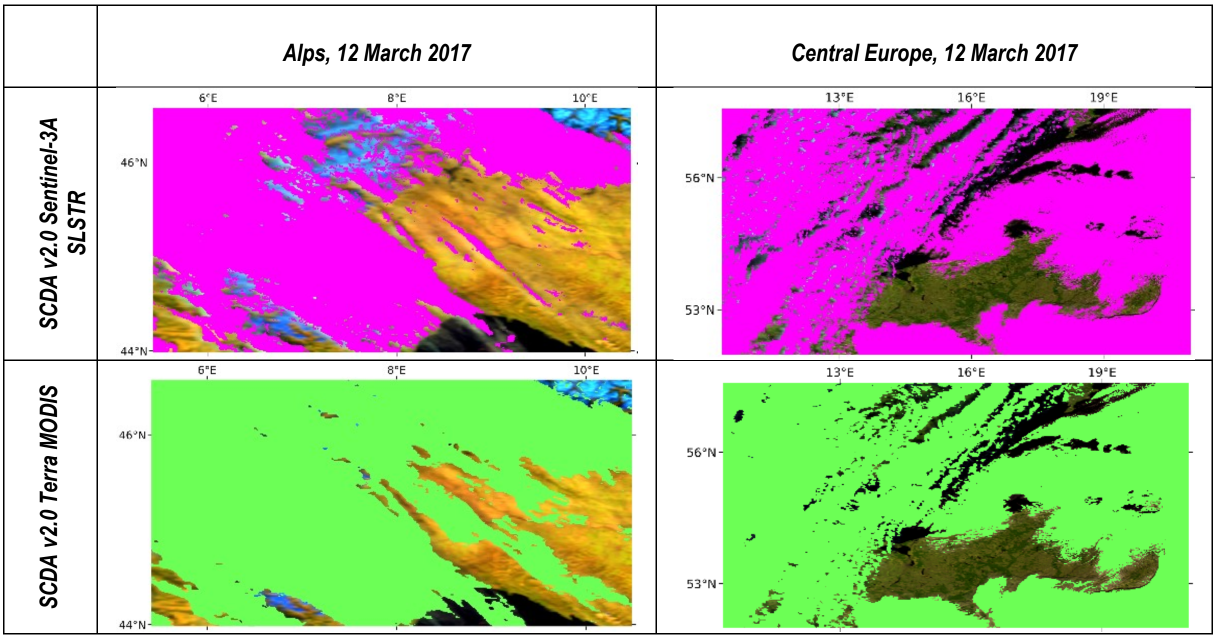


Figure 3.8: Cloud masks generated by the SCDA v2.0 from Terra MODIS and Sentinel-3A SLSTR data acquired on the same date with only 3 minutes delay for two test sites in Europe.

Table 3.6: Confusion matrix and matching accuracy for cloud masks from SLSTR and MODIS data for test sites in Europe on 12 March 2017.

Region	Date	Cloud products used for comparison	TP	FP	FN	TN	Accuracy
Central Europe	12.03.2017	S3 cloud mask vs MOD35	94.10	5.90	46.55	53.45	0.74
		SLSTR SCDA v2.0 vs MODIS SCDA v2.0	97.76	2.24	43.12	56.88	0.77
		SLSTR SCDA v2.1 vs MODIS SCDA v2.1	98.43	1.57	63.76	36.24	0.67
Alps	12.03.2017	S3 cloud mask vs MOD35	97.01	2.99	56.46	43.54	0.70
		SLSTR SCDA v2.0 vs MODIS SCDA v2.0	96.07	3.93	44.21	55.79	0.76
		SLSTR SCDA v2.1 vs MODIS SCDA v2.1	98.20	1.80	53.71	46.29	0.72

3.4. Conclusions

For MODIS and SLSTR SCDA v2.0 works best and is most mature and well tested one. SCDA v2.1 overestimates cloud coverage over free areas and is not tested enough yet. MODIS product cloud mask MOD35 misclassifies to many snow-covered pixels as clouds, in particular over fractional snow. SLSTR cloud product significantly overestimates clouds over snow and is not recommended to use. Cloud CCI product from MODIS is only available for Europe for the period 2003 – 2015, so it cannot be applied for our purposes. Cloud CCI product for SLSTR is significantly overestimating clouds over snow. For those two sensors we finally agreed to use SCDA v2.0 as a standard cloud mask.

For AVHRR we cannot use neither SCDA v2.0 nor SCDA v2.1 as it requires using simultaneously bands 3a (1580 – 1640 nm) and 3b (3550 – 3930 nm) that unfortunately are not available at the same time. Cloud masks derived from Metop satellites significantly overestimate the clouds over snow and snow-free pixels. *Cloud_cci* cloud mask version 2.0 does not work very well over snow areas, whereas version 3.0 shows much better performance. CLARA A-2 NOAA-16 and NOAA-17 also work quite well over snow, but they are less conservative as *cloud_cci* cloud mask version 3.0. Taking everything into consideration we decided to use Cloud CCI cloud mask version 3.0 for AVHRR.

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