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aerosol_cci2

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EXECUTIVE SUMMARY

This document describes the aerosol products delivered at the end of the baseline Aerosol_cci2 project (10/2017): the Essential Climate Variables (ECV – the level2 and 3 output products). This document is targeted at end users (climate modellers and data assimilation users) and thus aims at providing a condensed summary of the key information needed for the appropriate usage of the products. This document takes into account all ECV datasets contained in the Aerosol_cci Climate Research Data Package (CRDP) (including mature earlier products from phase 1).

The document includes for all ECVs a description of the products (geophysical content, flags and metadata, format, grid and projection) and, most importantly a discussion of their known limitations and strengths as well as tools used for their analysis and display.

The input products currently used are: ATSR-2 / AATSR reflectances (forward and nadir), MERIS reflectances (over ocean), POLDER polarized reflectances, GOMOS residual extinctions (occultation), IASI thermal spectra and OMI UV-visible spectra. Output products are (multi-spectral) aerosol optical depth and derived quantities from ATSR-2 / AATSR, MERIS, IASI, POLDER together with GOMOS stratospheric extinction profiles and OMI absorbing aerosol indices.

Validation of all products has been completed and is described in the Product Valdiation and Intercomparison Report (PVIR), version 3.4 of 18/08/2017. Further assessment of the capabilities and limitations of the datasets has been conducted in several user case studies, which have been summarized in the Climate Assement Report (CAR), version 2.4 of 21/11/2017. This PUG contains a brief summary of validation results.

This document consists of 8 sections. After an introduction it starts with a description of the product content (sec. 2) and the direct access to the products, the flags and metadata (sec. 3), the data format (sec. 4), and the product grid and projections (sec. 5). The most important section is the one on known limitations and strengths of each product (sec. 6) – this section has been updated based on validation of 12 months of data. Finally, tools to read, visualize and analyse the products are summarized (sec. 7).

Issue	Date	Modified Items / Reason for Change

0.9	12.07.2012	First draft issued
1.0	20.09.2012	Completion of document (all algorithms) Issue of first version
1.1	01.07.2013	Update of section 6.2 (strengths and limitations of ECV output products) and section 9 based on completed validation of 12 month datasets of the ECV products. Update of section 2 (addition of direct product access information from readme file at ICARE server) Addition of 2 appendices (slide sets summarizing general benefits of the Aerosol_cci ECV products and product sheets for each dataset)
1.2	26.11.2013	Update (this document + 2 appendices) including ECV products / validation until November 2013
1.3	13.03.2014	Corrections according to RIDs raised 18.12.2013
Phase 2		
1.0	26.03.2015	Update for end of year 1 in phase 2
1.1	30.04.2015	Completion with partner input
2.0	26.07.2016	Update to year 2 datasets + their preliminary validation (year 1 datasets)
2.1	29.11.2017	Update based on latest validation results; replace appendices with references to latest PVIR and CAR.
2.2	13.12.2017	Minor updates based on ESA requests
2.3	08.01.2018	One correction in section 6.1

TABLE OF CONTENTS

1 INTRODUCTION

The purpose of this Product User Guide is to provide practical information to help users make use of the data products in the Aerosol_cci Climate Research Data Package (CRDP).

The scope of this Product User Guide is the set of mature products contained in the CRDP at the end of the baseline Aerosol_cci2 project (10/2017).

1.1 References

1.1.1 Applicable Documents

[AD1] The Statement of Work, reference CCI-PRGM-EOPS-SW-12-0012, issue 1, revision 2, dated June 7th, 2013, and its specific annex C (altogether the SoW).

[AD2] The Contractor's Proposal reference 3010317 revision 1.2 , dated 04 April 2014

1.1.2 Reference Documents

[RD1] Aerosol_cci Product Specification Document, v3.1, 04.01.2017

[RD2] Product Validation and Intercomparison Report, version 3.4, 18.08.2017

[RD3] Climate Assement Report, version 2.4, 21.11.2017

[RD4] Aerosol_cci_17year_validation report, version 1.0, 01.03.2015

2 THE GEOPHYSICAL PRODUCT CONTENT

2.1 Overview over the ECV datasets

The primary products delivered from Aerosol_cci are multi-annual global datasets of total column Aerosol Optical Depth (ATSR-2 / AATSR, MERIS, POLDER: total aerosol; ATSR-2 / AATSR and POLDER also Fine Mode AOD / Ångström exponent; IASI: mineral dust aerosol) together with stratospheric extinction profiles (GOMOS) and Aerosol Absorbing Index (multi-sensor spectrometers; co-funded through Aerosol_cci). All products provide also a pixel-level uncertainty value.

Following global products including quality flags / uncertainties are provided at the end of the phase 2 project (including the period covered by each dataset, the resolution provided and the validated aerosol parameters contained):

Mature full mission processed datasets

algorithm	version	sensor(s)	responsible provider	Main aerosol parameters	Resolution coverage	period(s)
ADV / ASV	2.31 (also 2.30_plume)	AATSR	FMI	AOD, FMAOD/ANG	10km, 1° global	2002-2012
	2.31 (also 2.30_plume)	ATSR-2	FMI	AOD, FMAO/ANG	10km, 1° global	1995-2003
ORAC	4.01	AATSR	UOxford / RAL	AOD, FMAOD/ANG	10km, 1° global	2002-2012
	4.01	ATSR-2	UOxford / RAL	AOD, FMAOD/ANG	10km, 1° global	1995-2003
SU	4.3	AATSR	USwansea	AOD, FMAOD/ANG	10km, 1° global	2002-2012
	4.3	ATSR-2	USwansea	AOD, FMAOD/ANG	10km, 1° global	1995-2003
Ensemble (uncertainty -weighted)	2.6	AATSR	DLR	AOD,	10km, 1° global	2002-2012
	4.3	ATSR-2	DLR	AOD,	10km, 1° global	1995-2003
AERGOM	3.00	GOMOS	BIRA	stratospheric extinction profiles + AOD+ ANG	60x5° 5-daily averages Global	2002-2012
MAPIR	3.51 (also 3.2-3.4-3.5-merged)	IASI	BIRA	Dust AOD	12km, 1° global	2007-2015
LMD	1.3	IASI	LMD	Dust AOD	12km, 1° global	2007-2015
ULB	7	IASI	ULB	Dust AOD	12km, 1° global	2007-2015
IMARS	5.2	IASI	DLR	Dust AOD	12km, 1°	2007-2015

					global	
GRASP	0.07.00	POLDER	LOA	AOD, SSA, FMAOD / ANG	6km / 1° 4 land regions Africa	2005-2013 12/2007-11/2008

Note that following global products including quality flags / uncertainties were provided and evaluated at end of phase 1:

Old datasets (mature datasets from phase 1 - recommended for use)

algorithm	version	sensor(s)	responsible provider	Main aerosol parameters	Resolution coverage	period(s)
ALAMO	2.2	MERIS	HYGEOS / ICARE	AOD	10km, 1° global ocean	2008 [1)]
AAI	1.01	OMI	KNMI	AAI	0,25° global	2005, 2008 [2)]

[1)] complete MERIS time series available from ICARE
[2)] complete time series 1978 – 2014 from OMI, GOME, SCIAMACHY, GOME-2 available from TEMIS

Note that further experimental products not described in this user guide are provided on request.

ESA Aerosol_cci products are publically and freely available at http://www.icare.univ-lille1.fr/archive/?dir=CCI-Aerosols **and at** ftp.icare.univ-lille1.fr. Unrestricted access is provided without user registration – a user shall use the common CCI user account: account name: cci; password: cci

The following license is valid for using the Aerosol_cci products:
The products provided on this server are openly and freely available. No warranty is given by their providers. Users are obliged to acknowledge the ESA Climate Change Initiative and in particular its Aerosol_cci project together with the individual algorithm developer.
We encourage interaction with the algorithm developers on proper use of the products and would like to receive a copy of all reports and publications using the datasets. An offer of co-authorship should be considered, if the CCI datasets constitute a major component of a scientific publication.

2.2 ECV datasets from ATSR instruments

Table 2.1: Spectral channels of the AATSR instrument

Channel	Wave-length (nm)	Band-width (nm)
1	550	20
2	665	20
3	865	20
4	1610	60
5	3740	380
6	10850	90
7	12000	1000

The **AATSR** instrument is a scanning radiometer, sensing at thermal infrared, reflected infrared and visible wavelengths with two ~500 km wide conical swaths, with 555 pixels across the nadir swath and 371 pixels across the forward swath. The specifications of AATSR and ATSR-2 are the same, except that the ATSR-2 instrument employed a reduced swath of visible channels over and near oceans due to data transmission restrictions. The set of channels are listed in Table 2-1. The nominal pixel size is 1 km^2 at the centre of the nadir swath and 1.5 km^2 at the centre of the forward swath. For the AATSR level 1 products the forward pixels are sampled to 1km in order to be of the same size as the nadir pixels. The conical scan provides two views of the surface and improves the capacity for atmospheric correction and enables observations of the ocean surface under a solar zenith angle of ~55° in the forward direction. The channels at 1.6µm and 0.87µm are especially important to correct for the impact of aerosols, especially above coastal waters, since at this spectral range there is nearly no backscattering of solar radiation emanating from the water body. For land aerosol retrieval, the bands at shorter wavelengths (550nm and 665nm) where aerosol scattering is greater with respect to surface scattering are important.

Total column Aerosol Optical Depth (AOD) is derived from **AATSR** currently provided with three different algorithms (ADV/ASV, ORAC, SU). All deliver AOD at 550 nm and several other wavelengths; further derived parameters (e.g. Angstrom coefficient, fine mode AOD, mixing fractions of fine/coarse, salt/dust in coarse, absorbing/non-absorbing fine aerosols) are provided by several of them. The AOD uncertainty provided from AATSR is calculated through error propagation (ADV/ASV, ORAC algorithms) or parameterization of the error dependencies to the geophysical retrieval conditions (SU algorithm). AOD products from all

AATSR algorithms are provided as level 2 products (one file per orbit) and as level 3 products (daily and monthly gridded 1° x 1° datasets).

2.3 ECV dataset from the MERIS instrument

The **MERIS** instrument (Bezy, 2000) is a medium spectral resolution imaging spectrometer on board of ENVISAT, having 15 channels in the wavelength range of 0.412 – 0.900 µm. It's scan is composed of 5 cameras, giving a swath width of 1100 km and a spatial resolution of 0.3 km in the full resolution mode (FR) and 1.2 km in the reduced resolution mode (RR). This enables every 2 – 3 day observation of a certain location on the globe. The instrument performes a nadir scan with a maximum viewing angle of ±42 degrees. The MERIS channels and their use within the BAER algorithm is presented in Table 2.1. Channels for the determination of the aerosol optical thickness (AOT) are marked as well for the retrieval part over ocean (O) as well for the retrieval part over land (L). Channels for the determination of the auxilliary parameter to adapt the land surface model, the normalized differential vegetation index (NDVI) are also indicated.

Table 2.2: Spectral channels of the MERIS instrument

MERIS channels	
Wavelength (µm)	Band width (µm)
0.4127	0.00994
0.4426	0.00995
0.4899	0.00996
0.5098	0.00996
0.5597	0.00997
0.6196	0.00998
0.6646	0.00999
0.6808	0.00749
0.7083	0.00999
0.7534	0.00750
0.7615	0.00374
0.7784	0.01501
0.8648	0.02004
0.8849	0.01001
0.9000	0.01002

The absolute accuracy in TOA reflectance is for MERIS about 3 % (Delwart et al, 2003, Martiny et al., 2005a) and SeaWiFS 4 % (Martiny et al., 2005b). This is sufficient, if one is considering, that disturbing effects, like land surface and Rayleigh path reflectance are not accounted in the above estimation. For the aerosol retrieval over land it is of importance, that the instrument is not reaching saturation in its radiometric sensitivity. There is no such problem for MERIS.

Total column Aerosol Optical Depth (AOD) is derived from **MERIS** with one algorithm (ALAMO) over ocean only which delivers AOD at 550 nm and 865 nm; further derived parameters (e.g. fine mode AOD, aerosol layer altitude) are provided. The information content and quality of these derived parameters is still under investigation. The AOD uncertainty provided from MERIS is calculated as standard deviation of AOD within the 10x10 km2 super pixel. The AOD product from MERIS is provided as level 2 products (one file per orbit) and as level 3 products (daily and monthly gridded 1° x 1° datasets).

2.4 ECV dataset from the GOMOS instrument

GOMOS (Global Ozone Monitoring by Occultation of Stars) on board ENVISAT is a UV/Visible/near-IR spectrometer that works in occultation mode: while orbiting the Earth, the instrument measures the transmission of light from stars that are setting below the Earth's horizon. Since the starlight has to pass through the Earth's atmosphere, it is partly scattered or absorbed by atmospheric gases and particles. The measurements therefore can be used to retrieve gas concentration and aerosol extinction profiles. Using a scanning mirror and a star tracker, GOMOS continuously observes selected stars; during one orbit, several different occultations are measured. In this way, several hundreds of occultations with good global coverage can be measured per day. Measurements are taken both on the dark and sun-illuminated side of the Earth, although in the latter case scattered sunlight represents an extra source of error for retrievals. During one orbit about 30 to 50 occultations can be measured, demonstrating the potential of using stars as the light source: the measurement rate is much higher in comparison to the usual solar occultation technique, which is limited to the two occultations for sunrise and sunset. The price to pay is the smaller S/N-ratio, due to the fact that the Sun is a much brighter light source.

While GOMOS originally was conceived as an instrument designed to measure highly accurate ozone profiles, a few other species can also be derived. Typically, the UV/Vis wavelength range combined with the sensitivity of the GOMOS spectrometers allows the retrieval of ozone, NO_2, air, NO_3, O_2 and aerosol extinction profiles. While ozone can be retrieved up to 100 km of altitude, the other species are usually only detectable from the upper troposphere to about 50 km. The actual altitude range differs for different species and depends on the abundance of the species and on the amount of light available; for aerosol/clouds in the UTLS, profiles can be typically obtained between 10 and 35 km.

The spectrum of the starlight is measured by four spectrometers operating in a wavelength range from 250 to 950 nm. Additionally, GOMOS is equipped with two fast photometers of which the signals are used to correct for star scintillation and to retrieve high-resolution temperature profiles. More specifically, the GOMOS instrument consists of:

- Two spectrometers A1 and A2 (SPA1 and SPA2) covering the UV- Visible wavelength range (248-690 nm) with a spectral pixel width of 0.31 nm and a spectral resolution of 0.8 nm, with the purpose of measuring optical absorption by O_3, NO_2, NO_3, aerosol extinction and neutral density. A few other trace gases are also detectable (OClO, Na)

- A spectrometer B1 (SPB1) covering the longer wavelength range (755- 774 nm) with a spectral pixel width of 0.045 nm and a spectral resolution of 0.13 nm, with the purpose of measuring O_2 absorption.

- A spectrometer B2 (SPB2) covering the near-IR wavelength range (926-954 nm) with a spectral pixel width of 0.052 nm and a spectral resolution of 0.13 nm. It was included to measure water vapour absorption bands.

- Two fast photometers, sampling the blue (473-527 nm) and the red (646-698 nm) spectral domain at a sampling frequency of 1 kHz. Their main purpose is the removal of star scintillation in the spectrometer measurements.

GOMOS was primarily intended to deliver accurate altitude profiles of trace gas concentrations. Atmospheric particle populations pose a more challenging problem since the spectral shape is unknown, with the direct consequence that it is a priori impossible to find out which kind of particles are in the line of sight of the instrument. This is the reason why GOMOS delivers only one common product, perhaps somewhat misleadingly dubbed “aerosol extinction”. It should be understood that this data product embraces stratospheric aerosols, tropical subvisual cirrus clouds and Polar Stratospheric Clouds (PSCs) - or indeed even any unknown extinction phenomenon with a smooth spectral dependence.

Within the ESA AERGOM project a new algorithm was developed which exploits the stellar occultation instrument **GOMOS** to derive aerosol and cloud (tropical subvisual cirrus and PSC) extinction profiles in the upper troposphere and stratosphere. Based on this level2 product, the Aerosol_cci stratospheric product from GOMOS is provided as level 3 products (daily and monthly gridded 2.5° x 10° datasets) and contains aerosol extinction profiles together with stratospheric integrated (above the tropopause) aerosol optical depth.

2.5 ECV dataset from the OMI instrument

OMI aerosol information requires measured reflectances at two wavelengths plus the calculated theoretical for a Rayleigh-scattering only atmosphere at the reference wavelength, in this case the longer wavelength of the two. This calculation results in a residual value which if positive indicates the presence of UV absorbing aerosol like smoke and dust. The positive residual values are typically referred to as the Absorbing Aerosol Index (AAI). In this case, OMI utilizes the ultraviolet (UV) spectral range to detect the presence of UV-absorbing aerosols in the atmosphere. OMI additionally uses information from the visible spectral range to retrieval aerosol optical depth (AOD), however only AAI will be discussed in this document. Because the AAI is a ratio, many errors are averaged out. Errors in the AAI are driven by any errors in the measured radiances that are not the same at each wavelength, which could include simple offset errors in the measured radiance, random errors, and unknown wavelength dependence of the surface albedo between the given wavelength pair.

From **OMI** the Absorbing Aerosol Index (AAI) is the primary output product. The Aerosol_cci AAI product from OMI is provided as level 3 products (daily and monthly gridded 0.25° x 0.25° datasets). The OMI AAI product is combined with AAI datasets from other sepctrometers to prepare a multi-sensor multi-annual time series of AAI.

2.6 ECV datasets from the IASI instrument

IASI exploits high resolution spectra between 8 and 12 µm to analyse spectral structures of silicates and thereby determine the infrared extinction of desert dust. Depending on the algorithm auxiliary information is used to constrain perturbing factors such as surface emissivity, temperature and water vapor content. Clouds are either flagged by a pre-processing step or are assigned a posteriori as probability in the retrieval. Different IASI retrievals do also allow estimation of an "effective dust layer height" or a "mean aerosol height" and mineral composition. IASI dust observations are available for night and day overpasses of the Metop spacecraft.

From **IASI** the mineral dust AOD (D_AOD) is the primary output product. The Aerosol_cci D_AOD product from IASI is provided as level 2 and 3 products (daily and monthly gridded 1° x 1° datasets). In a round robin exercise 4 algorithms were used and their results are intercompared and evaludated with external reference data (AERONET SDA coarse mode AOD, campaign and model data).

From **IASI** first multi-annual datasets for a regional subset covering the Saharan and Arabian deserts as well as parts of the Atlantic Ocean and central Asia has been processed with all four algorithms. Product evaluation and intercomparison are still ongoing. Validation is so far based on predecessor version covering entire 2013.

2.7 ECV dataset from the POLDER instrument

POLDER-1, 2, 3 instruments measure angular distribution of both total and polarized radiation reflected to the space. The observations in 6 window channels where the effect of absorption by atmospheric gases are minimal are usually used for aerosol retrievals. Three channels provide linear polarization measurements (Stokes parameters Q and U).

The specification of POLDER-1, 2 instruments is similar to POLDER-3 instrument except of difference in polarization channel (0.490 μm polarization channel for POLDER-3 instead of 0.443 μm for POLDER-1,2) and near-infrared channel (additional 1.020 μm channel in POLDER-3). The CCD-matrix in POLDER-3 instrument is turned on 90 degree in comparison with POLDER-1,2 instruments. As a result POLDER-3 has smaller cross-track (1600 km instead of 2200 km for POLDER-1, 2) but wider along track (+/-57 degree along-track field of view for POLDER-3 instead of +/- 43 degree for POLDER-1, 2).

Table 2.3: Spectral channels of the POLDER-3 instrument

POLDER-3: 6 km 1-pixel resolution in nadir. Swath: 1600 km cross-track. Field of view (along-track): +/- 57 degree (14-16 viewing directions).		
Central wavelength (μm)	Band width (μm)	Polarization
0.4435 (aerosol retrieval)	0.0134	-
0.4909 (aerosol retrieval)	0.0163	yes
0.5638 (aerosol retrieval)	0.0154	-
0.6699 (aerosol retrieval)	0.0151	yes
0.7629	0.0109	-

0.7627	0.0381	-
0.8637 (aerosol retrieval)	0.0337	yes
0.9071	0.021	-
1.0196 (aerosol retrieval)	0.0171	-

Table 2.4: Spectral channels of the POLDER-1,-2 instrument s

POLDER-1, 2: 6x7 km 1-pixel resolution in nadir. Swath: 2200 km cross-track. Field of view (along-track): +/- 43 degree (14 viewing directions).		
Central wavelength (μm)	Band width (μm)	Polarization
0.4445 (aerosol retrieval)	0.02	yes
0.4449 (aerosol retrieval)	0.02	-
0.4922 (aerosol retrieval)	0.02	-
0.5645 (aerosol retrieval)	0.02	-
0.6702 (aerosol retrieval)	0.02	yes
0.7633	0.01	-
0.7631	0.04	-
0.8608 (aerosol retrieval)	0.04	yes
0.9077	0.02	-

New PARASOL algorithm GRASP (Generalized Retrieval of Aerosol and Surface Properties) is designed to retrieve complete aerosol properties: particle size distribution, shape, complex refractive index, and concentration. From these parameters the following ECV variables are determined: spectral AOD (total AOD as well as AOD for fine and coarse modes), Angstrom Exponent (AE), spectral Single Scattering Albedo (SSA). In addition, simultaneously with aerosol the algorithm retrieves the parameters of the reflection matrix (Bidirectional Reflection Matrix (BRDF and BPDF)) of underlying surface, which defines different kind of surface characteristics ("black sky" albedo, "white sky" albedo, Normalized Difference Vegetation Index (NDVI) etc).

GRASP/POLDER products are provided as level 2 products (6x6 km one pixel resolution) and as level 3 products (daily and monthly gridded 1° x 1° datasets).

3 THE DATA FORMAT

All Aerosol_cci products are provided in netCDF format (preferrably version 4) – this format has been chosen to comply with mostly used standards in the atmospheric climate modelling community. In agreement with the entire CCI program (guided by the Data Standards Working Group) naming of product files has been defined as follows:

Filename	
	<Indicative Date>[<Indicative Time>]-**ESACCI**-<Processing Level>_<**AEROSOL**>-<Data Type>-<Product String>[-<Additional Segregator>][-v<GDS version>]-fv<File version>.**nc** (filename parts in [ ] are optional)
example	**Lv2**: 20120201011908-**ESACCI**-L2P_**AEROSOL**-AER_PRODUCTS-AATSR-ENVISAT-ORAC_51898-fv03.02.**nc**" **Lv3**: 20130417-**ESACCI**-L3P_**AEROSOL**-AER_PRODUCTS-IASI_METOPA-DLR-IMARS_v3.3-DN-20130417000000Z_20130417235959Z-fv1.**nc**
Date type	
	AER_PRODUCTS (multiple variable datasets) AOD (total column visible AOD datasets) FM_AOD (the fraction of AOD ascribed to fine mode aerosol particles) D_AOD (total column infrared dust AOD datasets) S_AOD (AOD due to aerosol particles in the stratosphere) AAOD (Absorbing AOD) ATY (aerosol type datasets) AAI (absorbing aerosol index datasets) AEX (stratospheric extinction profile and AOD datasets) REFF (effective radius of the column-integrated particle size distribution)
Product string	
	Instrument_platform, e.g. AATSR-ENVISAT
	Algorithm, e.g. ADV version 1.42
	MERGED (data from more than one platform and/or sensor)
	AVHRR (data from AVHRR, more than one platform)
	Synergetic (data retrieved by using information from more than one platform)
Additional segregators	
	Additional segregators are an optional part of the filename, examples include: - Orbit identifier - Length of period covered, e.g. daily, monthly, specified period - land or sea area - resolution (spatial)

AOD products from mid-visible sensors (all algorithms) are provided as level 2 products (one file per orbit) and as level 3 products (daily and monthly gridded 1° x 1° datasets); dust AOD products from the thermal infrared sensor IASI are provided as level 2 products (one file with all observations from descending overpasses of one day and one with all ascending observations) and as level 3 products (daily all ascending, all descending and all averaged and monthly gridded 1° x 1° datasets); AAI and stratospheric extinction products are provided only as level 3 products (daily and monthly gridded datasets). Each file contains the auxiliary variables (time, lat/lon) together with the main output variable (AOD AAI, stratospheric extinction) and further derived quantities.

The main variables contained in the output files are listed in the following tables for each sensor (ATSR-2/AATSR, MERIS, IASI, POLDER, OMI, GOMOS):

Variables contained in the ATSR-2 / AATSR files of the three algorithms ADV, ORAC, SU (levels 2 and 3)						
Variable product	**ADV L2**	**ADV L3**	**ORAC L2**	**ORAC L3**	**SU L2**	**SU L3**
For level 3 mean values within the grid box are provided if not specified otherwise; for some products also standard deviations within the grid box are provided						
geolocation, observation angles						
pixel_number	x		x		x	
latitude	x	x	x	x	x	x
longitude	x	x	x	x	x	x
pixel_corner_latitude1-4	x		x	x		
pixel_corner_longitude1-4	x		x	x		
time	x		x		x	
satellite_zenith_at_center	x		x	x	x	x
sun_zenith_at_center	x		x	x	x	x
relative_azimuth_at_center	x		x	x	x	x
instrument_view			x	x	x	
aerosol optical depth and its uncertainties						
For level3 ORAC provides in addition to mean also median, lowerquartile, upperquartile, and interquartile_mean						
AOD550	x	x	x	x	x	x
AOD670	x	x	x		x	
AOD870	X (ocean)		x		x	
AOD1600	x	x	x		x	
AOD550_uncertainty	x		x		x	x
AOD670_uncertainty	x				x	x
AOD870_uncertainty			x		x	x
AOD1600_uncertainty	x				x	x
aerosol type information						
ANG550_670	x	x			x	
ANG550_870			x			
FM_AOD550	x	x	x		x	
FM_AOD_fraction						
weak_absorbing_fraction					x	
dust_fraction					x	
aerosol_type			x	x		
REFF			x			
REFF _uncertainty			x			
quality information and diagnostics						
AOD_quality_index, quality_flag	x	x	x			
iterations			x			
iterations_mean				x		
fit_error			x			
fit_error_mean				x		
surface information and its uncertainties						
surface_type_number			x	x	x	
surface_reflectance550	x	x	x	x	x	x
surface_ reflectance 670			x	x	x	x
surface_ reflectance 870			x	x	x	x
surface_ reflectance 1600			x	x	x	x
surface_ reflectance550 _uncertainty			x	x		
surface_ reflectance670 _uncertainty			x	x		
surface_ reflectance870 _uncertainty			x	x		
surface_ reflectance1600 _uncertainty			x	x		
other geophysical conditions						

cloud_fraction	x		x	x	x	
fraction_of_water	x	x				
pixel_count		x		x		x
aerosol_type_count				x		
interquartile_count				x		

Variables contained in the MERIS ALAMO files (levels 2 and 3)		
Variable product	**ALAMO L2**	**ALAMO L3**
geolocation, observation angles		
pixel_number	x	
latitude	x	x
longitude	X	x
pixel_corner_latitude1-4	X	
pixel_corner_longitude1-4	X	
aerosol optical depth and its uncertainties		
AOD550	x	x
AOD865	x	x
AOD550_std	x	x
AOD865_std	x	x
aerosol type information		
fAOD550	x	x
fAOD865	x	x
fAOD550_std	x	x
fAOD865_std	x	x
R_eff	x	x
R_eff_std	x	x
Aerosol_Altitude	x	x
Aerosol_Altitude_std	x	x

Variables contained in the OMI AAI files (levels 3)	
Variable product	**AAI L3**
geolocation, observation angles	
lat	x
lon	X
sun_zenith	X
aerosol absorbing index	
aai	x

Variables contained in the GOMOS stratospheric aerosol files (levels 3)	
Variable product	**AERGOM L3**
geolocation, observation angles	
latitude	x
longitude	X
altitude	X
aerosol variables and their uncertainties	
AEXT550	X
AEXT550_uncertainty	X
ANG400-800-AEX	X
ANG400-800-AEX_uncertainty	X
S_AOD550	X
S_AOD550_uncertainty	X
ANG400-800-AOD	X
ANG400-800-AOD_uncertainty	X
other diagnostics	
AEXT550_Ndata	X
S_AOD550_Ndata	X
Tropopayse_height	X
PSC_occ	X

Variables contained in the IASI mineral dust AOD files (levels 2 and 3)				
Variable product	**IMARS**	**MAPIR**	**LMD**	**ULB**
geolocation, observation angles				
latitude	x	x	x	x

longitude	X	X	X	X
time	X	X	X	X
Satellite_zenith_at_center	X	X	X	X
aerosol variables and their uncertainties				
D_AOD1100	X	X	X	X
D_AOD1000	X	X	X	X
D_AOD550	X	X	X	X
D_AOD1100_uncertainty	X	X	X	
D_AOD_10000_uncertainty		X		x
D_ALT		X	X	
D_REFF			X	
Diagnostic flags				
dust_flag	X	X	X	X
surface_type_number	X	X	X	X
pre_quality_flag	X	X	X	X
post_quality_fag	X	X	X	X

Variables contained in the POLDER -1,2,3 GRASP files (levels 2 and 3)		
Variable product	GRASP L2	GRASP L3
geolocation, observation angles		
pixel_number		x
latitude	x	x
longitude	x	x
aerosol optical depth		
AOD443	x	x
AOD490	x	x
AOD565	x	x
AOD670	x	x
AOD865	x	x
AOD1020	x	x
aerosol type information		
ANG670_865	x	x
FM_AOD443	x	x
FM_AOD490	x	x
FM_AOD565	x	x
FM_AOD670	x	x
FM_AOD865	x	x
FM_AOD1020	x	x
LidarRatio443	x	x
LidarRatio490	x	x
LidarRatio565	x	x
LidarRatio670	x	x
LidarRatio865	x	x
LidarRatio1020	x	x
aerosol single scattering albedo		
SSA443	x	x
SSA490	x	x
SSA565	x	x
SSA670	x	x
SSA865	x	x
SSA1020	x	x
surface information		
NDVI	x	x
DHR443	x	x
DHR490	x	x
DHR565	x	x
DHR670	x	x
DHR865	x	x
DHR1020	x	x

4 THE PRODUCT FLAGS AND METADATA

All Aerosol_cci products use metadata following the CF convention (all AOD datasets use now CF-1.6) – this metadata convention have been chosen to comply with most standards used in the atmospheric climate modelling community. In agreement with the entire CCI program (guided by the Data Standards Working Group) naming of global attributes and common variables (e.g. time and space grid, etc.) have been harmonized and are used by Aerosol_cci. In addition, the specific aerosol variable names have been agreed within the Aerosol_cci team to assure consistent parameter naming in the ECV products. Each product contains an uncertainty parameter for the major output variable and further specific quality variables depending on the instrument information content and algorithm.

The products are using following conventions:

Metadata and file structure	
	products are compliant with CF metadata convention 1.6
	Level 2: cell = <no of pixels in file> with associated coordinates latitiude, loingitude, time
	Level 3: longitude = <no of pixel columns in array>, latitude = <no of pixel lines in array> or longitude = <no of pixel columns in array>, latitude = <no of pixel lines in array>, alt = <no of layers>
Compliance check with CF convention	
	possible at: http://titania.badc.rl.ac.uk/cgi-bin/cf-checker.pl http://puma.nerc.ac.uk/cgi-bin/cf-checker.pl http://aerocom-test.met.no/upload
Visualisation	
	with standard tools such as panoply http://www.giss.nasa.gov/tools/panoply/ for level 3
	with idl runtime code and source files for level 2 (e.g. freely available from http://www.globaerosol.info/project_description/data.htm tools).
	With ESA CCI toolbox http://climatetoolbox.io/

For the output variables the common naming throughout all Aerosol_cci products of phase 2 is given in the following table:

Parameter	Parameter name
Aerosol Optical Depth (AOD) at a wavelength of nnn nm	AODnnn
Ångström Exponent evaluated between for the wavelengths pair nnn-mmm	ANGnnn_mmm
Fine Mode AODnnn	FM_AODnnn
Dust AODnnn	D_AODnnn
Stratospheric AOD	S_AOD
Absorbing Aerosol Index	AAI
Absorbing Aerosol Optical Depth	AAODnnn
Aerosol Type	ATY
Aerosol Effective Radius (for total AOD or for stratosphere)	REFF
Stratospheric aerosol extinction profile	AEX

Following global attributes are used in all Aerosol_cci files (note that few of them, which are not crucial for file identification or for data search may be missing in some files):

Usage information	
	Title (succinct description of the dataset)
	Institution (where the data was produced, use names from CCI common vocabulary (http://www.esa-cci.org/; click on data standards working group on left hand side), e.g. Finnish Meteorological Institute (FMI)
	Source (original data source(s), e.g. AATSR L1B GBT, version as read in with the data file) Multiple source datasets separated by commas.
	History (processing history of dataset) (e.g. "2012-08-21 13:56:16 - Product generated from ORAC-SW dual-view, 3.0. AATSR L1b ver. 6.03"
	References (references to algorithm, ATBD, technical note describing dataset)
	Tracking_id (a UUID (Universal Unique Identifier) value)
	Conventions (the CF Version) = "CF-1.6"
	Product_version (the product version of this data file)
Discovery metadata[#]	
	summary (a paragraph describing the dataset)
	keywords (a comma separated list of key words and phrases)
	id
	naming authority (the combination of the naming authority and the id should be a globally unique identifier for the dataset)
	keywords_vocabulary (if you are following a guideline for the words/phrases in your "keywords" attribute, put the name of that guideline here)
	cdm_data_type (the THREDDS data type appropriate for this dataset)

	comment (miscellaneous information about the data)
	date_created (the date on which the data was created)
	creator_name
	creator_url
	creator_email
	project (the scientific project that produced the data: “Climate Change Initiative – European Space Agency”)
	geospatial_lat_min (decimal degrees north, range -90 to +90)
	geospatial_lat_max (decimal degrees north, range -90 to +90)
	geospatial_lon_min (decimal degrees east, range -180 to +180)
	geospatial_lon_max (decimal degrees east, range -180 to +180)
	geospatial_vertical_min (assumed to be in metres above ground unless geospatial_vertical_units attribute defined otherwise)
	geospatial_vertical_max (assumed to be in metres above ground unless geospatial_vertical_units attribute defined otherwise)
	time_coverage_start (format yyyymmddThhmmssZ)
	time_coverage_end (format yyyymmddThhmmssZ)
	time_coverage_duration (should be an ISO8601 duration string)
	time_coverage_resolution (should be an ISO8601 duration string)
	standard_name_vocabulary (the name of the controlled vocabulary from which variable standard names are taken) (for names missing in the vocabulary inform the DSWG)
	license = “ESA CCI Data Policy: free and open access”
For **gridded (level3) data on a regular lat/lon grid**, the following attributes shall be included in the files (not compulsory for level2 data, or data on other grids, e.g. polar stereographic) :	
	geospatial_lat_units
	geospatial_lon_units
	geospatial_lon_resolution
	geospatial_lat_resolution
Global attributes	
	inputFileList = "ATS_TOA_1PRUPA20080122_003758_000065272065_00202_30817_9667.N1"
	startDate = "2008-01-22" (date of first observation)
	dateTime = "2009-01-02 11:55:24" (UTC time of first observation of the data set processed)
	productID = "20080122003758-ESACCI-L2P_AEROSOL-AER_PRODUCTS-AATSR_ENVISAT-ORAC_30817-fv02.02.nc "
Optional global attributes (with examples of content: “content”)	
	platform = "ENVISAT"; separated by comma’s if more than one
	sensor = "AATSR"; separated by comma’s if more than one
	Spatial resolution = "10x10 km" (a string describing the approximate resolution of the product)
	projection = "Sinusoidal [Neq = 4008]"
	content = "Aerosol Optical Depth"
Diagnostic variables*	
	sun_zenith at center (not available/necessary for IASI)
	satellite_zenith at center
	relative_azimuth at center
	quality_flag(s)
	aerosol_type_number (the one used in the retrieval or the one selected by the retrieval) – external table provided in the metadata file will define its properties as applied in the algorithm
	cloud_fraction (if defined for algorithm in ATBD)
	PSC_occurrence (for stratospheric aerosol retrieval: variable name: PSC_occ)

	surface_albedo[440,550,670] (not available/necessary for IASI)
	vegetation_index (if defined for algorithm in ATBD)
	fraction_of_water (if defined for algorithm in ATBD)
	surface_type_number (if defined for algorithm in ATBD)
	fit_error or similar fit quality check

Discovery metadata allows information about the data to be harvested into catalogues and data federations. For dataset discovery, the netCDF attributes recommended in http://www.unidata.ucar.edu/software/netcdfjava/formats/DataDiscoveryAttConvention.html

The CF-compliant standard variable name is standard_name = "atmosphere_optical_thickness_due_to_aerosol"; wavelength specification is only added in the long_name = "Aerosol Optical Depth at 550nm"; for the other variables (aerosol type, etc.) no CF-compliant standard variable names exist yet.

*Diagnostic variables are optional, as appropriate and defined in each ATBD, with explanation in meta data.

As appropriate each variable is described by following qualifier attributes:

qualifier attributes for each variable	
	long_name
	standard_name (see CF standard name list – if no standard name is contained in the CF convention, yet, this attribute must be left out)
	units (unless dimensionless variable: can be missing or then set to “no_units”)
	valid_range
	coordinates
	fill_value[&]
	missing_value[&]

[&] missing_value: no value is provided; **do not put ‘NAN’**
fill_value: no value has been retrieved but instead of reporting missing_value a fill_value is provided using a certain method based on earlier observations

5 THE PRODUCT GRID AND GEOGRAPHIC PROJECTION

The Products are provided in two projections:

- level 2 vector for projected products on super-pixel resolution: sinusoidal projection on a grid of 4008 columns for 2004 rows, with a spatial resolution of 10 km, to be used for orbit products from ATSR and MERIS

- level 3 gridded (equirectangular latitude-longitude projections on 1.0° x 1.0° grid for total column AOD, on 0.25° x 0.25° grid for AAI and on 2.5° x 10° grid for stratospheric extinction), to be used for gridded daily and monthly products

6 KNOWN LIMITATIONS AND STRENGTHS OF THE PRODUCTS

6.1 Input data sets

The **AATSR** instrument offers several key advantages for aerosol remote sensing, which can be summarised thus:

1. The instrument channels, measurement system and spatial resolution are well suited to aerosol retrieval. In particular, the unique dual-view system employed by the ATSR instruments aids in separating the surface and atmospheric contributions to the TOA signal.

2. AATSR is part of a long-term instrument series, with the ATSR-2 instrument (the first to have the visible wavelength channels needed for aerosol retrieval) providing data from June 1995. ATSR-2 and AATSR provide a continuous, consistent dataset (with at least 12 months of overlap) from mid-1995 to April 2012, and the SLSTR instruments on Sentinel-3 (Sentinel-3A was launched in Feb 2016, and will be joined by Sentinel-3B in 2018).

3. The (A)ATSR instruments are well calibrated, with frequent on board calibration of both long and shortwave channels. This has been further improved by additional vicarious calibration efforts for the visible channels.

The primary short-coming of the (A)ATSR instruments are their relatively poor spatial coverage, with a swath width of a mere 512 km (which is largely a consequence of the dual-view measurement system). SLSTR will improve upon this, but will still only provide a ~750 km swath in dual-view. Additionally, coverage with observations is not stable throughout the entire missions. As fig. 3.15 of the Product Validation and Inter-comparison Report [RD2] shows, numbers of available pixels decrease significantly near the ends of each mission (i.e. unfortunately during the overlap period in 2002 / 2003 and for the last 3-6 months of ENVISAT 2011 / 2012). For these periods use of the data for regional assessments or trend analysis needs extra care.

MERIS is a very stable and well-calibrated instrument designed for ocean-colour remote sensing. One key limitation of MERIS for aerosol retrieval is that it provides only nadir observations, thus containing limited information on the phase function (multi-directionality). The other important limitation is the lack of spectral bands above 1 micron for cloud detection (especially cirrus clouds remain critical). Its strength lies in the spectral information at 15 wavelengths with rather small bandwidth. MERIS onboard ENVISAT provides a data record from mid-2002 until April 2012; on Sentinel-3 the successor instrument OLCI is active (Sentinel-3A was launched in Feb 2016, and will be joined by Sentinel-3B in 2018).

GOMOS as horizontal pointing instrument allows retrieving vertical aerosol profiles. A great strength of GOMOS (as compared to limb emission or scattering instruments) is that it uses the occultation technique, which greatly simplifies the analysis of the measured light and is a self-calibrating method. It has a good spectral coverage and spectral resolution, an excellent vertical resolution and a very good pointing accuracy. However, there are a number of drawbacks from the technique as it uses various (~200) stars as light sources: variable measurement conditions due to different star brightness and surface temperature, low S/N compared to solar occultations, partial and variable global coverage (much better than solar occultation, but worse than limb instruments in sun-synchronous orbits). A current limitation of the instrument is that only night-time stellar occultation measurements can provide information to retrieve aerosol profiles. It should also be mentioned that despite some correction applied to the spectra, some residual scintillation effects are present in the data, which can cause artificial structures in the data. A drift has been observed in transmission data measured during several occultations, especially in the last years of the mission, but this bias should be corrected in the most recent data release. Unfortunately, the instrument is not in operation anymore since ESA lost contact with Envisat in 2012.

OMI measurements are very stable with little sensor degradation however since 2008 there has been a so-called “row anomaly” (Dobber et al., 2008; OMI calibration, 2012). The “row anomaly” is a dynamic instrument error that manifests as a suppression in signal of the radiance (earth) measurement. It been observed in the data since May 2008 and affects various rows in a given OMI orbit. The latest status of this problem can be found on the OMI instrument website (OMI calibration, 2012). The OMI AAI data record will be continued with the TROPOMI instrument which was successfully launched onboard Sentinel-5 Precursor or S-5P on 13 October 2017.

The four **IASI** retrieval algorithms require a couple of input data, which are different for all four algorithms. Specifically the input format of the level-1 IASI data is currently estimated to remain inconsistent for the full mission reprocessing. The input data are available from EUMETSAT either in full spectral resolution or in a principal component scores product, which requires a lot less disk space for storage and thus is preferred over the full resolution data format. Nevertheless at least one algorithm showed substantial sensitivity to the choice of input data format, the exact reason for which and its quantitative impacts on product quality are still under investigation. A couple of algorithms also rely on other auxiliary datasets such as external databases for surface emissivity and the EUMETSAT Level-2 atmospheric products from IASI. While the surface emissivity is not expected to show large inconsistencies within one IASI dataset for Aerosol_cci2, the level-2 atmospheric products cannot be made available consistently by EUMETSAT in reasonable time allowing for the full mission processing within the project. The impact of the different versions of the input product has to be fully assessed quantitatively but it is already known that they can be important. Therefore, the AOD time series obtained with the dust retrieval algorithms using this inconsistent auxiliary dataset suffers from the somewhat inconsistent quality of the previous versions of the level2 IASI algorithm. Characterisation of version 6 of the level2 data is online (http://www.eumetsat.int/website/wcm/idc/idcplg?IdcService=GET_FILE&dDocName=PDF_IASI_L2_MB_PVR&RevisionSelectionMethod=LatestReleased&Rendition=Web), while the characterisation of the previous versions can be found in the literature (August et al, 2012, and references therein). The ULB and BIRA scientists have noted that the surface temperature of deserts is most often underestimated, in all versions of the data (even though at different levels of underestimation depending on the level2 data version).

The **POLDER-3** instrument offers unique opportunities of multi-angle, multi-spectral measurements of both radiance and linear polarization (Stokes parameters Q and U). The instrument is well suited for advanced retrieval of extended set of aerosol and surface properties. 9 years of PARASOL-3 measurements provide a long term instrument series needed for climate research. 1600 km cross-track for POLDER-3 ensure almost global coverage every 2-3 days. The primary shortcoming of the POLDER-3 instrument is its coarse spatial resolution (about 6 km pixel resolution), which may result in cloud contamination. Another shortcoming is that the band 443 nm of POLDER-3 is with poor accuracy. Very often it is not recommended to use this channel in the retrieval.

6.2 The output products (ECVs)

The following table summarizes validation results the level2 at satellite pixel resolution (so-called level2) for the Aerosol_cci products (specified in the Product Specification Document (PSD) [RD1]). Datasets over the entire periods for all sensors (POLDER only selected regions). The detailed validation is described in the Product Validation and Intercomparison Report (PVIR) ([RD2]).

algorithm	spatial resolution coverage	rmse/bias land	rmse/bias ocean
ADV (AOD level2)	AATSR 10km, 1° global	0.11 / - 0.03	0.09 / + 0.02
	ATSR-2 10km, 1° global	0.14 / + 0.02	0.29 / + 0.11
ORAC (AOD level2)	AATSR 10km, 1° global	0.14 / + 0.01	0.16 / + 0.11
	ATSR-2 10km, 1° global	0.11 / + 0.03	0.15 / + 0.05
SU (AOD level2)	AATSR 10km, 1° global	0.14 / + 0.02	0.06 / + 0.01
	ATSR-2 10km, 1° global	0.16 / + 0.06	0.09 / + 0.08
ensemble (AOD level2)	AATSR 10km, 1° global	0.12 / - 0.01	0.07 / + 0.01
	ATSR-2 10km, 1° global	0.14 / + 0.02	0.18 / + 0.08
IMARS Dust AOD	IASI 10km, 1° global dust belt	0.26 / - 0.02	
LMD Dust AOD	IASI 10km, 1° global dust belt	0.13 / - 0.02	
MAPIR Dust AOD	IASI 10km, 1° global dust belt	0.30 / + 0.17	
ULB Dust AOD	IASI 10km, 1° global dust belt	0.11 / - 0.01	
GRASP AOD SSA ANG	POLDER 6km, 1° regions land [1)]	0.00 … 0.12 / + 0.08 … 0.23 0.05 … 0.08 / + 0.00 … 0.04 0.27 … 0.37 / - 0.05 … + 0.04	
ALAMO (AOD level2)	MERIS 10km, 1° global ocean	-	0.10 / +0.03
AAI	OMI 0,25° global	Direct validation is not possible (no geo-physical quantity); evaluation through model inter-comparison	
AERGOM (extinction level3)	GOMOS 60x5° global	$< 1 \cdot 10^{-4}$ km^{-1} (above 15 km altitude; few validation matches only)	

[1)] POLDER GRASP validation includes very difficult bright / desert stations / separate validation for 4 regions (Banizoumbou, Kanpur, Mongu, Beijing)

All nadir / total column datasets exploit satellite observations from polar orbiting platforms, so that all observations occur at similar local overpass time (ATSR, MERIS morning ~10:30: POLDER, OMI afternoon a ~13:30, IASI 10:30 and 21:30); no daily variation can be observed accordingly.

AATSR-AOD

The key feature of the current Aerosol_cci **ATSR-2 / AATSR** products is that 3 algorithms are used, which provide 3 different products. Based on the intensive intercomparison of the 3 AATSR algorithms, it was found that no single algorithm exhibits superior performance in all circumstances. Additionally, an uncertainty-weighted ensemble is used to combine the strengths of the algorithms at every pixel, where at least 2 algorithms have a valid result (which works well over land, but not so well over ocean). Gernerally, there is a trade-off between coverage and data quality. In the overlap period of the two instruments ATSR-2 / AATSR (8 months in 2002 / 2003) only small differences are generally found except over Northern Africa. Time series show no or little obvious degradation over the 17 year period or steps between the two sensors, although variability seems increased for the earlier ATSR-2 period (with less coverage). Overall, about 50-60 % of pixels fall within the GCOS required interval over land (and 30-60% over ocean), while 30-60% of pixel-level uncertainties meet the statistical interval for a normal distribution.

Thus a user needs to choose the algorithm best suited to his / her application region. Over land the SU algorithm performed slightly better than the other two (in particular with its pixel-level uncertainties and Angström exponent), whereas over ocean the SU algorithm has less coverage than the ORAC and ADV algorithms. It should be noted that the density of validation data over open ocean and over the Southern hemisphere is low, such that validation there is a difficult task.

The datasets showed similar characteristics when compared to other satellite AOD products (MODIS, MISR, SeaWIFS), but for high AOD (> 0.2) the performance is weaker. Inside the Sahara dust-source regions validation is difficult due to lack of ground-based refrence stations (AERONET), but comparison to observations with other sensors / retrieval principles (IASI thermal infrared, POLDER polarization) show reasonable consistency.

The main advantages of the datasets are:

1. All three AATSR datasets show a good correlation, low bias and good RMS error when compared to AERONET – the quality even exceeds that of MODIS in some regions (Europe and North America) for AOD<0.2, while quality is lower for AOD>0.2.
2. All three algorithms provide retrieved uncertainties on all retrieved parameters (based on the uncertainty characterisation of the measurements and forward model) and a variety of retrieval statistics which can be used for product characterisation and quality control. The absolute values reported have been found to be underestimates in most cases.
3. All three datasets reach back to 1995 (5 years before MODIS start).

The main limitations of the dataset are:

1. Coverage: with a swath width of 512 km global coverage can only achieved every 6 days.
2. Cloud masking including post-processing on the 10x10 km2 product boxes after AOD retrieval (to reduce spurious cloud contamination by spatial homogeneity testing) has improved significantly, but may still be a source of error; it certainly is still a major cause of differences between the 3 algorithm results (esp. over open ocean).
3. Pixel-level uncertainties are underestimates that do not yet fully represent all known, quantifiable sources of error (e.g. cloud contamination, coastal waters).

4. Work is ongoing to fully understand the reasons for the differences between the 3 different algorithms

17 year time series of the two ATSR instruments retrived with the four algorithms show a bias between the different datasets on the order of 0.02 and varying strength of seasonality as well, while the overall trends agree very nicely. However, there are distinct regions, where significant differences occur (e. g. Indonesia, where a specific cloud post-processing in the ADV algorithm has likely reduced masking of high AOD biomass burning aerosols in the early years due to a strong El nino 1997).

The consistency of the cloud masks used in Aerosol_cci against Cloud_cci (AATSR AOD) was assessed showing that the fraction of mutually inconsistent pixels is smaller than 1% (analyzed erroneously as at the same time fully cloudy and fully cloud-free) and that the fraction of neglected pixels is about 20% (containing twilight zone of mixed cases, but also missed pixels for safety from cloud contamination).

Additional aerosol (e.g. mixing fractions between the 4 components) and diagnostic (e.g. cloud, surface fit quality) parameters are contained in the level2 files.

MERIS-AOD (ocean only)
Over ocean the **MERIS** product proofed of good quality using the ALAMO algorithm, since spatial inhomogeneities are less dominant than over land. Over ocean which is almost dark in red and near infrared bands enough independent information is available for aerosol retrieval as well as cloud detection. The main advantage of the MERIS product is its wider swath (as compared to AATSR) of 1100 km. Note that over land only experimental products with far lower quality have so far been achieved due to issues with cloud flagging and surface brightness parameterization. Further work has started to test further MERIS algorithms.

GOMOS stratospheric extinction
Within the ESA AERGOM project a new algorithm was developed which exploits the stellar occultation instrument **GOMOS** to derive improved aerosol extinction profiles in the upper troposphere and stratosphere. With respect to the official GOMOS aerosol product, Aergom uses an extended spectral range in the UV/VIS, a refined aerosol spectral paramerisation and an improved Rayleigh scattering correction to retrieve stratospheric aerosol extinction profiles with very good vertical resolution (~2-3 km) and good precision between 15 and 35 km. However, it must be noticed that this product is very recent (so far, only scientific data are available) and the assessment of the data quality is still ongoing. The retrievals are limited to night-time measurements only, and can sometimes produce unrealistic profiles (for some occultations with dim/cold stars) that must later be removed from the dataset. The origin of these anomalies is still unclear. The product may also contain cirrus clouds in certain cases (identified as aerosols), which can make the interpretation of the resulting profiles more difficult. It is important to have in mind that the Aergom profiles uncertainty is strongly dependent on the occultation's star temperature and brightness. Aerosol_cci uses the AERGOM profile datasets to produce gridded (5-daily 5° x 60° datasets) aerosol extinction profiles together with gridded stratospheric integrated (above the tropopause) aerosol optical

depth – with the weekly resolution the dataset is best suited to identify aerosol extinction due to small and medium size volcanic eruptions in the lower stratosphere.

The main advantages of the datasets are:

1. Though with limited number of stations the validation shows that for an important part of the profile accuracies are within required boundaries (stability could not yet be assessed)
2. The specifically adapted spatio-temporal resolution is suitable to minor volcanic episodes in the troposphere

The main limitations of the dataset are:

1. Coverage using as many stars as can provide sufficient signal-noise ratio is still rather limited
2. Currently there is no continuation sensor in orbit

It should be noted that an experimental mission has been approved for ~2020 (ALTIUS, ESA Earth Watch program), which can be used to continue the stratospheric observation capabilities of GOMOS in mid-term.

The datasets do also contain further variables: extinction at 6 wavelengths, Angström coefficient, stratospheric AOD, tropopause height, cloud information (PSC, cirrus).

<u>OMI AAI</u>

The Absorbing Aerosol Index (AAI) is a qualitative quantity which shows the presence of absorbing aerosols. However, its values are also dependant on sensor characteristics (wavelength choice), aerosol properties (most important: aerosol layer height and absorption) and retrieval conditions (solar zenith angle and surface albedo). The AAI is a very robust and well-tested dataset and as such has very few limitations or warnings for usage. The primary strength of the AAI is data availability both in time and space. Because the AAI can be calculated also in the presence of clouds it means that unlike aerosol optical depth retrieval, it has daily global coverage in the case of OMI or near-global coverage depending on a given sensor swath width. Near-daily or daily global coverage leads to robust statistical sampling for eventual calculation of global and regional trends. One of the primary goals for use of the AAI in this project is to produce a long-term time series of AAI using several sensors. In order to combine datasets offsets between various data series as a result of differences in calibration, time of overpass, spatial sampling, and wavelength pair choice. The goals for this project is to combine the TOMS (Nimbus-7), GOME, and OMI datasets, where OMI will be checked against the GOME-2 and SCIAMACHY datasets as the data is available for a similar time period. A summary is given in Table OMI-1 of all the AAI datasets currently available as well as the future TROPOMI.

Table OMI-1. Satellite instruments measuring AAI.

Instrument /	Wavelength Pair	Years of Available

Platform	(nm)	Data
TOMS / Nimbus-7	340 / 380	1978 – 1993
GOME / ERS	340 / 380	1995 – 2003
TOMS / Earth Probe	331 / 360	1996 – 2005
SCIAMACHY / Envisat	340 / 380	2002 – 2012
OMI / Aura	354 / 388	2004 – present
GOME-2 / ERS-2	340 / 380	2007 – present
TROPOMI / S-5P	340 / 380 and 354 / 388	2015 –

The AAI is dependent upon several factors including aerosol wavelength pair choice viewing geometry, optical depth, single scattering albedo (SSA), aerosol layer height, and underlying surface (cloud) albedo. These dependencies have been investigated and are reported in a technical note to aid in the interpretation of the AAI. Variation in AAI as a function of AOD, aerosol layer height and underlying surface albedo for a single layer of "strongly absorbing" aerosol particles depends strongly on surface albedo for aerosol layers with lower optical depth and lower altitude. As optical depth and layer height increase the effect is minimized. For aerosol layers with an optical depth greater than 1.0 the layer height can be discerned if the surface albedo remains constant. For even thicker layers with an AOD larger than 2.0 the layer height can be discerned even if the surface albedo is inconsistent. This effect is dependent on how strongly absorbing the aerosol layer is and diminishes with increasing SSA of the aerosol layer. Strongly and moderately absorbing aerosol types like those from dust and strongly absorbing fine particles like smoke lead to positive values in AAI whereas, weakly absorbing and near-surface aerosol layers like sea salt or sulfates lead to near-zero and negative aerosol index values. There are also differences in AAI values based on choices of wavelength pair. The OMI wavelength is chosen to be 354/388 nm which differs from the most common 340/380 nm pair (TOMS) due to the layout of OMI spectral channels to avoid inter-channel noise.

<u>IASI Dust Optical Depth</u>

IASI provides a complementary aerosol product to the AATSR datasets, by sensitivity to only mineral dust AOD. It can make 2 observations per day, since thermal signal is available also during night. Of the four algorithms two perform well (ULB, LMD) when compared to AERONET Singular Value Decomposition coarse mode AOD at 550 nm, while the other two show significant bias or lack of coverage (likely due to too conservative quality filtering). The IASI products contain dust AOD at 10 µm (the direct inversion wavelength) and at 550 nm. It should be noted that the AOD at 550 nm is converted from AOD at 10 µm with a factor, which introduces significant additional uncertainty (fixed value for three algorithms; depending on co-retrieved dust mineralogical composition in IMARS).

The main advantages of the datasets are:

1. IASI provides a complementary aerosol product to the AATSR datasets, by containing only mineral dust AOD
2. It can make two observations per day, since thermal signal is available also during night.

The main limitations of the current dataset are:

1. Coverage is partly restricted to the (extended) global dust belt
2. The conversion factor from thermal 10 µm retrieved AOD to mid-visible AOD at 0.55 µm introduces significant uncertainty, but allows comparison to AERONET and other mid-visible satellite retrieved dust AOD estimates; no reference data are available at 10 µm

Note that the best algorithm (ULB) achieves its quality with a neural network fitting to ground-based training data, but contains no other aerosol properties, while the other 3 algorithms provide additional potentially useful information (MAPIR: dust altitude and effective radius, LMD: dust altitude, IMARS: dust mineralogical composition and effective radius). It should be noted that information of effective radius and mineralogy have high potential to constrain on pixel basis the conversion factors from 10 µm to 0.55 µm and thus reduce uncertainties in the main Dust AOD product.

GRASP/POLDER

The new POLDER algorithm GRASP (Generalized Retrieval of Aerosol and Surface Properties) is designed to retrieve complete consistent aerosol properties globally. Over land, the algorithm also retrieves the parameters of underlying surface simultaneously with aerosol. In all situations, the approach achieves a robust retrieval of complete aerosol properties including information about aerosol particle sizes, shape, absorption and composition (refractive index). In order to achieve reliable retrieval from PARASOL observations even over very reflective desert surfaces, the algorithm was designed as simultaneous inversion of a large group of pixels within one or several images. Such, multi-pixel retrieval regime takes advantage from known limitations on spatial and temporal variability in both aerosol and surface properties. Specifically the variations of the retrieved parameters horizontally from pixel-to-pixel and/or temporary from day-to-day are enforced to be smooth by additional appropriately set a priori constraints. This concept provides satellite retrieval of higher consistency. Within CCI phase 2 GRASP algorithm it was demonstrated that GRASP algorithm provides highly accurate retrieval of aerosol and surfaces properties over four selected regions including very high AOD values and bright surfaces.

The main advantages of the datasets are:

1. Consistency of several aerosol (and surface) properties retrieved in one algorithm
2. AOD attribution to fine and coarse mode is much better than in other retrievals
3. GRASP level 2 AOD local comparisons do well at high AOD cases over continents

The main limitations of the dataset are:

1. Currently limited coverage
2. More evaluations are needed to understand some remaining issues in level3 data (AOD biases to model datasets in biomass burning regions with weak AERONET coverage)

Lower GCOS fractions are related to poorer GRASP perfomances at lower AOD (e.g. large relative overestimates at lower AOD) while lower RMSE are caused by a much better GRASP perfomance at higher AOD. It also should be noted, that for the Beijing and Kanpur zones the number of matches over the span of eight years is higher for the GRASP retrieval than for the AATSR retrieval, yet those are also regions with relative large positive GRASP biases at low AOD.

An assessment of the capabilities and limitations of the ATSR, IASI, GOMOS, AAI datasets for different applications was conducted in several user case studies, which are summarized in the Climate Assessment Report (CAR) [RD3].

7 TOOLS TO ANALYSE AND VISUALIZE THE DATA

Following tools are available for reading, visualizing and analysing (validation, inter-comparison) the output products. Those tools can be assessed from the Aerosol_cci website under resources/tools (http://www.esa-aerosol-cci.org/?q=tools).

Description of the AEROCOM tools used for MetNo CCI-Aerosol validation:
The so called AEROCOM tools are MetNo main tool to visualise and analyse output from climate models and satellite data and to compare those to data from at the moment 20 different observational data sources. The data can be 2d or 3d data, daily or monthly, and analysis is based often on aggregated monthly data. The tools could work for a wider range of different ECVs, but is applied currently for aerosol optical properties.

The visualisation part of the AEROCOM tools can plot 2d fields, plot time series of satellite vs. ground data at the same time and location, and displays the comparison as scatter plots, histograms and other plot types.

The tools can filter data based on different criteria (spatial, temporal, based on values of the ECV itself or a connected ECV, e.g. can base comparison only on common points of different satellite products, etc.) for the analysis. They also calculate different statistics and scores and export them into text files for further analysis. They are based on the proprietary software IDL and are run as batch jobs.

Because the tools can only read data that is formatted according to the AEROCOM protocol, data from the CCI-Aerosol community needs to be reformatted using the open source software nco (http://nco.sourceforge.net/). To make the visualisation more user friendly, a web front end is used (http://aerocom.met.no/cgi-bin/aerocom/surfobs_annualrs.pl?MODELLIST=CCI-AEROSOL) to present the analysis.

ICARE/LOA tools for reading, visualizing and analyzing the output CCI products
ICARE Multi-sensor visualization and analysis tool (http://www.icare.univ-lille1.fr/browse/?project=cci). This interface allows users to compare CCI data sets to each other, and to other data sets from the ICARE archive (e.g., MODIS, MACC, etc.). All key parameters of each sensor product can be selected independently for visualization. For each product, a link to the product documentation is provided. For a given parameter, a unique color scale is used for direct visual inter-comparison. The geographic selection, date selection, and product selection, can be modified independently, while the other two selection criteria remain unchanged. All data sets are displayed in Plate-Carree projection to make inter-comparison and geographic selection straightforward. CCI daily and monthly level-3 products don't require any reprojection. CCI level-2 products are originally produced in sinusoidal grid, so they are re-gridded on-the-fly upon selection in the graphical interface. Additional interactive capabilities are available, such as display of data values, or X/Y plot comparison.

ICARE CCI Extract tool (http://www.icare.univ-lille1.fr/extract/cci)

This interface was developed to interactively extract CCI product values in the vicinity of validation sites. Several validation networks are supported, including AERONET. Single or multiple parameters from CCI aerosol products can be selected for extraction. A time period and a search radius can be specified. For each selected validation site, and each overpass of the satellite, all data values found within the specified range are displayed, if any, along with the corresponding acquisition time and pixel location. Those extract values can be directly compared to validation data off-line.

CCI toolbox http://climatetoolbox.io/
The ESA Climate Change Initiative (CCI) has implemented its own toolbox, where users can access products on all ECVs from the CCI program in a common infrastructure.

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