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Aerosol_cci

USER REQUIREMENT DOCUMENT

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EXECUTIVE SUMMARY

This document summarises requirements for new or improved aerosol products from satellite remote sensing for climate research. Reviewed are user needs based on feedback from GCOS, CMUG, MACC/ICAP and AeroCom as well as core users in the team.

The document starts with the definition of relevant terms and abbreviations (section 1). After introducing the nature of the aerosol climate science (section 2), data needs expressed by major user groups are presented (section 3). The remaining part of the document details user requirements with respect to specific aerosol parameters (section 4), it addresses the required accuracy needs at different scales (section 5), makes suggestions for the error characteristics of level 2 and level 3 data (section 6), reiterates needed spatial resolutions (section 7), makes a case for atmospheric product associations (section 8), covers temporal and global data coverage needs (section 9) and outlines requirements for data format requirements (section 10), metadata needs (section 11) and grid projections (section 12). Finally, relevant references (section13) and useful web-links (section14) are provided.

Issue	Date	Modified Items / Reason for Change
1.0	15.12.2010	First issue of the document
1.1.	17.12.2010	Revisions through internal review by science leader
1.2.	21.12.2010	Incorporation of revisions and comments by the author
1.3	27.01.2011	Minor update based on RIDs from the project officer
1.4	28.02.2011	Revision based on feedback from MACC /ECMWF
1.5	03.08.2012	Added feedback from CMUG to v1.4 and responses / clarifications in sec 3.3
Phase 2		
2.0	14.11.2014	major rewrite for phase 2 activities
2.1	15.11.2014	review by science leader
2.2	16.11.2014	indirect effect user additions
2.3	17.11.2014	stratospheric user additions
2.4	20.11.2014	final science leader review and iteration
2.5	02.09.2015	user update
2.6	23.09.2015	science leader review
2.7	16.01.2017	final updates by core users, including by new user BSC
2.8	27.01.2017	science leader review
3.0	13.03.2017	science leader revision based on ESA RIDs

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1 DEFINITIONS AND ABBREVIATIONS

This section summarizes the major definitions relevant for the user requirements.

AAOD (Absorption Aerosol Optical Depth) is the vertically normalized atmospheric column integrated aerosol absorption at a certain wavelength (usually at 550 nm, the reference wavelength in global modelling) [note, AAOD = AOD*(1-SSA)]

ACPC (Aerosols, Clouds, Precipitation and Climate) is a joint GEWEX / IGAC initiative on those interlinked processes

AeroCom is an open science initiative founded to intercompare aerosol modules in global modelling and evaluate overall model performance as well as the treatment of specific aerosol processes against available (and trusted) observations.

AERONET represents a federated network of globally distributed ground-based CIMEL sun-/sky-photometers, which is maintained (calibration facility, data processing and aerosol and water vapor products access) by NASA (National Aeronautics and Space Administration) and PHOTONS (PHOtométrie pour le Traitement Opérationnel de Normalisation Satellitaire)

AOD (Aerosol Optical Depth) is the vertically normalized atmospheric column integrated aerosol extinction at a certain wavelength or waveband (usually at 550nm, the reference wavelength in modelling). AOD is also often referred to as Aerosol Optical Thickness (AOT).

ATSR (Along Track Scanning Radiometer) was a multi-channel imaging radiometer (with dual view capabilities in the visible and near-IR solar spectrum). Two versions are used for aerosol retrieval: ATSR-2 on board of the European Space Agency's ERS-2 satellite (1995-2002) and the advanced ATSR (AATSR) on ESA's ENVISAT satellite (2002-2012).

CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization) is a two-wavelength polarization-sensitive backscatter lidar that provides high-resolution vertical profiles of aerosols and clouds on board NASA's CALIPSO satellite.

CAMS (Copernicus Climate Monitoring Service) Successor project of MACC.

CF (Climate and Forecast) naming convention metadata are designed to promote the processing and sharing of files created with the NetCDF API.

CMIP (Coupled Model Intercomparison Project) is a WCRP initiative which defines a standard protocol to study the output of coupled circulation models (which have been strongly used in the IPCC assessments) – it defines the common data / metadata format **obs4MIPs** to increase the use of satellite data in the modelling community (by having a similar data format for both model output and satellite retrievals),

CMUG (Climate Model User Group) is a part of ESA's Climate Change Initiative (CCI) and is composed of members of major climate research institutes in Europe. The group is tasked to oversee the usefulness of new climate data records produced for CCI selected ECVs.

DOI (Digital object identifier) provides an actionable, interoperable and persistent link to a data set.

ECV (Essential Climate Variables) are geo-physical quantities of the Earth-Atmosphere-System that are technically and economically feasible for systematic (climate) observations.

FCDR (Fundamental Climate Data Records) represent long-term records of measurements or retrieved physical quantities from remote sensing. FCDRs require consistency across multiple platforms with respect to (1) calibration, (2) algorithms, (3) spatial and temporal resolution, (4) quantification of errors and biases and (5) data format. FCDRs also need to manifest applied ancillary data.

FMF (Fine Mode Fraction) is the fraction of the total AOD which is contributed by aerosol particles smaller than 1μm in diameter. Due to their smaller size these aerosol particles are referred to as fine-mode aerosol, in contrast to larger or coarse model aerosol particles.

GCOS (Global Climate Observing System), located at WMO in Geneve, is intended to be a long-term, user-driven operational system capable of providing the comprehensive observations required for (1) monitoring the climate system, (2) detecting and attributing climate change, (3) assessing impacts of, and supporting adaptation to, climate variability and change, (4) application to national economic development and (5) research to improve understanding, modelling and prediction of the climate system.

GOMOS (Global Ozone Monitoring by Occultation of Stars) is an instrument on board the European satellite ENVISAT. The main scientific objective of this stellar occultation instrument is to monitor ozone and ozone trends as function of altitude in the upper atmosphere (stratosphere, mesosphere). GOMOS also measures atmospheric parameters related to (stratospheric ozone) chemistry like NO2, NO3, H2O and aerosol as well as ozone dynamics like temperature, air density and turbulence.

IASI (Infrared Atmospheric Sounding Interferometer) on European MetOp platforms senses the thermal heat emission from the Earth (with a Michelson interferometer) mainly to provide atmospheric temperature and humidity profiles.

ICAP (International Cooperative for Aerosol Prediction) is an international forum for aerosol forecast centers, remote sensing data providers, and lead systems developers to share best practices and discuss pressing issues facing the operational aerosol community.

MACC / followed by **CAMS** (Monitoring Atmospheric Composition and Climate) was the EU-funded project responsible for the development of the pre-operational Copernicus atmosphere monitoring service. MACC monitored the global distributions and long-range transport of greenhouse gases (carbon dioxide, methane), of aerosols that result from both natural processes and human activities and of reactive gases (tropospheric ozone, nitrogen dioxide). It evaluated how these constituents influenced climate and estimates their sources and sinks.
MERIS (Medium Resolution Imaging Spectrometer) is a multi-spectral sensor onboard ENVISAT

MISR (Multi-angle Imaging Spectro-Radiometer) is a multi-spectral sensor on NASA's EOS Terra platform with (9) multi-directional view capabilities.

MODIS (Moderate Resolution Imaging Spectro-Radiometer) is a multi-spectral sensor on NASA's EOS Terra and Aqua platforms.

OMI (Ozone Monitoring Instrument) is a UV multi-spectral sensor on NASA's EOS Aura platform.

POLDER (POLarization and Directionality of the Earth's Reflectances) is a passive optical imaging radiometer and polarimeter for studies on radiative and microphysical properties of clouds and aerosols on the French CNES PARASOL (Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar).

SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric ChartographY) was a high spectral resolution passive sensor (in the UV and the visible solar spectral region) with both nadir and limb measurement capabilities on the ESA's ENVISAT platform.

SDS-WAS (Sand and Dust Storm Warning and Alert System) is a dust warning system for Europe, the Mediterranean and Northern Africa operated by the Barcelona Supercompouting Center on behalf of WMO.

SSA (Single Scattering Albedo) quantifies the fraction of the attenuation (or extinction) due to scattering at a certain wavelength (usually at 550 nm, the reference wavelength in global modelling). Alternately, [1-SSA] indicates the absorption potential (of an attenuation process).

2 INTRODUCTION

Aerosol properties are highly diverse in space and time. This is usually well captured by satellite remote sensing. Still, aerosol property maps are only offered for selected aerosol (column) properties and then often at limited accuracy. European aerosol retrieval products have closed the former gap with NASA datasets (MDOSI, MISR, SeaWIFs), they are sometimes even better (e.g. in some regions or globally versus a monthly model climatology), can provide complementary information (e.g. IASI dust AOD, ATSR-2 five years longer history, PARASOL consistent retrieval of several aerosol parameters), but have their remaining weaknesses (e.g. weaker skill at high AOD, limited coverage compared in particular to MODIS). In addition Aerosol_cci products offer systematic supplementary skills with pixel-wise uncertainty estimates and combination of strengths of different algorithms through uncertainty-weighted ensembles.

The goal of ESA's Aerosol_cci initiative is to extract aerosol information from European satellite sensors in a way most useful to the climate community. Under this initiative sensor data from European instruments (e.g. ATSR-2, AATSR, MERIS, SCIAMACHY, IASI, OMI, PARASOL, GOMOS) are (re-) processed. Retrieved aerosol properties are critically assessed and (if necessary) improved to satisfy or exceed data product requirements. These user defined requirements are based on user responses (survey, joint discussions, personal communication) or published requirement documents (e.g. GCOS tables). Their summary is presented in this User Requirement Document (URD).

The expectation for any new aerosol retrieval product should be that it is better than existing products or able to add (useful) complementary detail to any existing product. Such complementary aspects are the stratospheric AOD fraction, details on aerosol absorption, improvements to coverage and associations between aerosol and cloud properties. Only if superior performance and aspects can be demonstrated in comparisons to established and mature products (e.g. MODIS or MISR), a user is likely to use these new data.

3 PUBLISHED USER REQUIREMENTS

This section lists requirements as expressed by major users with applications in the field of climate science. These requirements have been established by considering requirements expressed by GCOS and CMUG and by drawing on feedback from the aerosol data using communities of AeroCom (evaluations in global modelling) and ICAP (aerosol data assimilation). Furthermore, core users in Aerosol_cci expressed their specific needs for their application communities. An overview of different user segments for aerosol products is given in Table 1.

Table 1: ***overview of Aerosol_cci users***

user segment	**application**	**major user need**	**user examples**
process studies	understand processes, improve parameterization in models	high resolution	Obs4MIPs, CMIP
aerosol-cloud interaction	understand processes, reduce associated IPCC uncertainty	high resolution associated products of aerosol and cloud variables (most important: cloud droplet number concentration)	ACPC
model development	initialize, evaluate models	several year datasets high information content (e.g. fine mode AOD, dust AOD, stratosphere)	AEROCOM EMAC
radiative forcing	monitor trends and variability	vertical profiles absorption	GCOS
aerosol monitoring	monitor trends and variability	stable long-term time series	GCOS
reanalysis	consistent time series, data assimilation	bias-free data pixel-level uncertainty	CAMS
forecasting	warning, data assimilation	NRT data	ICAP, CAMS, SDS-WAS

GCOS requirements for aerosols

GCOS has summarized requirements for accuracy and stability of many atmospheric data, including data for aerosol properties in (so-called 'GCOS'-) 'tables'. The associated GCOS document points out that atmospheric aerosol is only a minor constituent in the atmosphere by mass, but a critical component in terms of impacts on climate and especially climate change. Atmospheric aerosols influence the global radiation balance directly by scattering and absorbing radiation, and indirectly through influencing cloud reflectivity, cloud cover and cloud lifetime. A large fraction of today's aerosol in the atmosphere, especially in developing and developed areas, is of anthropogenic origin. The IPCC has identified anthropogenic aerosols as one of the more uncertain ingredients in efforts to understand climate change. Important aerosol properties are the mid-visible AOD (aerosol optical depth), which summarizes the total attenuation of sun-light in the atmosphere due to aerosol particles and the mid-visible SSA (single scattering albedo), which quantifies the solar attenuation fraction due to scattering processes (as opposed to absorption). Additionally needed information on aerosol size can be derived from AOD data at different solar wavelengths.

GCOS requirements for aerosol were further refined in 2016 to better qualify the underlying applications and determine realistic threshold (= minimum) requirements (GCOS-200); these are summarized inTable 2.

Table 2: ***GCOS requirements for aerosol properties***

variable	**resolution**			**accuracy**	**stability** *per decade*
	horiz. (km)	**vertical** (km)	**temporal**		
AOD (column)	5-10	N / A	4 h	max (0.03, 10%)	0.02
SSA (column)	5-10	N / A	4 h	0.03	0.01
layer height	5-10	N / A	4 h	1 km	0.5 km
extinction (profile)	200-500	1 (at ~10km) 2 (at ~30km)	1 week	10%	20%

These requirements for accuracy and stability are difficult to meet. Especially, the high temporal requirement can only be achieved with either a set of polar-orbiting or a set of geostationary platforms and only when solar light is available (UV-VIS instruments); nighttime observations are possible with infrared instruments but so far do lack validation due to missing reference measurements.

CMUG requirements for aerosol

The advising climate user group (CMUG), which oversees developments and tests new products of ESA's climate initiative also summarized requirements in several documents. The group pointed out that aside from (atmospheric column) amount (which is captured by the AOD) also additional information on aerosol composition (most important via the AAOD), on aerosol size (via the AOD spectral dependence) and on aerosol shape (via the depolarization) are needed to quantify the aerosol radiative impact or the aerosol impact on cloud microphysics.

Moreover, data resolution requirements for these properties differ by user application. For instance, progress in process understanding, such as interactions between aerosol, clouds and precipitation, requires much finer spatial and temporal resolutions (compared to long-term records for trend analysis) and also an aerosol stratification (at least on AOD) by altitude into the major cloud altitude regimes in order to quantify the relevant aerosol properties at cloud altitude. On the other hand aerosol retrieval applications in data assimilations require not only high (temporal) resolution data (for better coverage) but also a detailed error characterization while in addition for near-real time (NRT) applications) retrieval products need to be available within hours.

Based on these diverse requirements a more detailed user application associated catalogue was established by CMUG in Table 3. The requirements are estimated - as a function of the application - for horizontal resolution, for the observing cycle and for errors, addressing precision, accuracy and stability.

Table 3: ***CMUG requirements for aerosol properties (from CMUG 2010)***

property	**use**	**hor. res**	**obs. cycle**	**precision**	**accuracy**	**stability**	**error**
AOD (at 2-4 λ)	***process***	highest	highest	0.020	0.040	---	all errors
AOD (at 2-4 λ)	***assimil.***	highest	highest	Pix err	pix err	pix err	all errors

AOD (at 2-4 λ)	***decadal***	1x1 deg	monthly	0.010	0.020	0.005	qualitative
AOD (at 2-4 λ)	***trending***	1x1 deg	monthly	0.010	0.020	---	qualitative
AAOD (at 2 λ)	***process***	highest	highest	0.005	0.010	---	all errors
AAOD (at 2 λ)	***trending***	1x1 deg	monthly	0.002	0.004	---	qualitative
AOD, strat	***process***	highest	highest	0.005	0.010	---	all errors
AOD, strat	***trending***	1x1 deg	monthly	0.002	0.004	---	qualitative
AOD, high	***process***	highest	highest	0.010	0.025	---	all errors
AOD, high	***trending***	1x1 deg	monthly	0.005	0.010	---	qualitative
AOD, mid	***process***	highest	highest	0.010	0.025	---	all errors
AOD, mid	***trending***	1x1 deg	monthly	0.005	0.010	---	qualitative
AOD, low	***process***	highest	highest	0.010	0.025	---	all errors
AOD, low	***trending***	1x1 deg	monthly	0.005	0.010	---	qualitative
AOD, PBL	***process***	highest	highest	0.010	0.025	---	all errors
AOD, PBL	***trending***	1x1 deg	monthly	0.005	0.010	---	qualitative
depolariz.	***process***	highest	highest	5%	10%	---	all errors
depolariz.	***trending***	1x1 deg	monthly	5%	5%	---	qualitative

- AOD (at 2-4 λ) indicates the requirement for AOD data at multiple solar wavelengths to address aerosol size. A minimum of two AODs are required for the Ångström parameter and a minimum of four AODs are required for the fine-mode AOD fraction, the AOD associated with the smaller aerosol sizes defined for those smaller than 0.5μm in radius,
- minimum required altitude stratification for AOD (if possible at multiple solar wavelengths) is for the stratosphere (no cloud interactions), for the upper troposphere (below 440hPa or above 6km), for the middle troposphere, for the lower troposphere (above 690hPa or below 3km) and for the planetary boundary layer (below 1-2km over land and below 1-0.5km over oceans)

AeroCom requirements for aerosol

The aerosol global modelling community self-organized itself under the umbrella of the AeroCom initiative to participate in common diagnostics and common analyses (experiments). These analyses gave new insights into the range of simulated aerosol lifetimes and global distributions for aerosol component mass, optical properties and associated radiative forcing, as well as sensitivity of these fields to different processes. A database (http://aerocom.met.no/data.html) allows to evaluate model performance against (trusted) observations (from ground and space), to intercompare simulations among different models and monitor performance progress of individual models and satellite data-products over time. During the last years, new model sensitivity experiments have been conducted and updated diagnostics have been requested to complement ongoing work for the IGAC Atmospheric Chemistry and Climate initiative and to contribute directly to the IPCC Assessment Reports. Results and additional needs are regularly discussed at annual AeroCom workshops at different international locations.

Aerosol distributions from satellite retrievals have always been recognised as a key to evaluate aerosol property patterns. Major requirements for these satellite retrievals are:

netCDF data format *… for easy usage of satellite data products in evaluations*
While it is recognized that any satellite data product requires careful interpretation, it is on the other hand very inefficient to ask each individual modelling team to work up specific satellite formats (although satellite simulators could be quite useful … but this is another story). Comparisons of satellite data products to simulations in global modelling are simplified, if satellite data products are delivered in a lat-lon gridded netCDF data format, with appropriate

attributes following the CF convention (as specified for model output in the AeroCom protocols and the CMIP5 protocols). Providing data in this format greatly enhance the capacity of modellers to explore satellite data (e.g. via the AeroCom web-site).

documented quality and precision
Any satellite data product should be accompanied by an error estimate. Quantitative (absolute) errors are preferred over so called quality flags. Independent quality measurements from ground based sun-photometry and even comparisons to mature retrieval products by other satellite sensors should guide such error estimates. Such comparisons should be conducted by groups not involved in algorithm development. Products at different scales and (if offered) for different quality levels should be evaluated with the same tools. Any new satellite product should reach or exceed the quality and performance of established products of MODIS, MISR or POLDER (over oceans). The consistency of different aerosol products (AOD, size and composition) should be documented. Reasons for differences among satellite products should be identified. Spatial coverage (in cloud-free regions) should be as frequent as possible.

identify dominant aerosol species *… for links to emissions and sources*
Aerosol species information cannot be retrieved from satellite observations, but indicators for dominant aerosol size (via the AOD spectral dependence) and (unless prescribed) for overall absorption (via AAOD) offer indirect information on dominant aerosol types. The resulting capability to distinguish between dust, sea salt, wildfires or pollution, as dominant aerosol type, reveals background on air-mass history (e.g. source, transport and even processing).

long term trends *(many years) for regions and global*
Trends and interannual variability require a long term record to be available for aerosol science. To establish anomalies and trends in radiative impacts it is essential to monitor atmospheric perturbations as a function of time. Together with emission inventories and models such long term information may allow the monitoring of emissions and changes in climate. This can be especially powerful for short-lived species such as aerosol particles. Even if a global trend is difficult to detect, regional (multi-year to decadal) trends will be – given that the applied aerosol satellite data-set is homogeneous. The longest aerosol data records from satellites go back to 1980, but with limited sensors capabilities available aerosol data products are few and limited in accuracy. And in terms of subsequent sensors temporal inconsistencies must be understood. To understand if indicated trends by those older but also of more capable newer satellite data-records are real or artefacts, an AeroCom (model simulations with observed meteorology and best guesses for emission model input) exercise is focusing on the period 1980-2010.

absorption
Dust and organic (and here especially Black Carbon (BC) or soot) aerosol absorb radiation. The self-heating often stabilizes elevated aerosol layers. And the top of atmosphere (TOA) climate warming potential by BC has recently received some attention, due to its large uncertainty. Absorption in underdetermined satellite retrievals is usually prescribed and incorrect assumptions for absorption corrupt the accuracy of AOD satellite retrievals. The information content stemming from AERONET sky-photometers and surface in-situ observations requires a better global coverage to establish better first guesses in satellite retrievals. Retrieving accurate absorption data remains a challenge. Current estimates for aerosol column absorption are either more qualitative (MISR, OMI UVAI) or if offered quantitatively as AAOD depend on further assumptions (OMI requires elevated aerosol, its central altitude and an aerosol type assumption for the needed spectral conversion).

Moreover, also for the aerosol radiative forcing impacts also the specific vertical location of the aerosol absorption matters.

vertical distribution *…evaluations with CALIOP, IASI and GOMOS*
Information on the vertical distribution is offered by active remote sensing (e.g. CALIPSO), spectral information (e.g. O2 band in POLDER), multi-views (e.g. MISR), IR-blackbody temperature (e.g. IASI) and for the stratosphere via limb-scanning (e.g. GOMOS). The vertical distribution is an essential element to understand aerosol transport and aerosol processing in global modelling (e.g. wet removal, new particle formation, local heating). Information on vertical distributions is also needed for more accurate aerosol direct forcing estimates in case of absorbing aerosols (as absorbing aerosol above clouds make the aerosol direct forcing less negative). In-situ aircraft latitudinal transects on BC content have demonstrated aerosol vertical deficiencies in global modelling but these in-situ samples are very sparse compared to the spatial coverage of satellite data. Vertical profiles of aerosol backscattering from CALIOP have demonstrated the usefulness of aerosol vertical distributions in model interpretations, as did MISR geometry data to assign biomass burning plume top altitudes or GOMOS with respect to recent volcanic eruptions (e.g. Kasatochi). Thus, explorations to get quality data on vertical distribution global maps for (all) aerosol properties with these and alternate methods is strongly encouraged.

Explore and understand sampling biases of reference data
Reference data by sun-/sky-photoemtry (e.g. AERONET) only sample during day-time (new developments for lunar photometers during nighttime start to become available, which can be used to validate night-time satellite products, e.g. from IASI) and only during cloud-free conditions. Hereby direct attenuation (sun-) measurements only require an unobstructed view of the sun, while (sky-) radiance samples (for the retrieval of size-distributions and composition) require a completely cloud-free sky and only sample at lower sun-elevations. These temporal sampling conditions may introduce unknown biases in monthly and daily statistics of these aerosol reference data to global modelling and to satellite retrievals. Another aspect is the potential spatial bias, as local sun-/sky-photometer samples may not represent surrounding averages (of satellite multi-pixel average and to modelling grid regions on the order of 100km x 100km). Satellite observations, with better spatial coverage are needed to provide spatial context and to fill reference data gaps where ground based information is scarce or not available. Hereby, a better temporal coverage of satellite observations (e.g. a wider swath of polar orbiting platforms, or geo-stationary sampling) increases the chance to observe cloud-free scenes at a given day and in a specific region.

capabilities for fast re-processing of the entire dataset *… after identification of errors*
Algorithm updates also based on repeated evaluations to reference data require regular re-processing to improve retrieval capabilities. Subsequently, improvements need to be quantified against established evaluation benchmark reference data and performance results need to be documented in the open and peer-reviewed literature or in reviewed reports.

CAMS requirements for aerosol

The CAMS service pursues the goal to predict and re-analyse chemical weather (aerosol, greenhouse gases and reactive gases in the atmosphere) by using the IFS model system at ECMWF (European Center for Medium range Weather Forecasts). The CAMS strategy is to assimilate instantaneous satellite products (of known uncertainty) in order to obtain an improved reanalysis product, that is constrained by observations. A major benefit is the complete temporal and spatial coverage (by filling the sampling holes) and consistent detail for properties not available from observations. For data assimilation in operational forecasts, most recent (so called near-real-time) satellite retrieval products are needed; re-analysis requires consistent time series of historic data. Currently, in aerosol standard assimilations mid-visible AOD data from MODIS on EOS Terra (ca 10.30 am local time) and EOS Aqua (ca. 1.30 pm local time) are applied to constrain the forecast model.

The CAMS requirements for these standard assimilations have been formulated for in near-real time available MODIS level 2 AOD data along individual swath stripes. All individual data pixels require their own uncertainty estimates and data format should be in netCDF. The AOD data should be consistent with other independently retrieved atmospheric properties (e.g. wild-fires). Two different requirement levels are identified, threshold and target requirements. The ***threshold requirement*** defines the limit below which an observation becomes ineffective and is not anymore of use in climate-related application. In contrast, the ***target requirement*** indicates observation capabilities that are expected to lead to significant model improvements in climate applications. Threshold and target requirements as expressed for AOD by the CAMS community are summarized in Table 4.

Alternate assimilations have explored extra information content of vertical distributions (of CALIPSO backscattering) and of aerosol size (fine-mode AOD over oceans). The improved forecast indicates that this extra detail on aerosol properties (if being made available in near-real time) is highly desirable to constrain transport and composition in data assimilations.

Table 4: ***CAMS requirements for AOD (level 2, near-real-time products)***

	threshold requirement	**target requirement**
	coverage and sampling	
geographic coverage	global	global
temporal sampling	500 observed locations *per hour*	1000 observed locations *per hour*
temporal extent	*1991-present*	*1982-present*
	resolution	
horizontal resolution	20km	5km
vertical resolution	N/A	N/A
	error / uncertainty	
precision	0.05	0.02
accuracy	0.05	0.02
stability	N/A	N/A
error characteristics	*global statistics*	*sample statistics*

Aerosol_cci core user requirements

User case studies planned for the second year of Aerosol_cci phase 2 (and also in the second phase CMUG project) will analyse Aerosol_cci datasets used in the following applications:

- stratospheric aerosol-chemistry-climate interaction based on 10 years of GOMOS data
- aerosol direct effects and their trends based on 17 years of ATSR data
- trend analysis using 30 years of absorbing aerosol index data from OMI and other instruments TOMS, GOME, SCIAMACHY, GOME2 (from Phase 1)
- aerosol-cloud interaction based on 17 years ATSR time series

overall requirements stated are:

- consistent data formats
- capability for (annual?) reprocessing of full data
- aerosol types matching those used in modeling
- pixel uncertainty
- improvement of retrieval results with high aerosol loading
- consistent error characteristics
- POLDER retrievals for regions where no ground-based reference data are available (remote oceans, land regions with sparse AERONET coverage)
- at least Ångström exponent and Fine Mode AOD
- sufficient documentation on data access at website
- peer reviewed paper as reference

stratospheric aerosol-chemistry-climate interaction tasks need

- 10+ years time series on vertical profiles for stratospheric extinction
- High temporal resolution (e.g. 5 days) could be more important than high horizontal resolution (60 deg longitude x 5 deg latitude sufficient) for attribution and evaluation of volcanic effects
- polar stratospheric clouds (PSC) should be added as separate variable

Given the sparse observation density and low absolute values of aerosol extinction in the stratosphere, a consistent long time series and a good compromise of temporal and horizontal resolution are the key requirements. This will then also allow specific process analysis associated to individual stratospheric volcanic events.
Data on PSCs are useful for evaluation and improvements of chemistry-climate models (CCM).

aerosol-(water) cloud interactions
major aerosol requirements are

- fine-mode aerosol mid-visible AOD (AOD associated with aerosol smaller than 0.5um in radius) which is preferred over the aerosol index AI (= AOD * Ångström exponent)
- fine-mode aerosol mid-visible extinction at cloud base from aerosol profiling
- fine-mode aerosol composition for kappa (humidification capability) estimates
- fine-mode aerosol effective radius (if available) for CCN estimates

major water cloud requirements are

- cloud top altitude
- cloud optical depth and cloud top effective radius (Nakajima King: 0.55um +3.7um)
- CDNC estimates (from radius and opt.depth)
- liquid water content
- cloud thermodynamic phase (from multispectral information, cloud temperature, polarization measurements if available)

- retrieval detail on cloud cover and viewing geometry quality to apply data quality filters (e.g. use VIS/nIR retrievals only for higher cloud cover, no extreme side viewing)
- larger scale cloud structural (inhomogeneity) parameters

demonstrated cloud and aerosol association in space and/or time.

- associations should be investigated within different threshold distances and/or time-periods
  - at the highest possible resolution
  - at the resolution of global modeling use a satellite simulator for comparable model output
  - nearest neighbour associations between aerosol and cloud retrievals using a minimum distance reduce effects by aerosol water uptake in humid environments around clouds, cloud contamination, aggregation or 3D effects
- for an averaging statistical analysis these associations should be summarized in joint histograms between aerosol properties (fine-mode AOD (alternatively AI) or derived CCN) and cloud properties (CDNC, effective radius, liquid water content)
- associations should be investigated at resolutions of global modeling
- for robust statistical associations at high spatial resolution a good data coverage is required (wide swath/short revisit time for polar orbiting platforms, consistent long time series)

Diagnostic comparisons of output from global modeling benefit from the applications of satellite simulator data-filters.

aerosol-(ice) cloud interactions
major aerosol requirements are

- coarse-mode aerosol mid-visible AOD (AOD associated with aerosol larger than 0.5um in radius) or AOD in the TIR window
- coarse aerosol mid-visible or TIR extinction (and temperature) at cloud altitude
- (far-IR data based) dust effective radius

major ice cloud requirements are

- ice-cloud top altitude
- ice cloud optical depth and cloud top effective radius (Nakajima King type method)
- ice cloud water content (and temperature)
- cloud thermodynamic phase (from multispectral information, cloud temperature, polarization measurements if available)
- retrieval detail on cloud cover and viewing geometry quality to apply data quality filters (e.g. use VIS/nIR retrievals only for higher cloud cover, no extreme side viewing)
- larger scale cloud structural (inhomogeneity) parameters

demonstrated (ice-)cloud and (dust-) aerosol association in space and/or time as for water clouds (see above).

EMAC dust modelling

Aerosol_cci data will also be useful for evaluation and improvements of modelling. The ECHAM5/MESSy Atmospheric Chemistry (EMAC) group has expressed its interest to use data of the following quantities and resolution to evaluate their model:

Quantities:
- Dust AOD measured at 10 μm

- Dust AOD measured at 550 µm
- Total AOD measured at 550 µm

Temporal resolution:
- daily (swath) data for studying individual dust outbreaks
- monthly data for studying seasonality
- longest multiyear time series possible to study perennial variations

Spatial resolution:
- ~ 1 degree or higher to match the T106 model resolution for multiyear simulations
- ~ 0.5 degree or higher to match the T255 model resolution for simulations of individual events
- highest resolution possible to disclose emission sources and provide insights into the transport dynamics

4 AEROSOL PARAMETERS

Aerosol AMOUNT (column average)

AOD (Aerosol Optical Depth at 550 nm): The AOD is a spectrally dependent optical property. The AOD in global modelling usually refers to the value at the mid-visible ("green") wavelength at 550nm. Similarly, this AOD at 550nm is also picked as reference wavelength, in remote sensing in order to allow direct comparisons among different retrievals. If the AOD is not retrieved at this wavelength, then a spectral adjustment can be performed with the Ångström exponent (see below) - as long as the spectral absorption does not vary. Aside from the total AOD also subcomponents of the total AOD are of interest, most important (1) the AOD in the stratosphere, (2) the AOD attributed to the smaller sub-micron aerosol sizes (fine-mode, see also FMF) and by default to (3) the AOD attributed to the other super-micron aerosol sizes (coarse-mode) and (4) the dust AOD contributions to the coarse mode.

AOD subcomponents (at 550 nm)

stratospheric AOD contributions (in comparison to those in the troposphere) are usually a minor fraction of the total AOD. Stratospheric aerosol loads are caused by volcanic eruptions that emit aerosol (ash and sulfate precursor gases) in the lower stratosphere, where smaller sulphate aerosol due to the lack or removal processes can remain for some time (on the order of years). After major eruptions (El Chichon, Mt Pinatubo) the global average stratospheric AOD can be comparable to that of the troposphere. However, in the absence of major eruptions in the last three years (as since 1996) the stratospheric AOD contributions are at most a few percent. However, to maintain observing capabilities following major volcanic eruption, a distinction of the stratospheric AOD from the total AOD is desirable. This holds also for BC penetrating the lower stratosphere in the Asian Monsoon.

fine-mode AOD is mainly caused by aerosol from wild-fires, ocean DMS release, volcanic sulphate and fossil fuel burning or (human) pollution. The dominant fraction of the fine-mode AOD contribution in urban industrial regions is of anthropogenic origin. Thus, from a climate change perspective there is general interest in fine-mode AOD in those regions. Moreover, fine-mode AOD is an output in global modelling. Thus, quantifying this property (see FMF below) is a very useful quantity in evaluating simulations in global modelling.

coarse-mode AOD is mainly caused by dust and sea salt as well as by ash briefly after volcanic eruptions. Higher coarse mode AOD values are usually tied to dust. The coarse mode AOD is defined as the fraction of the total AOD which is not fine-mode AOD (see, FMF below) (coarse = total – fine) and useful for evaluations of simulated coarse mode AODs in global modelling.

dust AOD is the dominant contributor to the coarse mode AOD, especially if coarse mode AOD values are large. Coarse mode dust is absorbing, is often found at altitudes well above the ground and has significant radiative effects not only in the solar but also in the infrared spectral region. In addition, most of the rare ice nuclei (IN) in the atmosphere contain dust. Thus, knowing the coarse mode AOD along with estimates for the ***dust altitude*** are needed elements in quantifying IR greenhouse effects of aerosol and addressing IN concentrations of interactions with ice-cloud microphysics in global modelling.

Aerosol SIZE (column average)

Ångström exponent: The Ångström exponent is a general indicator for particle size. Its determination requires AOD retrieval data simultaneously at two different wavelengths. The Ångström exponent defines the (usually negative) linear slope in log/log space and is close to zero if coarse mode (or super-micron) particles dominate and almost 2 if fine mode (or sub-micron) particles dominate. The two wavelengths to compute an Ångström exponent should be somewhat spectrally separated. To determine the Ångström exponent commonly AOD data at 440nm and 870 nm are applied, as these wavelengths involve reliable data from (ground) sun-photometry. As satellite retrievals and (even global modelling output) do not always offer AOD values near these two wavelengths usually AOD data closest to these wavelengths are picked.(hereby, the error introduced by spectral differences is usually small).

FMF: The Fine Mode (AOD) Fraction defines how much of the total AOD is apportioned to sub-micron size aerosol or aerosol size smaller than 1μm in diameter. This size information is more useful than the Ångström exponent - especially in evaluations of global modelling. Global models via their commonly used modal size-approaches by default distinguish between coarse mode AOD and fine mode AOD contributions. Unless detailed size-distributions from ambient aerosol are available (as via inversions of sky radiance data), the fine-mode AOD can also be estimated from AOD retrievals (as offered by sun-photometry or even satellite data). This (so called SDA) method requires simultaneous AOD retrievals at four different (solar) wavelengths, hereby taking advantage that the fine/coarse AOD split influences the spectral dependence of the Ångström exponent. In satellite retrievals the fine-mode fraction usually cannot be retrieved and is prescribed by the choice of the retrieval model. Still, having the fine-mode AOD fraction from the applied model can be a very useful diagnostic help in (AOD) evaluations.

AI: The Aerosol Index (AI) is defined as the product of AOD and Ångström exponent. The AI is a good qualitative representation for the fine-mode AOD (FMF*AOD) and a useful quantity, when FMF is not available, as in most aerosol satellite retrievals. The fine-mode

AOD in conjunction with the ***fine-mode altitude*** and ***fine-mode composition*** defines the number of cloud condensation nuclei, so that the CCN concentration at (water-) cloud-base can be estimated, which is an essential property needed for aerosol-cloud process understanding. Since process understanding examines impacts due to differences in CCN, for studies of relative change, AI can be used as substitute for the fine-mode AOD.

r,eff (strato) is the aerosol effective (number concentration weighted) radius of sulphate aerosol in the stratosphere. In order to quantify the climate impact of stratospheric sulphate after major volcanic eruptions (when stratospheric AOD can become comparable to tropospheric AOD), next to AOD also the typical sulphate sphere size matters in quantifying the local (mainly IR) stratospheric heating. Effective radii usually increase with increasing stratospheric AOD (typically r,eff~0.15μm at cleaner conditions, but r,eff~0.5μm after major eruptions). To determine the effective radius, independently retrieved AOD at different solar wavelengths are required (as for the Ångström exponent or FMF).

Aerosol ABSORPTION (column average)

1-SSA This so-called co-Single Scattering Albedo [1-SSA] describes the absorption potential but not the absolute absorption (see AAOD). Attenuation (or extinction) from interactions of radiation with atmospheric particles (such as aerosol) is caused by scattering or absorption. The ratio of scattering to extinction (= absorption plus scattering) is quantified by the Single Scattering Albedo (SSA). Thus, by definition the ratio of absorption to extinction defines [1-SSA]. The (spectrally varying) SSA is a requirement for radiative transfer simulations. In most satellite retrievals the absorption potential [1-SSA] is prescribed. However, satellite retrieval validation and model comparison are easier done with the absolute quantity AAOD (see next paragraph), since the many cases of low AOD are then reduced in their statistical importance. Absorption is spectrally dependent and usually refers to the mid-visible (550nm), if no specific wavelength information is given. The absorption potential [1-SSA] is an influential property when retrieving AOD from satellite sensed solar reflections. Still, the applied [1-SSA] value, once made available, offers useful diagnostic help in evaluations of AOD retrievals.

AAOD (Absorption Aerosol Optical Depth, usually reported at 550 nm). The AAOD is a spectrally dependent optical property and defines the absolute absorption by aerosol. The AAOD is the product of AOD (for column amount) and [1-SSA] (for column absorption potential). In terms of quantifying aerosol absorption, the AAOD is preferred over potentials of SSA or [1-SSA], especially when involving any type of averaging.

UV-AAI: The Ultra-Violet Absorbing Aerosol Index (UV-AAI) is a qualitative measure for absorption. The UV-AAI is more sensitive to aerosol absorption at higher altitudes. Thus, additional information on aerosol altitude is required but usually only available from modelling only in a statistical sense (CALIOP profiles could be used, but this has not yet been done). Also the UV-AAI sensitivity to absorption near the surface (e.g. pollution) is weak. In addition, the retrieved absorption in the UV is different than in the mid-visible solar spectral region, where solar radiation is at a maximum. To perform the needed spectral adjustment, not only information on aerosol size but also information on aerosol composition is required (use of a newly available MISR climatology needs to be tested). Comparison to global modelling is difficult (require model simulators) and difficult to interpret. Thus, a quantification of aerosol absorption via AAOD (as attempted with OMI data) is preferred over UV-AAI data.

Aerosol SHAPE (column fraction)

Non-spherical The non-spherical aerosol particle shape can be detected with polarization measurements (e.g. POLDER) and active remote sensing (ground lidars, CALIOP space lidar). Non-spherical shapes are mainly associated with dust. Since dust usually has most of its AOD contributions in the coarse mode, the nonspherical information is often translated into a coarse-mode dust fraction.

Aerosol vertical distributions

Extinction profile: The vertical distribution of the AOD is expressed by the extinction profile. Such data are available via limb scanning from satellites in a (cloud-free) upper atmosphere (e.g. GOMOS) and via active remote sensing by lidar from space and ground. The currently operating CALIOP space lidar captures only backscatter profiles, such that the estimated extinction profile is somewhat contaminated by the prescription for the extinction to backscatter ratio. Still, even a general idea on the vertical placement of aerosol is very useful for (1) model evaluations on vertical and horizontal transport and radiative effects, and (2) on aerosol-cloud interactions, as vertical co-location between aerosol and clouds is needed. Plume height (from stereo observations) or effective layer height (from O2A band spectrometry or TIR sensors) could be a useful estimation of vertical aerosol distribution.

Dust altitude: The depolarization profile informs on the vertical distribution of nonspherical particles (ice clouds, dust). Most lidars from ground and space detect depolarization, thus can identify atmospheric layers containing ice clouds and dust. Dust altitude can also be detected by IR data (e.g. IASI) as dust is (1) absorbing in the IR windows, (2) usually composed of larger aerosol sizes and (3) generally elevated (at colder temperatures than the underlying surface).

Important **supplementary properties**

Clear-sky detection: Aerosol retrievals generally require usually cloud-free conditions. However, identifications of clouds-free scenes are often difficult due to overlooked presence of sub-pixel low clouds or cirrus. In many satellite retrievals there is a delicate balance between providing good coverage versus being restrictive on potential cloud contaminations.

Solar surface albedo: In nadir aerosol satellite retrievals the solar surface albedo has to be known with high accuracy; for multi-angle observations it needs to be less well-characterized, but still influences AOD retrieval accuracy. However, the solar surface albedo is spectrally dependent and varies with region and season. Another complication in satellite retrievals is the dependence on the viewing geometry (BRDF). Thus, satellite retrievals are often not possible over regions with snow cover, over land regions with dry or no vegetation and over oceans regions affected by glint.

Category 1 aerosol properties are
- **AOD**, **AODf** (fine-mode AOD) and **AAOD** for optical characterization and evaluations **stratospheric AOD** and **eff.radius** for stratospheric aerosol monitoring
- **AODf** (fine-mode AOD or **AI**) and **fine-mode eff.radius** for links to water clouds

- coarse-mode **dust AOD** (and **far-IR AOD**) for links to ice clouds
- aerosol altitude placement through **vertical backscattering / extinction profiles** for vertical co-locating aerosol and clouds and for transport and process understanding

5 ACCURACY

Accuracy represents the degree of closeness of a measurement of a quantity to its actual value. Deviations from the actual value can be due to both bias (sampling) and noise (weak signal). The (minimum) required accuracy and stability depends on the data resolution (both in space and time) and the user application. Thus, in line with CMUG (and in contrast to the GCOS) requirements we suggest to associate requirements for accuracy to the data resolution and therefore indirectly to the application. As time and space scales are related, the accuracy requirements have been reduced to these five scales:

- satellite product scale: 2 hours, 0.1x0.1deg. (*ca. 10x10 km^2 at equator*)
- (global) model grid scale: daily, 1x1deg. (*ca. 100x100 km^2 at equator*)
- regional scale: monthly, 10x10 deg. (*ca. 1000x1000 km^2 at equator*)
- inter-annual scale: (season, 10 x10 deg. (*ca. 1000x1000 km^2 at equator*)
- decadal scale: annual, 10x10 deg. (*ca. 1000x1000 km^2 at equator*)

Accuracy requirements for “category 1” aerosol properties of three major applications (optical characterization, stratospheric monitoring, investigating links to clouds) are listed in Table 5, as a function of the five scales.

Table 5: ***Aerosol_cci accuracy requirements at recommended data product scales***

property spatial temporal	**sat. product** 0.1x0.1 deg 2 hours	**model grid** 1x1 deg daily	**regional** 10x10 deg monthly	**inter-annual** 10x10 deg seasonal	**decadal** 10x10 deg Annual
AOD, 550nm	**0.04**	0.020	0.010	0.008	0.006
AODf 550nm	**0.03**	0.015	0.008	0.006	0.005
AAOD, 550nm	**0.01**	0.005	0.003	0.0025	0.002
AOD, strato	**0.01**	0.005	0.003	0.0025	0.002
r, eff (μm)	**0.05**	0.03	0.02	0.02	0.02
AODf 550nm	**0.03**	0.015	0.008	0.006	0.005
AOD, dust sol	**0.03**	0.015	0.008	0.006	0.005
AOD, dust IR	**0.02**	0.010	0.005	0.004	0.003
ext. profile, vertical resolution	**1km**	500m	300m	300m	300m

Note: as fine-mode AOD and coarse-mode / dust AOD are the two fractions of the total AOD and their absolute values are thus typically lower, their accuracy requirements are defined slightly higher than for the total AOD. Both precision and stability have to be better than the accuracy values of Table 5. The precision has to be better by a factor of 2 and the stability has to be better by a factor of 4 (than the accuracy)

The optical characterization requires at least data on (total) AOD, (fine-mode) AODf and (absorption) AAOD. Monitoring on volcanic aerosol in the stratospheric requires data on stratospheric AOD and effective radii of stratospheric aerosol. Studies on aerosol-cloud interactions require foremost (fine-mode) AODf for links to water clouds and dust AOD for links to ice clouds. In addition, information on (aerosol) vertical profiles is highly desirable for the correct aerosol (concentration) placement with respect to the potentially influenced cloud. For simplicity the root mean square (RMS) is suggested as the measure for accuracy. It is preferred to represent accuracy in absolute values (thus, larger relative uncertainties at smaller values are permitted). Note, that for satellite retrieval accuracies (of level 2 data) at the smallest (satellite product) scale are most relevant. Satellite products at larger scales (gridded level 3 data) involve averaging procedures. Thus, if accuracy requirements are met at the lowest resolution (satellite product) then it is hoped that by noise-averaging the indicated higher accuracies at finer (temporal and/or spatial) resolutions can be achieved.

6 UNCERTAINTY CHARACTERISTICS

AOD uncertainty estimates for super pixels (level 2 products, e.g. with 10x10 km^2) as well as for gridded resampled datasets (level 3 products, e.g. with 1x1 deg.) add to the usefulness of data (e.g. in data assimilations). Hereby, a distinction into **systematic uncertainties** (bias) or **random uncertainties** (noise) is highly desirable since random errors tend to diminish with an increasing sample size.

There are many potential sources for uncertainties. There are uncertainties associated with the platform (drift), the sensor (degradation) and the retrieval. Hereby, retrieval uncertainties in aerosol remote sensing involve many potential sources. These include limitations (1) to choice of the 'best' aerosol model, (2) to the detection (and removal) of impacts by (water- or ice-) clouds, (3) to the characterization of the lower boundary condition (solar surface albedo, surface emissivity temperature) and even (4) to environmental properties (temperature, aerosol layer altitude placement). Some of these uncertainties are known and can be quantified while other uncertainties remain unknown. And even when focusing just on the known uncertainties it is not clear how to combine different uncertainties. uncertainties are not necessarily additive in nature due to dependencies among errors. In general though, it is better to be conservative (and assume additivity).

For level 2 individual (pixel) retrievals it is helpful to provide aside from the most likely values associated estimates for the **systematic** uncertainties (bias) and the **random** uncertainties (noise) and express those by an **upper bound** and by a **lower bound**. Thus, if there is a systematic uncertainty, the retrieval related uncertainties will not be symmetric around the most likely value.

For level 3 quantitative uncertainties estimates are difficult as uncertainties cannot be simply averaged. A save path is to apply the largest random and the largest systematic uncertainties and reduce the random uncertainties according to sample size. Another more practical path from a user perspective is to remove all individual retrievals which surpass pre-set upper and lower uncertainty bounds before data averaging. The idea here is that retrieval groups offer different level 3 data products, which are associated with different uncertainty constraints. This concept is regarded by the authors of this report to be more fruitful than so called quality flags, which are often ignored or overlooked by data-users. This way a user can pick among different level 3 data products and apply those that offer acceptable uncertainties. However, also offering several datasets may confuse users, who do not spend enough time on understanding the differences between them. In any case, a very clear and easily understandable communication is required here (a dedicated SHORT explanation in the Product User Guide). Clearly a tighter uncertainties requirement comes at the cost of reduced coverage (and potential biases). Those concepts for uncertainties quantification for level 2 and gridded (and averaged) level 3 products are outlined in Table 6 with recommendations for estimating error terms (systematic error E_{sys}, random error E_{ran}, upper boundary ub and lower boundary lb) for those different concepts of error handling. Here n_{xx} denotes the associated number of pixels remaining after quality filtering with uncertainty thresholds max_n. In the aggregation to level3 data, the random error can decrease with growing numbers, while the systematic error is determined by the largest systematic error.

Table 6: ***Aerosol_cci error quantification requirements***

product level	**systematic**	**random error**	**up bound**	**lower**

	error		ub	boundary ul
Level 2	Esys= Σ_i Esys	Eran= Σ_i Eran	Eran+Esys	Eran - Esys
Level 3 - *all level 2 (nall)*	max,na (Esys)	max(Eran) /sqrt(na)	Eran+Esys	Eran - Esys
- lev2 (ub,lb < max1)	max,n1 (Esys)	max(Eran) /sqrt(n1)	Eran+Esys	Eran - Esys
- lev2 (ub,lb < max2)	max,n2 (Esys)	max(Eran) /sqrt(n2)	Eran+Esys	Eran - Esys
- lev2 (ub,lb < max3)	max,n3 (Esys)	max(Eran) /sqrt(n3)	Eran+Esys	Eran - Esys

Note, as the maximum permitted error decreases (max3 < max2 < max1 < no max) the number of available level2 samples for the level3 will decrease too (n3 < n2 < n1 < nall). This reduced sub-sample certainly will also impact the most likely level3 average (or median).

7 RESOLUTION

The smallest spatial resolution is the retrieval area (also called super pixel, where statistics from a number of individual pixels can be exploited) on the order of 10x10km^2 or even finer. For many applications (evaluations, analyses), however, coarser spatial resolutions through 'averaging' are requested. For instance, global modelling output has a spatial resolution on the order of 100x100km^2 and inter-annual or trend analyses are best performed on the basis of larger regions on the order of 1000x1000 km^2.

Thus, (aerosol) satellite data products output are requested on three different scales, as introduced in the accuracy section and Table 5. Note, that for the requested products in Table 5, spatial and temporal scales are correlated in size.

Most aerosol products in satellite remote sensing can only address column averaged (or integrated) properties. Still, vertical distributions are useful constraints for the evaluation of transport in global modelling and needed requirements for process understanding in global modelling (e.g. aerosol-cloud interactions). Considering their sparseness and limitations (via geometry methods, lidar coverage, O2-band estimates, IR dust methods), expectations should not be high. Still, 1km altitude stratifications for instantaneous data and 500m altitude stratifications on a statistical basis would already be extremely useful.

8 PRODUCT ASSOCIATIONS

A less well understood aspect in global climate modelling of aerosol is the link between aerosol and its environment. Potentially important are interactions with clouds. The climate effects of anthropogenic aerosol via their scattering and absorption as well as via their interactions with clouds are large sources of uncertainty in climate predictions. Aerosol can supply extra cloud and ice nuclei (which can lead to changes in cloud macro-physical properties such as optical depth, geometrical dimensions, water content) and can influence the on-set of precipitation. Alternatively, clouds can remove aerosol (by wet deposition), change the aerosol composition and size (by heterogeneous chemistry or coagulation) or redistribute aerosol by convection processes. These interactions involve at times relatively rapid processes that may compensate each other. Thus, observed associations between aerosol and clouds are sought, in order to establish constraints to aerosol processing in clouds and cloud modifications in global modelling. The idea is to match co-located or adjacent retrievals of aerosol and clouds from the same platform at the smallest scales and create at different coarser scales (daily, 100x100km^2 and monthly, 1000x1000km^2) joint histograms (similar to ISCCP) for relevant properties.

For simplest aerosol links to properties of water clouds, the aerosol number concentration matters. Aerosol number is largely defined by the fine-mode AOD (or alternatively by the AI).

- number proxy (AODf or AI) vs cloud droplet number conc.
- number proxy (AODf or AI) vs cloud liquid water path (LWP)
- number proxy (AODf or AI) vs cloud optical depth(@ const. LWP)
- number proxy (AODf or AI) vs cloud eff. radius (@ const. LWP)
- number proxy (AODf or AI) vs cloud eff. cover (cover*emiss.)
- number proxy (AODf or AI) vs cloud top altitude
- number proxy (AODf or AI) vs precipitation

For a more advanced aerosol reference in links to water cloud properties, information on available cloud condensation nuclei (CCN) are desirable. To estimate CCN data from observed aerosol optical properties, aside from fine-mode (AODf) also data on fine-mode effective radius, fine-mode composition (kappa), fine-mode vertical profile (for concentrations) and environment (supersaturation and temperature at cloud base) are needed. Although these relationships are more direct they also involve more uncertainties in data preparation.

- CCN proxy (AODf, reff, profile, kappa, SS, T) vs cloud droplet number conc.
- CCN proxy (AODf, reff, profile, kappa, SS, T) vs cloud liquid water path (LWP)
- CCN proxy (AODf, reff, profile, kappa, SS, T) vs cloud optical depth(@ const. LWP)
- CCN proxy (AODf, reff, profile, kappa, SS, T) vs cloud eff. radius (@ const. LWP)
- CCN proxy (AODf, reff, profile, kappa, SS, T) vs cloud eff. cover (cover*emiss.)
- CCN proxy (AODf, reff, profile, kappa, SS, T) vs cloud top altitude
- CCN proxy (AODf, reff, profile, kappa, SS, T) vs precipitation

(vertical) profile: global modelling or CALIPSO lidar, kappa, SS: global modelling, T; reanalysis

For aerosol links to properties of ice clouds the number of ice nuclei matters. These are mainly a function of dust concentrations and the environment (less at warmer temperature) at the ice cloud altitude

- IN proxy (dust AOD, dust (depol.) profile, T) vs ice crystal effective radius
- IN proxy (dust AOD, dust (depol.) profile, T) vs ice cloud eff. cover (cover*emiss.)

Co-located observations of both clouds and aerosol (with the same sensor) are in general not possible (with the exception of aerosol above clouds for which some first research products (e.g. POLDER, CALIOP, OMI) and one operational product (CALIOP) exist). Thus, close associations in space and time are the best method to provide constraints for aerosol-cloud interactions. Due to the long intervals for repeated measurements at the same location, polar orbiting satellites usually can only provide spatial associations and only for consistent long time series. These associations certainly cannot claim cause-consequence relationships. Still for selected regions, multi-dimensional associations, especially if stratified by aerosol type (kappa) or meteorological conditions, offer useful statistical observational constraints, as these relationships need to be matched by modelling. Concerns about retrieval data accuracy may not weigh in so strongly as relative changes are explored. At the current state of the art the immediate vicinity of clouds needs to be excluded due to potential cloud contaminations although it would be the most interesting region for associations between aerosol and clouds. Recent results indicate furthermore that the exclusion of aerosol retrievals in the humid environment in the vicinity of clouds reduces the effect of aerosol water uptake on CCN proxies like AOD or AI.

9 COVERAGE

Aside from retrieval accuracy also data coverage matters. Since different users have different accuracy requirements, different level 3 products are requested that satisfy different error criteria (see error section).

Daily coverage still is tied to the sensing swath, which is extremely narrow for space-lidars (CALIOP), relatively narrow for multi-viewing sensors (MISR, ATSR) but relatively wide (with almost one overpass per day) for standard multi-spectral passive sensors (MODIS, POLDER, MERIS, GOMOS, OMI, SeaWiFS, AVHRR). These standard sensors have sufficient daily samples in a 100x100km^2 region for confident monthly averages, whereas MISR and ATSR may at best address seasonal statistics. This aspect should be considered when exploring satellite remote sensing data for long-term trends.

On the other hand, when these sensor data are available for many years, then even the narrower swath instruments can offer useful multi-annual statistics. For instance, eight years of CALIOP lidar profiles offer useful global monthly statistics on aerosol vertical distributions.

Thus, satellite data-record length is a big plus for better general statistics and for investigations of long-term trends. At least 15 years of continuous retrievals are required before even trying to address (regional) trends in aerosol properties, assuming the earlier stated accuracy requirements are met.

10 PRODUCT FORMAT

The preferred output format in atmospheric global modelling is gridded **netCDF format**. For the netCDF format there are many tools to view (NCVIEW, see web-links in section 14) and simply manipulate these files (NCO, CDO, see web-sites in section 14). Having the same data-format for satellite retrievals, simplifies evaluations of global modelling tremendously. Even in case a user requests other data formats (hdf, grib or ASCII) there are tools for conversion from netcdf in these formats.

The strength of netCDF (similar to hdf, a twin format in which NASA's remote sensing output is delivered) is that aside from the (compressed) data and their dimensions also metadata are provided, which describe the data attributes. These attributes indicate the property name (long_name, standard_name, variable name), property units, data-source and performed data manipulations. These requirements for naming have been laid down in the respective documents on the CF (Climate and Forecast, http:// http://cfconventions.org/) convention and should be followed, to simplify data comparisons. Furthermore, a tool (CMOR) is available to assist in the development of a compliant format by outputting files which are consistent to CMIP requirements (variable names and associated metadata, but also file format and data fields). More information on netcdf tools and CMOR are given in the web-links section.

For netCDF output data files, **one observable per file and per year** is recommended. As an example, for AEROCOM the filenames should identify the project (aerocom), the data product (SPRINTARS-v384) and version (A2.CTRL), the frequency (daily), the variable name (od550aer) and the period (2006). As an example the "aerocom.SPRINTARS-v384.A2.CTRL.daily.od550aer.2006.nc" header is displayed in the Appendix. This example given here should be adopted as far as suitable in Aerosol_cci (note that Aerosol_cci follows the common data standards for the entire CCI programme while the AEROCOM naming standards have been fed into this CCI standard).

11 METADATA

Metadata, as mentioned in the format section should be included in the netCDF data-file. Aside from the self-explanatory naming of the file (including version frequency and time-period as explained in the format section) additional attributes should be included with links to relevant literature and publications referring to the given product and production cycle. In case of gridded level 3 data, information on averaging, error assessments, sample statistics (e.g. several daytime overpasses complicate the definition of daily averages at high latitudes) and applied ancillary data should be provided. This requirement does not replace the general requirements to provide in addition to the data matching maps describing statistical properties (pdfs or joint histograms), errors (upper and lower bound) and applied number of samples. For traceability and archiving purposes a digital object identifier (DOI) should be provided for the official products of the project.

12 GRID AND PROJECTION

For level 3 data an evenly spaced grid in lon-lat is requested for the three different spatial scales indicated in the accuracy section. The grid selection is a required element of the recommended netCDF format. Once in netCDF there are tools to easily convert to other grids and projections.

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14 WEB-LINKS

AeroCom Web Interface	http://aerocom.met.no/
Meetings:	http://aerocom.met.no/meetings.html
Protocols:	http://aerocom.met.no/protocol.html
Data:	http://aerocom.met.no/data.html
(CF) Metadata Convention	http://cfconventions.org/
CMOR rewrite tool:	http://www2-pcmdi.llnl.gov/cmor
NCO netCDF tools:	http://nco.sourceforge.net/
CDO netCDF tools:	https://code.zmaw.de/projects/cdo
netCDF browser:	http://meteora.ucsd.edu/~pierce/ncview_home_page.htm

15 APPENDIX

netCDF data-file example (AEROCOM)

This example below displays the header of a netCDF file (produced by ncdump -h) for gridded AOD data (AOD@550nm) of a global model (SPRINTARS). The file does not contain recommended supplementary information (error information, sample statistics), which should be packed into the same file as additional variables.

```
dimensions:
  time = UNLIMITED ; // (365 currently)
  lat = 160 ;
  lon = 320 ;
  bnds = 2 ;
variables:
  double time(time) ;
    time:bounds = "time_bnds" ;
    time:units = "days since 1850-01-01" ;
    time:calendar = "julian" ;
    time:axis = "T" ;
    time:long_name = "time" ;
    time:standard_name = "time" ;
  double time_bnds(time, bnds) ;
  double lat(lat) ;
    lat:bounds = "lat_bnds" ;
    lat:units = "degrees_north" ;
    lat:axis = "Y" ;
    lat:long_name = "latitude" ;
    lat:standard_name = "latitude" ;
  double lat_bnds(lat, bnds) ;
  double lon(lon) ;
    lon:bounds = "lon_bnds" ;
    lon:units = "degrees_east" ;
    lon:axis = "X" ;
    lon:long_name = "longitude" ;
    lon:standard_name = "longitude" ;
  double lon_bnds(lon, bnds) ;
  float od550aer(time, lat, lon) ;
    od550aer:standard_name = "atmosphere_optical_thickness_due_to_ambient_aerosol" ;
    od550aer:long_name = "AOD@550nm" ;
    od550aer:units = "1" ;
    od550aer:original_name = "taut" ;
    od550aer:cell_methods = "time: mean (interval: 1 day)" ;
    od550aer:missing_value = 1.e+20f ;
    od550aer:_FillValue = 1.e+20f ;
```

// global attributes:
:institution = "Research Institute for Applied Mechanics, Kyushu University, Fukuoka, Japan" ;
:institute_id = "RIAM" ;
:experiment_id = "AEROCOM-HCA-0" ;
:source = "SPRINTARS 3.84 atmosphere: CCSR/NIES/FRCGC AGCM (T106L56)" ;
:model_id = "SPRINTARS" ;
:contact = "Toshihiko Takemura (toshi@riam.kyushu-u.ac.jp)" ;
:references = "Takemura et al. (J. Geophys. Res., 2000, 17853-17873) (J. Climate, 2002, 333-352) (J. Geophys. Res., 2005, 2004JD005029)(Atmos. Chem. Phys., 9, 3061-3073)" ;
:experiment = "AEROCOM-HCA-0" ;
:frequency = "day" ;
:creation_date = "2010-01-19T06:49:19Z" ;
:history = "2010-01-19T06:49:19Z CMOR rewrote data to comply with CF standards and AEROCOM-ACC requirements. 2010-01-19T06:49:19Z CMOR rewrote data to comply with CF standards and AEROCOM-ACC requirements." ;
:Conventions = "CF-1.3" ;
:project_id = "AEROCOM-ACC" ;
:table_id = "Table 2D-D (July 2009)" ;
:title = "SPRINTARS model output prepared for AEROCOM-ACC AEROCOM-HCA-0" ;
:modeling_realm = "REALM" ;
:realization = 1 ;
:cmor_version = "2.0.0" ;

End of the document