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# Fit-for-purpose assessment of satellite aerosol and cloud datasets for constraining and monitor aerosol–cloud interactions

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**Abstract.** Aerosol-cloud interactions (ACI) remain one of the dominant sources of uncertainty in estimates of anthropogenic effective radiative forcing. Robust observational constraints on these processes require satellite datasets that are not only physically consistent but also demonstrably fit for the intended scientific purpose. Within the framework of the "Satellite observations to improve our understanding of aerosol–cloud interactions" (SATACI) project, we perform a comprehensive fit-for-purpose (F4P) assessment of existing satellite aerosol and cloud datasets used to (i) quantify aerosol indirect effects on liquid and mixed-phase clouds and (ii) support the feasibility study of a novel aerosol–cloud climate indicator. For each application, scientific and technical requirements are defined in terms of variables, spatial and temporal resolution, co-location capability, validation evidence, and the availability of uncertainty information. Candidate datasets from geostationary and polar-orbiting satellites are evaluated against these criteria, including datasets resulting from the ESA Climate Change Initiative and Copernicus Climate Change Service.

Overall, the study highlights the importance of application-specific dataset evaluation and emphasises the complementary roles of geostationary and polar-orbiting satellite observations. While geostationary sensors provide the capabilities to investigate the temporal evolution of aerosol–cloud systems, polar-orbiting climate data records remain essential for long-term monitoring and climate indicator development. Together, these observations provide a robust basis for advancing satellite-based constraints on aerosol–cloud interactions.

## 1 Introduction

Aerosol-Cloud interactions (ACI) influence both the microphysical and macrophysical properties of clouds, modulating cloud lifetime, cloud radiative effects, precipitation efficiency, and key climate feedbacks. Through their impact on cloud droplet number concentration, cloud optical thickness, cloud fraction, and phase transitions, aerosols affect the Earth's energy balance on regional to global scales. Despite decades of dedicated studies, the magnitude of aerosol indirect effects remains one of the

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largest sources of uncertainty in estimates of anthropogenic effective radiative forcing, as consistently highlighted in the latest Intergovernmental Panel on Climate Change (IPCC) assessment report (Arias et al., 2021). This persistent uncertainty reflects both the intrinsic complexity of aerosol–cloud processes and the challenges associated with observing them consistently across scales.

Satellite observations have long been recognised as a cornerstone for constraining ACI, owing to their global coverage, multi-decadal continuity, and the availability of complementary aerosol and cloud retrievals. A large body of literature has used satellite-derived aerosol proxies - such as Aerosol Optical Depth (AOD), Fine Mode Aerosol Optical Depth (FMAOD), Ångström exponent, and aerosol index - in combination with cloud properties including Cloud Droplet Number Concentration (CDNC), Liquid Water Path (LWP), and Cloud Fraction (CF) to infer aerosol–cloud relationships (e.g. Quaas et al., 2008; Gryspeerdt et al., 2016; Hasekamp et al., 2019; Bellouin et al., 2020). These studies have provided compelling evidence for aerosol-induced cloud microphysical responses, but have also revealed substantial sensitivity of inferred ACI metrics to dataset choice, spatial and temporal resolution, and methodological assumptions.

A recurring conclusion across observational studies is that the interpretation of satellite-based ACI signals is strongly influenced by scale mismatches and sampling limitations. Polar-orbiting satellites provide high spatial resolution but only snapshot views of cloud–aerosol systems, which may inadequately capture the temporal evolution of cloud responses to aerosol perturbations. Several studies have shown that instantaneous co-location can either under- or overestimate ACI effects depending on the timing of the observation relative to cloud development (Christensen et al., 2020; Alexandri et al., 2024; Smalley et al., 2024). These limitations have motivated increasing interest in geostationary satellite observations, which offer high temporal resolution and enable the investigation of diurnal variability and time-lagged aerosol–cloud relationships.

Another central challenge identified in the literature concerns the use of spatial aggregation. To co-locate aerosol and cloud retrievals, many studies rely on coarse spatial grids (often $1° \times 1°$ in latitude and longitude), which smooth local variability and can substantially alter inferred aerosol–cloud sensitivities. Conflicting results have been reported, with some studies suggesting underestimation of aerosol radiative forcing due to excessive averaging (Jia et al., 2021), while others indicate that coarse resolution can artificially enhance correlations by blending affected and unaffected cloud regimes (Goren et al., 2023).

Beyond liquid clouds, aerosol interactions with ice and mixed-phase clouds represent an additional, and in some respects even more uncertain, pathway through which aerosols influence the climate system (Storelvmo, 2017). Ice clouds play a major role in regulating the Earth's radiation budget, particularly in the upper troposphere, where small changes in ice crystal number concentration and cloud optical properties can lead to substantial radiative impacts (Hong et al., 2016; Matus and L'Ecuyer, 2017). Among aerosol species, mineral dust has long been identified as one of the most efficient ice-nucleating particle (INP), capable of triggering heterogeneous freezing at relatively warm temperatures compared to homogeneous ice formation (Kanji et al., 2017; Villanueva et al., 2025).

Despite this well-established microphysical role, observational constraints on dust impacts on cloud glaciation and ice cloud properties remain sparse and fragmented. In situ measurements are geographically limited, while satellite-based studies face challenges related to cloud phase discrimination, vertical overlap, and the separation of aerosol and cloud signals. As a result,

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estimates of dust-induced modifications of cloud glaciation temperature and ice crystal properties show large spread across models and observational studies, contributing to persistent uncertainty in aerosol radiative effects on cold clouds.

In parallel with process-oriented studies, there is growing demand from the climate research and climate services communities for robust, observation-based indicators that can track aerosol–cloud interactions over long time scales and support model evaluation and climate monitoring. The Effective Radiative Forcing (ERF) contribution due to ACI (ERFaci) is estimated at -1.3 [-2.0 to -0.6] $\mathrm{Wm^{-2}}$, while the remainder due to aerosol-radiation interactions (ERFari), or aerosol direct effect, is estimated to -0.3 [-0.6 to 0.0] $\mathrm{Wm^{-2}}$ (Forster et al., 2021). Despite the ACI contribution to the total anthropogenic ERF, aerosols and their impact on clouds are so far not included in the World Meteorological Organization's (WMO) climate indicators (Trewin et al., 2021). The development of a climate indicator for aerosols and their direct (ERFari) and indirect (ERFaci) effect on the climate therefore requires a careful balance between physical relevance, statistical robustness, and long-term stability. Such an indicator must be based on datasets with sufficient temporal coverage, documented uncertainty characteristics, and demonstrable consistency over time. Importantly, the feasibility of defining a meaningful aerosol–cloud indicator is not only a scientific question, but also a data suitability question, directly linked to the fitness-for-purpose of existing satellite climate data records.

Within this broader context, the "Satellite observations to improve our understanding of aerosol-cloud interactions" (SATACI) project was initiated to advance the use of satellite observations for ACI research and to explore the development of an aerosol–cloud climate indicator suitable for long-term monitoring and model evaluation. A fundamental prerequisite for such efforts is a critical assessment of existing aerosol and cloud datasets with respect to their ability to support different classes of ACI applications. Through a community survey within the SATACI project, a set of recurring scientific and technical requirements for satellite-based ACI studies have been identified, including the need for co-located aerosol and cloud retrievals, high temporal resolution to capture cloud evolution, physically meaningful aerosol proxies, explicit stratification by cloud phase and regime, and robust uncertainty information that can be propagated to derived ACI metrics. Importantly, these requirements differ substantially across application classes, ranging from process-oriented studies of cloud microphysics to climate-scale monitoring and indicator development.

Major international initiatives such as the European Space Agency Climate Change Initiative (ESA CCI), the Copernicus Climate Change Service (C3S) and the Satellite Application Facility on Climate Monitoring (CM SAF) have produced a broad suite of aerosol and cloud climate data records designed to meet the requirements of climate research and monitoring. These initiatives emphasise traceability, temporal stability, and documented uncertainties, in line with guidance from the Global Climate Observing System (GCOS). However, experience from the literature increasingly shows that general compliance with climate data standards does not automatically guarantee suitability for specific ACI applications, which may place conflicting demands on spatial resolution, temporal sampling, and uncertainty representation.

This paper presents a comprehensive review and fit-for-purpose (F4P) assessment of satellite aerosol and cloud datasets relevant to ACI studies, conducted in the framework of SATACI. Section 2 introduces the fitness for purposes methodology applied within this study. A emphasis is placed on uncertainty characterisation and propagation following the FIDUCEO principles (Mittaz et al., 2019), as these aspects are central to the robustness and interpretability of satellite-derived ACI

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constraints. Section 3 presents the candidate datasets for the three main application classes that are the focus of the SATACI project: (1) aerosol indirect effects on liquid clouds, (2) dust impact on cloud glaciation temperature (both activities relying primarily on Level-2 satellite products with high temporal resolution), and (3) the feasibility of aerosol–cloud climate indicators based on long-term Level-3 datasets. Section 4 summarises the fitness-for-purpose criteria and associated results for each of the three applications.

## 2 Fit-for-purpose methodology

The F4P exercise performed within this project refers to the evaluation of existing satellite datasets with respect to clearly defined scientific objectives, in terms of variables availability, temporal and spatial resolution, sampling characteristics, retrieval performance and uncertainty information required to address a specific class of scientific questions. This exercise is performed for each activity performed within the SATACI project, according to the following steps:

1. Identification of scientific requirements associated with a given ACI application;
2. Identification of the candidate aerosol and cloud datasets;
3. Review of existing validation documents;
4. Evaluation of the uncertainty characterisation;
5. Synthesis of the dataset suitability for the given application.

Fitness criteria are defined separately for each application class considered in this assessment. Particular attention is given to whether uncertainties are provided at the pixel level or only in aggregated form, and whether they can be meaningfully propagated to derived ACI metrics. For uncertainty information to be useful in further analyses, it must be clearly documented, traceable to identifiable error sources, and expressed in a form that allows a strict mathematical propagation. This includes information on the magnitude of uncertainties, their classification (random, structured, or systematic), and, where available, their correlation structure across space, time, or spectral dimensions. In cases where pixel-level uncertainty information is not provided, uncertainty estimates may be inferred from validation studies or inter-dataset comparisons, but such approaches inevitably introduce additional assumptions. Within SATACI, uncertainty characterisation and propagation follow a systematic approach based on the FIDUCEO guidelines for the application of metrology principles to satellite observations (Mittaz et al., 2019). This framework provides a consistent methodology for identifying sources of uncertainty through measurement equations, describing them using Digital Effect Tables, and propagating them using the law of propagation of uncertainty. Although originally developed for Level-1 to Level-2 satellite products, this approach is extended here to intermediate and Level-3 quantities relevant to ACI analyses.

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## 3 Satellite datasets and retrieval frameworks

This Section introduces the candidate satellite aerosol and cloud datasets considered in this study, together with their underlying retrieval methodologies, validation status, and uncertainty characterisation. The datasets which are likely to fulfill the fitness criteria for the SATACI studies are drawn primarily from long-term geostationary observations and complementary polar-orbiting products developed within the ESA CCI, the C3S (and associated research frameworks) and CM SAF. They collectively provide the aerosol and cloud variables required to investigate aerosol–cloud interactions across a range of temporal and spatial scales.

The purpose of this section is to document the key characteristics, strengths, and known limitations of each dataset in a neutral and application-independent manner. Emphasis is placed on the availability of pixel-level uncertainty information, and the degree to which each product has been validated against independent reference observations. This information forms the basis for the subsequent fit-for-purpose assessments, where the suitability of each dataset is evaluated in the context of specific scientific applications. The application-specific scientific requirements and the corresponding dataset selection are discussed in Sections 4.1 to 4.3, where the complementarity of the datasets and their fitness for different classes of aerosol–cloud interaction analyses are assessed.

### 3.1 CISAR/SEVIRI

The Combined Inversion of Surface and Aerosols (CISAR) algorithm is an Optimal Estimation (OE) retrieval designed to exploit the angular sampling of satellite observations to retrieve surface and atmospheric properties in a coupled inversion (Govaerts and Luffarelli, 2018). CISAR is here applied to SEVIRI observations from the Meteosat Second Generation (MSG) platform and is used primarily as a source of aerosol proxies at hourly resolution and 10 km sampling over a sub-portion of MSG disk, encompassing Southern Europe, North and Central Africa and the Arabian Peninsula. It provides total AOD (in SEVIRI spectral bands and at 550 nm) and fine-mode aerosol information. A key strength of the CISAR approach for aerosol–cloud interaction studies is its ability to retrieve aerosol properties in the vicinity of clouds and in the presence of optically thin clouds, without relying on a strict external cloud mask, substantially increasing the spatial coverage of the aerosol product (Luffarelli et al., 2022). Validation evidence indicates that CISAR AOD at 550 nm evaluated against AERONET (Giles et al., 2019) yields correlations of the order of 0.7 and RMSE around 0.12, and that the fine-mode fraction shows bias within about $\pm 10\%$ for AOD$< 1$. CISAR pixel-level uncertainties have also been evaluated following approaches used in broader aerosol validation exercises, with improved performance reported relative to earlier algorithm versions (Luffarelli et al., 2023; Sayer et al., 2020).

### 3.2 ORAC/SEVIRI

ORAC is a generalised optimal-estimation framework used to retrieve aerosol, cloud, and surface parameters from visible/infrared satellite radiances. ORAC provides AOD, Cloud Optical Depth (COD), Cloud Effective Radius (CER), CF, and Cloud Phase (CPH) with pixel-level uncertainty estimates for all retrieved quantities, derived consistently within the optimal-

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estimation framework. In addition, the FMAOD is inferred indirectly from multi-wavelength retrievals and aerosol-type assumptions; consequently, no explicit pixel-level uncertainty is currently provided for this quantity. While the CDNC is not directly provided in the dataset, this can be computed following the methodology proposed in Arola et al. (2022).

Within SATACI, ORAC is applied to SEVIRI observations at native spatial and temporal sampling (reported as 3 $\mathrm{km}$ at the sub-satellite point, 15 minutes). This dataset used within SATACI has been generated specifically for this study and does not yet have a dedicated validation report. The fitness-for-purpose assessment therefore draws on published validation of ORAC and Community Cloud retrieval for CLimate (CC4CL) cloud retrievals developed in the framework of the ESA Cloud_cci project, as well as earlier ORAC aerosol evaluations. These studies report correlations close to 0.8 between ORAC AOD and AERONET observations (Thomas et al., 2009).

For cloud optical properties, McGarragh et al. (2018) shows $\sim$10% agreement in COD relative to MODIS for COD$> 1$, with larger fractional errors for optically thin clouds. Similarly, the CER shows good agreement with MODIS data in most cases, to the exception of small particles and an associated small optical thickness. These findings directly inform common ACI filtering choices (e.g. excluding COD<1.0; CER < 5 $\mu\mathrm{m}$). Conversely, ORAC cloud phase shows agreement rates exceeding 80% against CALIOP even when thin clouds are included (Stengel et al., 2023). As no native pixel-level uncertainty is provided for cloud phase, phase classification uncertainty is inferred from validation results, with representative values of approximately 12.5% over ocean and up to 25% over bright surfaces. The ORAC cloud mask has also been evaluated against CALIPSO, suggesting systematic uncertainties of order 10% and random uncertainties of order 15% (Stengel et al., 2023).

### 3.3 RAL IMS Scheme Dust product

The RAL Infrared-Microwave Scheme (IMS) dust aerosol product provides satellite-derived information on mineral dust properties based on thermal infrared observations. The IMS scheme was originally developed to retrieve water vapour, temperature and stratospheric ozone profiles from the Infrared Atmospheric Sounding Interferometer (IASI), the Microwave Humidity Sounder (MHS) and Advanced Microwave Sounding Unit (AMSU) on the MetOp satellites (Siddans et al., 2015). The IMS extended scheme adds several other trace-gases, including CO and $CH_4$, as well as dust AOD and layer height. It is applied to all scenes, irrespective of cloud and includes the retrieval of cloud-top height; however the presence of extensive, thick cloud limits retrieval quality and of course no information on minor gases is available below optically thick cloud. Additionally, the retrieval is performed both during daytime and nighttime conditions. This all-sky capability represents a key advantage of the IMS scheme compared to visible-channel dust products, particularly for applications requiring continuous temporal sampling. Pixel-level uncertainties are delivered thanks to the OE framework. However, no specific evaluation of the dust product is publicly available.

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### 3.4 C3S Aerosol Product

#### 3.4.1 Dual View

The Copernicus Climate Change Service (C3S) aerosol product based on dual-view satellite observations from the Along Track Scanning Radiometer (ATSR)-2, Advanced Along-Track Scanning Radiometer (AATSR), and Sea and Land Surface Temperature Radiometer (SLSTR) sensors provides a long-term, harmonised record of AOD and FMAOD derived from along-track scanning radiometers. The C3S dual-view aerosol product is generated using multiple independently developed retrieval algorithms, developed by Swansea University (SU, Pearson et al. (2025), the Finnish Meteorological Institute (AATSR dual-view (ADV) for ATSR/AATSR and SLSTR dual-view (SDV) for SLSTR, Kolmonen et al. (2016), and the Optimal Retrieval of Aerosols and Clouds (ORAC) scheme operated by RAL Space (Thomas et al., 2009). In addition, a C3S ensemble product is provided by DLR, which uses pixel-level uncertainties as weighting to combine the individual retrievals to improve robustness and reduce algorithm-dependent biases (Ede Leeuw and Popp, 2020).

The C3S dual-view aerosol products provide global coverage at a spatial resolution of 1° × 1° and are distributed primarily as monthly means, with daily products also available. The temporal coverage spans 1995–2012 for ATSR-2 and AATSR, and from 2017 to the present for SLSTR, enabling the construction of multi-decadal aerosol climate records. The key variables provided include AOD and FMAOD, along with pixel-level uncertainty estimates that are traceable to the underlying retrieval assumptions.

The validation results of the aerosol product are reported in Table 1, in terms of linear correlation coefficient $R$, Root Mean Square Error (RMSE), Normalised Mean Bias (NMB) and Modified Normalised Mean Bias (MNMB), defined as in Griesfeller and Popp (2024). For total AOD, the AATSR-based products (2002–2012) show good overall agreement with AERONET, with correlation coefficients typically around 0.8 and RMSE of order 0.10–0.12, depending on the algorithm. The ensemble product consistently exhibits reduced bias and improved correlation relative to the individual retrievals, reflecting the benefit of combining independent approaches. For SLSTR-based products (2017–2023), validation statistics indicate slightly worse performance levels, with correlations between 0.6 and 0.8, and RMSE up to 0.15, depending on the algorithm. For FMAOD, the validation results reveal larger inter-algorithm spread and generally higher uncertainties than for total AOD, both for AATSR and SLSTR products. While correlations with AERONET remain moderate to good (typically 0.7–0.8 for AATSR and slightly lower for SLSTR), biases and normalised mean biases are more pronounced, especially for the ORAC products. The ensemble product again provides a more balanced representation, with intermediate bias and reduced sensitivity to extreme values.

#### 3.4.2 GRASP/POLDER

The GRASP/POLDER aerosol product provides multi-parameter aerosol retrievals derived from polarimetric satellite observations acquired by the POLDER instrument. The retrievals are generated using the Generalized Retrieval of Atmosphere and Surface Properties (GRASP) algorithm, which exploits the sensitivity of multi-angle, multi-spectral, and polarimetric measurements to aerosol microphysical and optical properties (Dubovik et al., 2011). Within the C3S framework, GRASP is applied to POLDER observations covering the period 2005–2013. This dataset is distributed as a Level-3 product at 1° × 1° spatial resolution with monthly temporal aggregation. The primary variables provided include AOD, FMAOD and Single Scattering Albedo (SSA). Pixel-level uncertainty estimates are available for all retrieved parameters, consistent with the GRASP inversion framework.

Validation of the GRASP/POLDER aerosol products is documented in the C3S Product Quality Assessment Report and is reported in Table 1. For total AOD, the validation statistics indicate good agreement with ground-based measurements, with low absolute bias and correlation coefficients typically around 0.8. The FMAOD retrievals show similarly good performance, with moderate biases and correlations generally exceeding 0.8, reflecting the strong sensitivity of polarimetric measurements to fine-mode aerosol properties. For the SSA, validation against AERONET inversion products demonstrates that the retrievals capture the main spatial and temporal variability of aerosol absorption, although uncertainties are larger than for AOD and FMAOD. The validation results are reported in Table 1, in terms of linear correlation coefficient $R$, RMSE, NMB and MNMB, defined as in Griesfeller and Popp (2024).

#### 3.4.3 IASI

The C3S satellite dust aerosol products provide a harmonised set of dust-specific aerosol datasets designed to support climate monitoring and process-oriented analyses. Within this framework, a family of dust aerosol products is generated using different retrieval algorithms applied primarily to the IASI instrument on board MetOp-A and MetOp-C, with a focus on Dust Aerosol Optical Depth (DAOD) and, where available, Dust Aerosol Layer Height (DALH). In this study, five C3S dust aerosol products are considered: an ensemble product and four individual retrievals: ULB (Clarisse et al., 2019), MAPIR (Vandenbussche et al., 2024), LMD (Capelle et al., 2014, 2018), and DLR IMARS (Samaras and Klüser, 2021).

All products contain pixel-level uncertainties derived by error propagation or parameterization, which have not yet been validated systematically. Uncertainties in the gridded products do not take into account correlations of uncertainties between individual pixels and thus represent an upper limit of uncertainties per grid cell. Monthly gridded (1°) datasets are derived from the Level-2 products, averaging values and associated uncertainties for each daily grid cell and to monthly averages (Popp et al., 2024b). The validation results are reported in Table 1, in terms of linear correlation coefficient $R$, RMSE, NMB and MNMB, defined as in Griesfeller and Popp (2024).

### 3.5 MODIS/Terra Collection 6.1 Dark Target

The Moderate Resolution Imaging Spectroradiometer (MODIS) Collection 6.1 aerosol product provides a long-standing and widely used global aerosol dataset derived from visible and near-infrared radiance measurements. In this study, the MODIS Collection 6.1 Dark Target aerosol product derived from observations acquired by the MODIS instrument onboard Terra is considered, providing AOD and FMAOD, and supplemented with data over land from Paul Ginoux (private communication), globally, monthly, at $1° \times 1°$ resolution for period 2000-2024 (Levy et al., 2013). The long temporal record and consistent processing makes MODIS C6.1 a key reference dataset for aerosol climatology, trend analysis, and intercomparison studies. However, it should be noted that this sensor is nearing its end of lifetime, so that future operational routine usage is not possible.

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**Table 1.** Evaluation results of the C3S AOD, FMAOD, DAOD and DALH against AERONET observations. The DALH is compared to CALIOP geometric mean height, globally, in the case of the MAPIR algorithm, and to the CALIOP extinction-weighted height, between 50ºS and 60ºN. The validation results are obtained from the C3S Product Quality Assessment Report (Griesfeller and Popp, 2024).

| Algorithm | Sensor | Version | Variables | NMB | MNMB | R | RMSE |
|---|---|---|---|---|---|---|---|
| ADV/SDV | AATSR | v4.1 | AOD | -12.0% | -12.6% | 0.81 | 0.12 |
| | | | FMAOD | -1.8% | -0.1% | 0.8 | 0.1 |
| | SLSTR | v2.3 | AOD | 4.3% | 9.4% | 0.77 | 0.11 |
| | | | FMAOD | 18.5% | 19.3% | 0.72 | 0.11 |
| ORAC | AATSR | v4.02 | AOD | 11.0% | 17.4% | 0.82 | 0.1 |
| | | | FMAOD | 29.9% | 33.7% | 0.70 | 0.11 |
| | SLSTR | v5.0 | AOD | 45.1% | 51.5% | 0.61 | 0.15 |
| | | | FMAOD | 76.9% | 70.7% | 0.51 | 0.15 |
| SU | AATSR | v4.35.1 | AOD | -9.1% | -4.9% | 0.81 | 0.12 |
| | | | FMAOD | 1.9% | 9.5% | 0.79 | 0.09 |
| | SLSTR | v1.14.1 | AOD | 25.8% | 32.1% | 0.79 | 0.11 |
| | | | FMAOD | 51.3% | 52.8% | 0.74 | 0.11 |
| Ensemble | AATSR | v3.2 | AOD | -3.0% | 3.2% | 0.85 | 0.11 |
| | | | FMAOD | 6.6% | 18% | 0.81 | 0.09 |
| | SLSTR | v2.4 | AOD | 10.4% | 20.8% | 0.75 | 0.11 |
| | | | FMAOD | 29.4% | 37.7% | 0.68 | 0.11 |
| GRASP | POLDER | v2.20 | AOD | 3.1% | 6.7% | 0.81 | 0.12 |
| | | | FMAOD | -2.1% | 4.8% | 0.82 | 0.09 |
| ULB | IASI | v9 | DAOD | 3.3% | 1.2% | 0.78 | 0.05 |
| MAPIR | IASI | v5.11 | DAOD | 93.7% | 83.4% | 0.65 | 0.07 |
| | | | DALH | | | | 1.3km |
| LMD | IASI | v2.2 | DAOD | 56.0% | 41.2% | 0.54 | 0.07 |
| | | | DALH | | | | 1.1km |
| DLR IMARS | IASI | v7.1 | DAOD | -44.5% | -60% | 0.23 | 0.08 |
| Ensemble | IASI | v1.4 | DAOD | 40.0% | 50.7% | 0.64 | 0.05 |

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The Dark Target AOD retrievals have been evaluated against AERONET observations across a wide range of regions and aerosol regimes, demonstrating good overall performance with typical correlation coefficients around 0.8 and root-mean-square errors of order 0.1 (Pu et al., 2020).

### 3.6 MODIS L3 MCD06 COSP Cloud properties

The MODIS Level-3 MCD06 cloud product provides global, gridded cloud property datasets derived from the MODIS instruments onboard the Terra and Aqua satellites (Swales et al., 2018; Hubanks et al., 2022). The MCD06 product combines cloud retrievals from both platforms into a single, internally consistent dataset, enabling improved temporal sampling and enhanced robustness for climate applications. The dataset is produced within the MODIS cloud processing framework and includes a subset of cloud variables mapped to the Cloud Feedback Model Intercomparison Project (CFMIP) Observation Simulator Package (COSP) diagnostics. The MCD06 COSP cloud properties include, among others, CF, LWP, CDNC and cloud optical properties, aggregated to monthly means at 1° × 1° spatial resolution from 2000 to 2022. These variables are derived from Level-2 MODIS cloud retrievals using consistent aggregation and quality control procedures.

Validation of MODIS cloud products has been extensively documented, with comparisons against active sensors such as CALIOP and CloudSat demonstrating generally good performance for cloud fraction and cloud-top properties, particularly for optically thick clouds (Marchant et al., 2020). This product is widely regarded as the community reference dataset for passive satellite cloud retrievals, owing to its long temporal coverage, consistent global processing, comprehensive documentation, and extensive validation against both active satellite sensors and ground-based observation.

### 3.7 C3S/CCI ATSR/SLSTR Cloud Product

The C3S/CCI ATSR/SLSTR cloud product provides a long-term cloud climate data record derived from observations acquired by the ATSR-2, AATSR, and SLSTR instruments. Developed within the ESA Cloud Climate Change Initiative (CCI) and extended under the C3S, the dataset is designed to ensure temporal consistency across sensors and platforms, enabling multi-decadal (1997 to 2023) cloud analyses suitable for climate monitoring. Cloud properties are retrieved using the CC4CL/ORAC framework, which applies an OE approach to derive cloud macrophysical and microphysical parameters from passive radiance measurements. The product includes CF, COD, LWP and CDNC, provided as Level-3 monthly means at 0.5° × 0.5° spatial resolution. Pixel-level uncertainty information from the Level-2 retrievals is propagated to the gridded products following documented aggregation procedures.

Validation of the ATSR/SLSTR cloud products is documented through extensive comparisons with independent satellite observations, including MODIS and CALIOP. These studies indicate good overall performance for cloud fraction and cloud optical properties, with larger uncertainties for optically thin clouds and in multilayer situations (Stengel et al., 2023). The consistency of the retrieval framework across sensors is a key strength of the dataset, supporting its use in long-term trend and variability studies.

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### 3.8 CLAAS-3

The Cloud property dAtAset using SEVIRI (CLAAS-3) is the operational cloud climate data record produced by the EUMETSAT Climate Monitoring Satellite Application Facility (CM SAF), based on observations from the SEVIRI instrument onboard MSG. The CLAAS-3 dataset includes COD, and CER derived from the 1.6 μm and 3.9 μm channels, CDNC, CF, and CPH over the full MSG disk from 2004 to the present, with native temporal resolution and pixel-level spatial sampling. Pixel-level uncertainty estimates are provided for most optical and microphysical variables.

Validation studies indicate that CLAAS-3 COD and CER exhibit good agreement with independent satellite references, across a wide range of cloud regimes (Benas et al., 2023). Comparisons against MODIS indicate that CLAAS-3 CDNC is well correlated but exhibits a systematic high bias of approximately 40% (corresponding to about +14 $cm^{-3}$), with a bias-corrected RMSE of order 14 $cm^{-3}$. For cloud fraction and cloud masking, CLAAS-3 has been evaluated against active and passive reference datasets, including CALIOP and surface synoptic observations. Reported uncertainties depend on filtering choices, particularly with respect to thin clouds, but daily cloud fraction uncertainties of order 15% can be assumed.

Cloud phase retrievals are evaluated against CALIOP observations, in terms of Probability Of Detection (POD) and Hansen Kuiper Skill Score (HKSS), showing generally good performance (POD equal to 94% and 75% for liquid and ice clouds respectively, and HKSS equal to 0.7), although reduced skill is reported over bright surfaces and for optically thin clouds. Pixel-level uncertainty estimates are not provided for cloud phase, and uncertainty of 15% is therefore inferred from validation statistics. Finally, the Cloud Top Temperature (CTT) retrieval has also been validated against CALIOP measurements, showing a bias of +8 K and a RMSE of 20 K (all clouds) (Meirink et al., 2022b).

### 3.9 Cloud_CCI SEVIRI

The Cloud_CCI SEVIRI dataset, based on the CC4CL/ORAC algorithm, developed within the ESA Cloud Climate Change Initiative (Cloud_CCI), provides a physically consistent retrieval of cloud macrophysical and microphysical properties from passive satellite observations (Thomas et al., 2023). The CC4CL/ORAC algorithm is based on an optimal estimation framework that simultaneously retrieves COD, effective radius, cloud top pressure and thermodynamic phase, while providing pixel-level uncertainty estimates derived from the inversion. The algorithm has been applied consistently across multiple sensors to generate long-term cloud climate data records, with particular emphasis on stability, traceability, and suitability for climate applications. The availability of well-documented retrieval assumptions and uncertainty characterisation makes CC4CL-derived products a robust reference for aerosol–cloud interaction studies and supports their use in consistency assessments and uncertainty propagation frameworks. Here, the CC4CL/ORAC algorithm is used to derive cloud properties at native temporal resolution, for observations acquired in 2019 over the MSG disk, at SEVIRI native pixel resolution. The derived Cloud Top Height (CTH) shows a bias of -2.5 km and a RMSE of 4.9 km for all clouds against CALIOP observations; no specific validation results are available for the CTT (Stengel, 2016).

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#### 3.9.1 SEVIRI_ML

The SEVIRI_ML dataset is a machine learning based module to derive a cloud mask, the cloud phase, the Cloud Top Pressure (CTP), the CTT, a multilayer flag and a Cloud Base Height (CBH) from SEVIRI measurements using its full spectral capabilities (Philipp, 2024). The dataset is available at native temporal resolution, for observations acquired in 2019 over the MSG disk, at SEVIRI native resolution. Pixel-level uncertainties are available for both CTP and CTT. While the CTP uncertainty represents the likelihood of false classification, the CTT uncertainty represents the 1-$\sigma$ random uncertainty. The validation results of the SEVIRI_ML CTT against CALIOP observations report a bias of -0.1 K, -3.3 K, 0.8 K and a RMSE of 18.8 K, 8.9 K, 12.3 K for all, liquid and ice clouds respectively (Phillipp et al, in preparation). The cloud phase obtained with the SEVIRI_ML algorithm is also evaluated against CALIOP observations, showing a POD equal to 0.88.

## 4 Fit-for-purpose assessment for aerosol–cloud interaction applications

In this section we discuss the requirements for datasets to provide new and insightful information on ACI separately for the cases of aerosol effects on liquid clouds, dust impacts on cloud glaciation and implementation of a climate indicator that provide a simple metric for ACI. Based on these requirements, a selection of datasets to be used for each study within SATACI is made and the strengths and weaknesses of each selected dataset described.

### 4.1 Analysis on aerosols indirect effect on liquid clouds

#### 4.1.1 Scientific requirements and dataset selection

The first study within SATACI is dedicated to examining the indirect effects of aerosols on liquid clouds, leveraging long-term datasets from ESA's CCI and other high-resolution geostationary satellite products. The study addresses multiple community-identified knowledge gaps, such as the need for better resolved and co-located aerosol and cloud retrievals, consistency assessments across datasets, uncertainty propagation frameworks, assessment of the temporal offsets between aerosol and cloud retrievals influence derived ACI metrics.

Despite high confidence in the fact that aerosols increase CDNC, the magnitude of these effects, as well as the impact of aerosol on CF, remain uncertain. Thus, this study requires co-located aerosol and cloud properties at high temporal resolution to investigate CDNC sensitivities, CF adjustments, and the role of time lags between aerosol and cloud observations. Required aerosol proxies include AOD and FMAOD, while cloud properties include CDNC, cloud fraction, and cloud phase.

The following criteria must be fulfilled for the datasets to be considered fit-for-purpose in this context:

1. Aerosol Proxies: Availability of AOD and FMAOD at appropriate spatial resolutions (ideally $\leq$10 km).

2. Cloud Properties: Availability of CDNC (or sufficient inputs to derive it), CF, and cloud phase.

3. Temporal Resolution: Sub-daily (ideally hourly) resolution to capture diurnal variability in aerosol–cloud processes.

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4. Spatial Resolution: Pixel-level observations at km-scale are essential to resolve localised aerosol–cloud interactions.
5. Uncertainty Information: Pixel-level uncertainty estimates with traceable definitions for both aerosol and cloud retrievals.
6. Temporal Coverage: At least one year of observations to ensure statistical robustness and sampling across seasons.
7. Co-location Capability: Co-located aerosol and cloud products within the same pixel or within a minimal spatial offset.
8. Validation Availability: Access to existing validation results to assess product quality.

In addition to these criteria, for satellite-based aerosol–cloud interaction analyses to be informative, retrieval uncertainties must be small enough that the expected aerosol-driven variability is not dominated by measurement noise. Cloud responses to aerosol perturbations are typically quantified through the susceptibility parameter ($\beta$), defined as the slope of the log–log relationship between CDNC and an aerosol proxy (e.g. AOD or FMAOD). Observational studies typically report values of $\beta$ in the range 0.3–0.7, depending on the metric and regime considered (e.g. McCoy et al., 2018; Quaas et al., 2008; Gryspeerdt et al., 2016). This implies that uncertainties of comparable magnitude may substantially limit the interpretability of inferred sensitivities. In the context of the fit-for-purpose assessment, uncertainty levels reported in the literature are therefore discussed in terms of qualitative confidence regimes rather than strict detection thresholds. As a practical guideline, uncertainties of order $\leq$30% are commonly considered compatible with high-confidence interpretation of aerosol–cloud relationships, uncertainties up to about 50% may still allow medium-confidence analyses under favourable conditions, while larger uncertainties (>50%) are generally associated with low-confidence or exploratory use.

Based on these requirements, the CISAR and ORAC retrieval frameworks applied to SEVIRI observations were initially considered as candidate datasets, complemented by the CLAAS-3 cloud property record (Sections 3.1, 3.2 and 3.8). These datasets provide the aerosol and cloud variables required by the ACI metrics considered in SATACI (e.g. AOD, FMAOD, CPH, CDNC, CF) at appropriate temporal and spatial resolutions. The selection of these datasets is guided not only by the technical requirements defined above, but also by the objective of evaluating the suitability of existing products derived from European satellites, and in particular datasets and algorithms derived within the ESA Climate Change Initiative (CCI) framework, for aerosol–cloud interaction studies.

However, additional analyses performed within the SATACI project revealed that aerosol retrievals from ORAC over land are not sufficiently accurate for the purposes of this study, particularly for fine-mode aerosol quantities. As a result, ORAC aerosol products were not retained for the derivation of aerosol–cloud interaction metrics. Conversely, the ORAC cloud retrieval framework provides improved cloud property estimates compared to CLAAS-3 for the variables required in this analysis, particularly for cloud optical properties and internally consistent retrievals of microphysical parameters. This dataset will thus be prioritised within this study.

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#### 4.1.2 Fit-for-purpose assessment and synthesis

Based on the evaluation of both cloud and aerosol products, the CISAR, ORAC and CLAAS-3 datasets are considered suitable to support the derivation of aerosol-cloud interaction (ACI) metrics in the context of this study (Table 2). A synthesis of strengths and limitations emerging from the fit-for-purpose assessment is as follows:

- The combination of the three datasets provides all aerosol and cloud properties identified in Section 4.1.1;
- The high temporal resolution of the selected products is critical for resolving diurnal variability and time-lagged responses in aerosol-cloud interaction processes. In addition, all datasets are available for at least a year (2020);
- All datasets are provided at a spatial resolution at km-scale, necessary to resolve localised ACI;
- The temporal and spatial resolutions of the three selected datasets allow easily collocation of aerosol-cloud products within the same pixel or within a minimal spatial offset;
- Uncertainty characterisation is robust for aerosol properties in CISAR and for cloud properties in CLAAS-3 and ORAC. The availability of pixel-level uncertainties allows the discrimination of the ACI constraints according to the confidence levels defined in Section 4.1.1;
- Validation against independent reference datasets, including AERONET, MODIS, CALIOP, and SYNOP observations, demonstrates generally good consistency, although non-negligible biases persist for specific variables and regimes (e.g. CDNC in CLAAS-3). A bias correction may be applied to the latter.

In conclusion, the combination of CISAR/SEVIRI, ORAC/SEVIRI, and CLAAS-3 provides complementary strengths that together satisfy the fit-for-purpose requirements for the analysis on aerosols indirect effect on liquid clouds. These datasets are therefore retained as the primary inputs for the derivation of ACI metrics associated to liquid clouds.

### 4.2 Impact of dust concentration on cloud glaciation temperature

#### 4.2.1 Scientific requirements and dataset selection

The second study within SATACI focuses on the impact of mineral dust on cloud glaciation temperature in mixed-phase clouds in the temperature range from 0°C to -39°C. Unlike aerosol indirect effects on liquid clouds, which are primarily governed by cloud condensation nuclei, this process is driven by the ability of dust particles to act as ice-nucleating particles (INPs), triggering heterogeneous freezing at temperatures warmer than those expected from homogeneous nucleation alone. Despite substantial experimental and modelling evidence supporting the role of dust in ice nucleation, observational constraints from satellite data remain limited and inconsistent. Key challenges include the need for better resolved and co-located aerosols and cloud retrievals, consistency across different datasets, and uncertainty propagation frameworks.

The fit-for-purpose (F4P) assessment therefore focused on identifying datasets which satisfy the following scientific requirements:

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**Table 2.** Selected datasets for analysis on aerosols indirect effect on liquid clouds. Variables in italics are excluded from this study.

| Dataset name | Algorithm | Data provider | Temporal coverage / resolution | Spatial coverage / resolution | Relevant variables | Pixel-level uncertainty | Documents / references |
|---|---|---|---|---|---|---|---|
| CISAR/ SEVIRI | CISAR – Optimal Estimation | Rayference | 2020; 1 hour | 10° S–50° N, 55° W–96° E; 10 km | AOD, FMAOD | Yes | Govaerts and Luffarelli (2018); Luffarelli and Govaerts (2019); Luffarelli et al (2023) |
| ORAC/ SEVIRI | ORAC – Optimal Estimation | RAL Space | 2020; 15 minutes | 10° S–50° N, 55° W–96° E; native (∼5 km) | *AOD*, *FMAOD*, COD, CER, cloud fraction, CPH | Yes | Thomas et al. (2009); McGarragh et al. (2018) |
| CLAAS-3 (CPP, CFC) | CFC: multi-spectral thresholding CPP: LUT-based inversion | CM SAF | 2004–present; selected year: 2020; 15 minutes / daily | SEVIRI full disk; native (∼5 km) | COD, CER, CDNC, CFC, CPH | Yes | Benas et al. (2023) |

1. cloud phase information capable of discriminating liquid, ice, and mixed-phase clouds;
2. CTT to identify the thermodynamic regime of glaciation;
3. high temporal resolution of cloud properties, allowing us to track the rapid evolution of CPH and CTT;
4. dust-specific aerosol metrics, such as DAOD and DALH;
5. pixel-level uncertainty estimates to support uncertainty propagation and consistency assessments.

To meet these requirements, the study primarily exploits satellite products provided in the framework of the ESA CCI and C3S initiatives. Cloud properties, including CPH and CTT, are derived from long-term geostationary cloud datasets, ensuring consistency and stability over the analysis period. The candidate datasets of cloud properties are CLAAS-3, the SEVIRI_ML dataset (Philipp, 2024), and the Cloud_CCI dataset obtained applying the CC4CL/ORAC algorithm to MSG/SEVIRI observations.

On the other hand, the dust aerosol product is obtained from polar-orbiting infrared sounders, such as IASI. This is done under the assumption that, compared to other aerosol types such as biomass burning or anthropogenic pollution, dust aerosol fields generally evolve more slowly, as they are linked to synoptic-scale emission events and long-range transport. IASI products have been widely used for dust retrievals, with mature datasets available both from RAL Space (IMS scheme, Section 3.3) and through the C3S Climate Data Store (Section 3.4.3), with the latter products being based on developments made with the ESA CCI programme.

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#### 4.2.2 Fit-for-purpose assessment and synthesis

For the cloud component, the key requirement is the simultaneous and internally consistent availability of CPH and CTT, since glaciation temperature is defined by the transition from supercooled liquid to ice phase at a given CTT. Among the candidate datasets described in Section 3, the SEVIRI_ML product (Section 3.9.1) was identified as the most suitable primary dataset. Both CPH and CTT are retrieved using a neural network framework trained to represent geometrical cloud-top properties, ensuring internal consistency between phase classification and temperature. Validation against CALIOP shows small biases in CTT (bias close to zero for all clouds, with RMSE on the order of 10–20 K depending on phase), highlighting higher performances compared to CLAAS-3 (Section 3.8). The CPH from the SEVIRI_ML product also appears to be superior to the CLAAS-3 dataset for ice clouds. Importantly, pixel-level uncertainties are available for both variables.

Substantial variability exists among the IASI dust products (Figure 1). This variability is reflected also in the bias and correlation relative to AERONET (Table 1). The ULB DAOD product shows the highest overall agreement (R ≈ 0.78, NMB ≈ 3%), indicating robust performance across dust regimes. In contrast, other algorithms exhibit either strong positive bias (e.g. MAPIR) or systematic underestimation (e.g. DLR IMARS). The ensemble product reduces some algorithm-specific spread but retains moderate bias. For DALH, only the MAPIR and LMD products provide vertical dust information. Validation against CALIOP indicates small mean biases (|bias| < 0.1 km) and RMSE around 1–1.3 km, suggesting that large-scale dust layer height is reasonably captured. However, no dedicated pixel-level uncertainty is provided for DALH, and the physical definition of Aerosol Layer Height (ALH) differs between products (geometric mean versus extinction-weighted height), which must be considered in interpretation. Based on this assessment, ULB is selected as the primary DAOD dataset for quantifying dust loading effects, while LMD is retained for analyses involving DALH, particularly for sensitivity tests assessing the role of vertical collocation between dust layers and cloud tops.

Overall, the F4P assessment confirms that a physically consistent and validated combination of datasets is available to investigate the impact of dust concentration on cloud glaciation temperature. The SEVIRI_ML cloud product ensures internally coherent phase–temperature retrievals at high temporal resolution, while the IASI-based ULB and LMD dust products provide validated DAOD and, where needed, DALH information. Table 3 summarise the selected dataset and the associated fitness for purpose exercise. The available uncertainties for CPH, CTT, and DAOD will, in a first step, be used for screening out more uncertain data that will be left out of the analyses. In a second step the uncertainties will be propagated into the analysed metrics.

### 4.3 Feasibility study for a new aerosol-cloud climate indicator

#### 4.3.1 Scientific requirements and dataset selection

The development of a climate indicator places stronger emphasis on long-term stability, global coverage, and internal consistency than on fine spatial resolution. Monthly to annual aggregates, traceable uncertainty information, and demonstrated temporal stability are essential to ensure the indicator's relevance for climate monitoring. Within this activity, satellite data will be used for 2 purposes: (1) to drive the indicator calculations with global gridded monthly data records over long periods,

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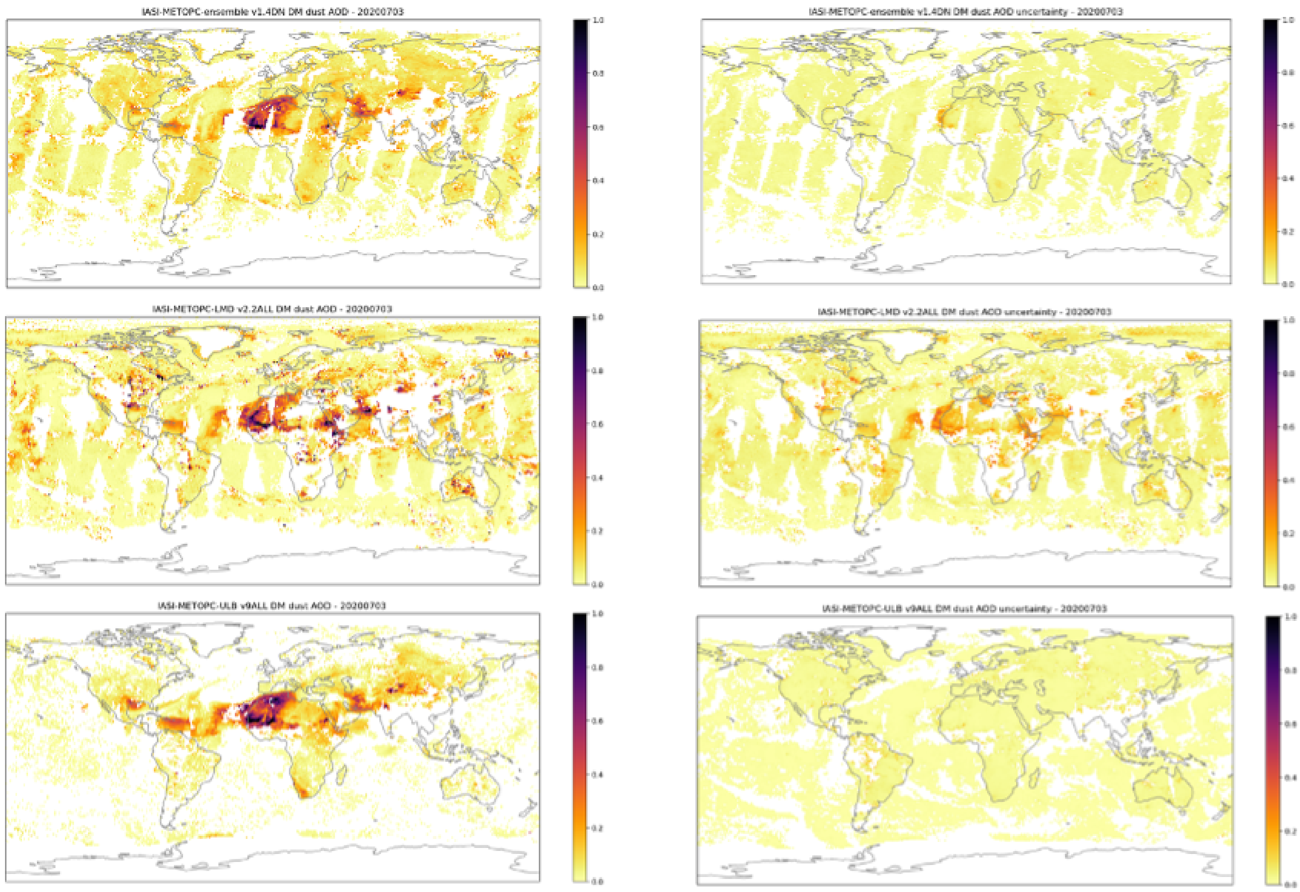


**Figure 1.** Exemplary maps of daily mean DAOD (left panels) for the C3S IASI example, LMD and ULB products. The right column shows the associated uncertainties.

**Table 3.** Selected datasets for the study on the impact of dust concentration on cloud glaciation temperature and the associated fitness for purpose results.

| Dataset name | Algorithm | Data provider | Temporal coverage/resolution | Spatial coverage / resolution | Relevant variables | Pixel-level uncertainty | Documents / references |
|---|---|---|---|---|---|---|---|
| Cloud_CCI SEVIRI | SEVIRI_ML | DWD | 2019; 15 minutes | MSG disk | CPH, CTT | Yes | Philipp et al. (in preparation) |
| C3S DAOD | ULB | Université Libre de Bruxelles (ULB) | 2007-present; daily, monthly | global | DAOD | Yes | Clarisse et al. (2024, 2019) |
| C3S DAOD | LMD | Laboratoire de Meteorologie Dynamique | 2007-present; daily, monthly | global | DAOD, DALH | Yes | Capelle et al. (2014, 2018) |

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and (2) to derive statistical associations of aerosol and cloud variables to parameterize indirect aerosol effects. For case (1), long-time consistency aspects are most important, to be able to calculate the temporal evolution of the climate indicator, while absolute accuracy is less important. For case (2), the statistical significance of the associations between the datasets is relevant, as it determines the minimum spatial and temporal aggregation windows required to achieve it. In both cases, the use of several alternative satellite datasets will allow to estimate the spread of results as one means of understanding their reliability.

A first version of the climate indicator will rely on satellite observations of AOD, FMAOD, CDNC and CF, while version 2 will include DAOD, SSA, ALH, LWP and COD. Furthermore, in version 1 of the indicator, one association of CDNC with FMAOD is exploited, which was derived from monthly FMAOD (Levy et al., 2013) and CDNC (Bennartz and Rausch, 2017) retrievals with MODIS collection 6 over oceans for the year 2008. In version 2, stratified and regional CDNC-FMAOD associations for 5-year periods of the Global Stocktake will be tested (using other cloud variables for the stratification).

The main criteria to assess the fitness for purpose of the candidate datasets are then:

1. Availability of required variables: AOD, FMAOD, (v2: DAOD, SSA, ALH); CDNC, CF, (v2: LWP, COD);
2. Time record consistency / stability meeting GCOS criteria;
3. Operational availability of future extensions;
4. Historic period covered (at least back to 2000) ;
5. Availability of gridded L3 (1 degree), monthly global datasets;
6. Uncertainty characterization and their validation.

It should be noted that cloud and aerosol properties need to be available with he same temporal and spatial coverage, and preferably derived from the same platform or instrument, in order to provide the most consistent spatio-temporal sampling. Absolute biases which are constant for an entire data record are less important as these can be corrected with post-processing or machine learning (e.g. AERONET based fixed bias correction for AOD, as function of AOD by DLR, or machine learning approach as in Lipponen et al. (2022)). Propagation of pixel level (L2) uncertainties to averaged gridded products requires full L1 uncertainty correlation characterization which is often not available. Then, uncertainties of L3 averaged gridded 1 degree / monthly products assume full correlation and calculate averaged uncertainties which provide an upper bound / worst-case for true uncertainties.

Given the need for a historic dataset, this study relies on C3S and CCI datasets to provide aerosol and cloud properties. Additionally, given the large community-consensus and the maturity of these datasets and associated validations, the MODIS L3 MCD06 COSP Cloud properties and MODIS Collection 6.1 Dark Target aerosol are used as a benchmark dataset (for the historic period, but not for future operational extensions) to support cross-dataset consistency assessments and climate-scale evaluations, complementing higher-temporal-resolution geostationary aerosol products and multi-parameter retrievals from polarimetric instruments. Satellite measurements of AOD and FMAOD can be obtained from the C3S/CCI datasets (Section 3.4).

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#### 4.3.2 Fit-for-purpose assessment and synthesis

Dataset stability is one of the main requirements for the study of the feasibility of a new aerosol-cloud climate indicator. Figures 2 to 4 show the stability (in terms of bias over time against AERONET) of the candidate aerosol datasets obtained from C3S and providing AOD, FMAOD, DAOD and SSA. These plots are taken from the Copernicus Climate Change Service (C3S) Product Quality Assessment Report (Griesfeller and Popp, 2024). As a reference, we use the GCOS stability criteria for AOD, which are [1/10y]: GOAL: 2% or 0.01, BREAKTHROUGH: 4% or 0.02, THRESHOLD: 10% or 0.04. In the plots, trends of the bias to AERONET are shown, calculated with the Theil-Sen algorithm; statistical significance is tested with Kendall's rank correlation (p value must be smaller than 0.1). These trend values are given for each algorithm in the plots and trend values are underlined if the significance test is passed. For AOD, all algorithms pass the goal criterion, except ORAC which meets the breakthrough criterion. For FMAOD and DAOD a good estimate should be half of the AOD criteria. Then ADV and GRASP meet the goal criterion, while ENS and SU meet the breakthrough criterion and ORAC almost the threshold criterion. For DAOD all algorithms meet the goal criterion while ULB meets the breakthrough criterion. Finally, for SSA, GRASP meets the threshold criterion 0.4%. Most, but not all bias trends are significant. As we can see from Table 1, FMAOD is generally overestimated (especially for most SLSTR products), which leads to overestimated cooling values in the climate indicator. A bias correction will need to be applied within this activity (fixed bias reduction or bias as a function of AOD vs. AERONET). On the other hand, the stability plots show that the record consistency is overall good with few exceptions; ADV / SDV has the highest dual-view record consistency (due to post-processing AI correction of SLSTR), while ORAC does only satisfy the weakest stability requirement. Hence, all C3S aerosol datasets are considered suitable for this study, to the exception of ORAC (due to its high bias) and POLDER (due to the limited period covered). Similarly, all IASI datasets are considered stable enough. Additionally, it should be noted that both IASI MAPIR and LMD datasets provide Dust Layer Height DALH measurements. Despite the good stability, the GRASP/POLDER dataset is once again excluded because of the limited temporal coverage. However, for a test of using satellite-based SSA, this is the only available dataset and shall therefore be tested in a later stage for this one decade of its availability.

Improved product versions are expected for key aerosol inputs. In particular, the Swansea University (SU) algorithm is currently being improved in the context of Aerosol-CCI+ Phase 2 (targeted for 2026). These developments are expected to further strengthen record consistency and uncertainty characterisation in future iterations of the indicator.

The DAOD has a larger spread over the 5 algorithms, reflecting both differences in retrieval assumptions and in the information content of infrared observations. Furthermore, the C3S dust aerosol product is only available starting from 2007. Based on the validation and stability assessment results, the ULB and the Ensemble Dust products appear to be the most suited for the development of the aerosol-cloud climate indicator.

In the current portfolio, the SSA is provided by the GRASP/POLDER record, but only over 2005–2013. This limited coverage prevents the use of POLDER as a backbone dataset for long-term monitoring back to 2000 and motivates its inclusion mainly for sensitivity tests and methodological development over the overlapping period. New measurements of SSA are expected from the 3MI instrument on EPS-SG, which will enable future extensions of the indicator with improved and extended

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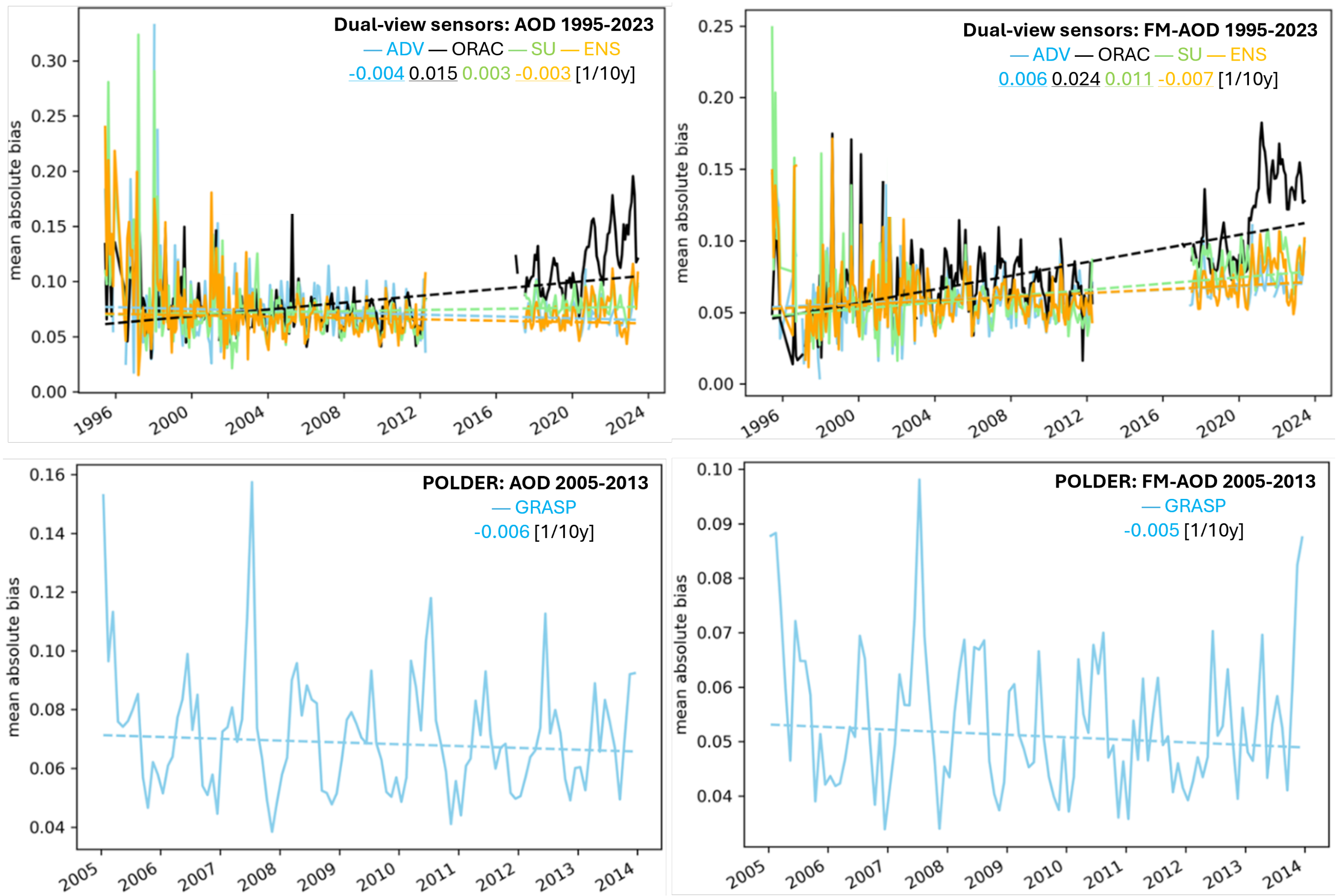


**Figure 2.** Total AOD (left column) and FMAOD (right column) bias trend analysis for the Long-Term Satellite (LTS) dual view retrievals of sensors ATSR-2, AATSR, SLSTR (ADV/SDV, ORAC, SU, ensemble algorithms) for all stations (upper row) and for the POLDER instrument (lower row). In the upper row the blue solid line represents the ADV retrieval, the solid black line the ORAC retrieval, the solid green line SU retrieval and the orange solid line the Ensemble. The dashed lines indicate the corresponding trend as calculated by the Theil-Sen algorithm. These results are obtained from Griesfeller and Popp (2024).

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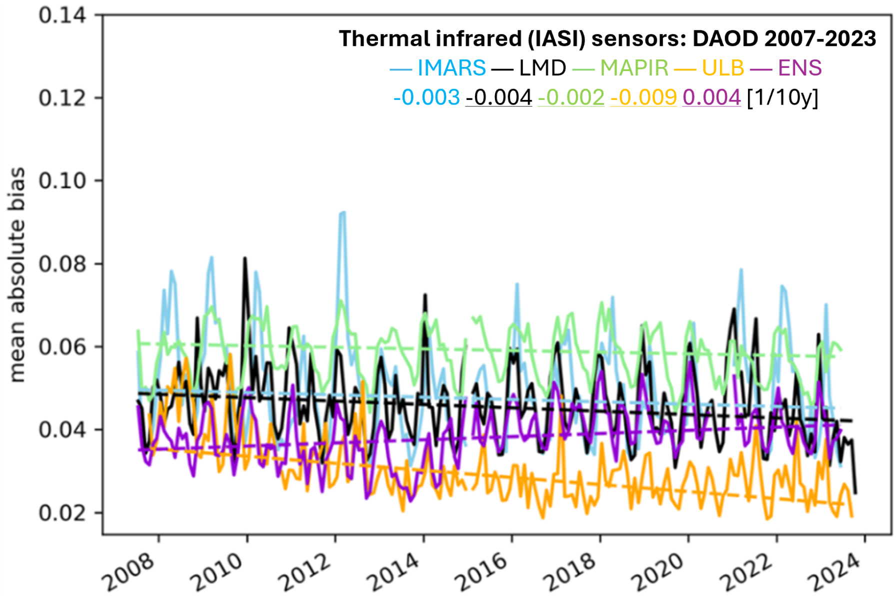


**Figure 3.** Dust AOD trend analysis for the IASI retrievals (DLR IMARS, LMD, MAPIR, ULB and ensemble algorithms). The blue solid line represents the DLR retrieval, the black solid line the LMD retrieval, the green solid line the MAPIR retrieval, the orange solid line the ULB retrieval and the violet solid line the ensemble. The dashed lines indicate the corresponding trend as calculated by the Theil-Sen algorithm. These results are obtained from Griesfeller and Popp (2024).

SSA information. In addition, recent observations from the PACE mission, carrying multi-angle polarimeters such as HARP-2 and SPeX, provide further opportunities to enhance SSA retrievals and extend the observational record.

For clouds, MODIS MCD06 COSP (combined MODIS Terra and Aqua) is treated as the community reference passive cloud product for climate applications and is therefore used as a benchmark for cross-dataset consistency checks. In addition, long-term cloud records suitable for indicator development are available from CLAAS-3 and from the ATSR/SLSTR ORAC/CC4CL cloud climate data record, providing CDNC, cloud cover/fraction, CER and COD over multi-decadal periods. These datasets exhibit generally good consistency with MODIS and CALIOP, and (where applicable) with SYNOP (Figure 5), although non-negligible biases remain for specific variables and regimes (e.g., the known CLAAS-3 CDNC high bias). Importantly, per-pixel uncertainty information is available for most cloud microphysical quantities (with exceptions such as cloud cover/fraction in some products), which is essential for subsequent uncertainty propagation.

A key outcome of the assessment is that CDNC, being a derived quantity, inherits large uncertainties from its input variables (primarily CER and COD), and this must be explicitly accounted for in the uncertainty propagation. More generally, the availability of multiple independent datasets for the same variable (both for aerosols and clouds) is considered a major advantage for this feasibility study, as the spread between datasets can be used as an additional proxy for structural uncertainty. This is particularly relevant when assessing the robustness of aerosol–cloud statistical associations used to parametrise indirect effects in the indicator framework.

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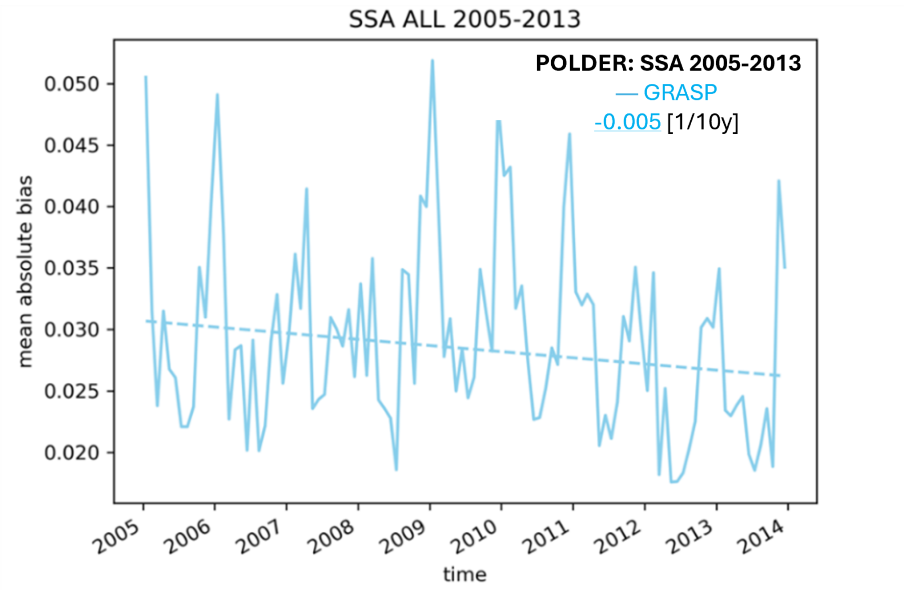


**Figure 4.** Single scattering albedo bias trend analysis for the POLDER GRASP retrieval. The dashed line indicates the corresponding trend as calculated by the Theil-Sen algorithm. These results are obtained from Griesfeller and Popp (2024).

Fitness-for-purpose regarding uncertainties is evaluated pragmatically: there is no quantitative requirement on maximum uncertainty levels for individual satellite input datasets in this feasibility study. The dominant requirement is that uncertainty estimates are available, documented, and sufficiently quality-assessed to enable uncertainty propagation from inputs to the indicator space. Consequently, record consistency and long-term stability are prioritised over absolute accuracy, and stable absolute biases are not regarded as critical provided that they can be corrected through post-processing.

In conclusion, the F4P assessment demonstrates that a consistent and complementary set of aerosol and cloud datasets is available to support the feasibility of a new aerosol-cloud climate indicator. The selected products and the associated assessment results are shown in Table 4. In addition, we will use the MODIS collection 6.1 aerosol dataset as a historic reference for the period 2000 - 2023 as this is a well-established dataset in the community and the full period is observed by one single instrument, while the Copernicus data records must be composed from a series of subsequent similar (but not completely equal) sensors (and exhibit a gap between 2012 and 2017). On the other hand, a future operational provision of the climate indicator cannot rely on MODIS which is soon reaching the end of its mission. For such an operational provision, the set of different Copernicus datasets meets the fit-for-purpose requirements for the derivation and interpretation of the proposed ACI indicator, and are therefore retained for the subsequent analysis.

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**Table 4.** Selected datasets for the feasibility study for a new climate indicator and associated and the associated fitness for purpose results.

| Dataset name | Algorithm | Data provider | Temporal coverage | Relevant variables | L3 (gridded 1°x1°, monthly) | Consistency / Stability | Operational availability | Uncertainty characterisation | Documents / references |
|---|---|---|---|---|---|---|---|---|---|
| C3S Dual View | ADV/SDV | FMI | 1995-2012, 2017-present | AOD, FMAOD | Yes | Yes | Yes | Yes | Kolmonen et al. (2016) |
| | SU | Swansea University | | | | | | | Pearson et al. (2025) |
| | Ensemble | DLR | | | | | | | (Ede Leeuw and Popp, 2020) |
| C3S GRASP / POLDER | GRASP | GRASP | 2005-2013 | Yes | Yes | Yes | No | Dubovik et al. (2011) | |
| C3S IASI | LMD | Laboratoire de Meteorologie Dynamique | 2007-present | DAOD, DALH | Yes | Yes | Yes | Yes | Capelle et al. (2014, 2018) |
| | MAPIR | BIRA | | | | | | | Vandenbussche et al. (2024) |
| | ULB | Université Libre de Bruxelles (ULB) | | DAOD | | | | | Clarisse et al. (2024, 2019) |
| | IMARS | DLR | | | | | | | Samaras and Klüser (2021) |
| | Ensemble | DLR | | | | | | | Popp et al. (2024a) |
| C3S / CCI ATSR SLSTR | CC4CL / ORAC | DWD / RAL | 1997-2023 | COD, LWP, CF, CDNC | Yes | Yes | Yes | Yes | Stengel et al. (2023) |
| CLAAS-3 (CPP, PPS) | CPP: LUT-based inversion; | CM SAF | 2004-present | COD, LWP, CF, CDNC | Yes | Yes | Yes | Yes | Benas et al. (2023) |

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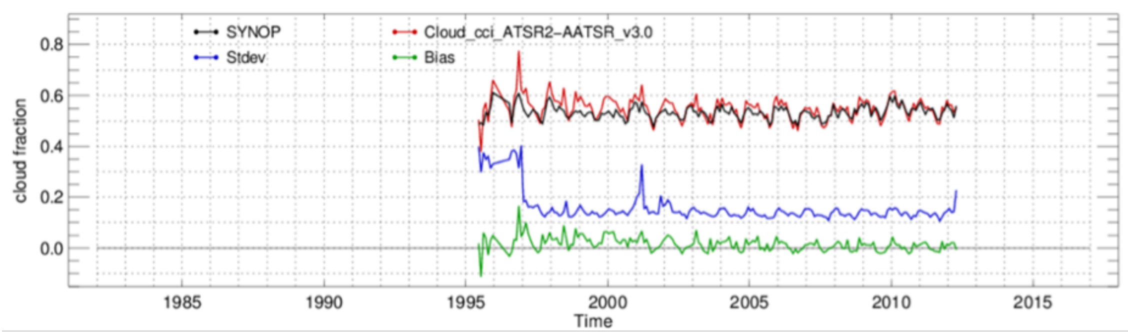


**Figure 5.** Stability of ORAC Cloud_cci ATSR record versus SYNOP data. These results are obtained from Stengel (2016).

## 5 Discussion

This fit-for-purpose assessment shows that the suitability of satellite aerosol and cloud datasets for aerosol–cloud interaction studies cannot be defined independently of the scientific application. The three applications considered here place partly different requirements and priorities of them on the input datasets. Analysis of aerosol indirect effects on liquid clouds and dust-induced cloud glaciation require km-scale, sub-daily, co-located Level-2 retrievals with traceable pixel-level uncertainties, whereas the development of a climate indicator places much stronger emphasis on temporal stability, global coverage, consistency across subsequent sensors, and the availability of long-term Level-3 monthly aggregates. One important methodological outcome of this study is therefore that a dataset that is fit for one ACI application is not necessarily fit for another, and that general compliance with climate data record standards does not automatically guarantee suitability for ACI analyses.

For aerosol indirect effects on liquid clouds, CISAR/SEVIRI, ORAC/SEVIRI, and CLAAS-3 provide complementary strengths: CISAR offers robust aerosol retrievals in the vicinity of clouds, ORAC provides an accurate cloud properties retrieval framework at high temporal resolution, and CLAAS-3 contributes an independent and well-validated cloud record over the geostationary domain. Together, these datasets satisfy the main requirements for analysing CDNC sensitivities, CF adjustments, and time-lagged aerosol–cloud relationships. At the same time, the assessment also identifies limitations that need to be explicitly considered in the subsequent analysis.

The results for dust impacts on cloud glaciation temperature further emphasise the importance of internal consistency between cloud variables. The preference for SEVIRI_ML reflects this requirement, because both variables are retrieved within the same framework and are accompanied by pixel-level uncertainties. On the aerosol side, the evaluation identifies ULB as the most suitable primary DAOD dataset and LMD as the most relevant complementary product when dust layer height is required. However, the substantial spread among IASI dust products shows that dust–cloud analyses remain sensitive to retrieval assumptions. This is particularly relevant for DALH, for which dedicated pixel-level uncertainty information is not yet available and for which the physical definition of aerosol layer height differs between products. Results on dust-induced glaciation should therefore be interpreted together with product-dependence tests and sensitivity analyses on vertical collocation.

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For the climate-indicator application, the assessment shows that long-term consistency and uncertainty traceability are more important than absolute retrieval accuracy. Several C3S/CCI aerosol and cloud records appear sufficiently stable to support indicator development. Nevertheless, practical limitations remain. FMAOD is often overestimated, especially in part of the SLSTR-era products, which would translate into an overestimation of aerosol cooling if left uncorrected. Likewise, CDNC is a derived quantity and therefore inherits substantial uncertainty from its input variables, primarily CER and COD. The current portfolio also shows temporal coverage limitations: GRASP/POLDER provides valuable SSA information, but with limited temporal coverage, making it more appropriate for sensitivity tests than as a backbone record for monitoring. MODIS remains a scientifically valuable historical benchmark because it provides a long record from a single instrument, but future operational provision of a climate indicator will need to rely more strongly on Copernicus datasets despite their dependence on multiple sensors and the existing gap between the AATSR and SLSTR periods. These findings support a staged indicator development, in which the most mature variables are prioritised first and more complex quantities are added progressively.

One important implication emerging from this assessment concerns the complementary role of polar-orbiting and geostationary satellite observations for ACI studies. Polar-orbiting instruments have historically formed the backbone of global ACI analyses because they provide multi-decadal records with consistent global coverage and well-characterised climate data records. These datasets are therefore particularly suited for climate-scale applications such as long-term monitoring, trend detection, and the development of aerosol–cloud climate indicators. However, their limited temporal sampling restricts their ability to resolve the rapid evolution of aerosol–cloud systems and to investigate time-lagged responses between aerosol perturbations and cloud microphysical adjustments. In contrast, geostationary observations provide high temporal resolution at km-scale spatial sampling, enabling the investigation of diurnal variability and short-timescale aerosol–cloud interactions that cannot be captured by polar-orbiting satellites alone.

A broader implication of this work is that uncertainty information should be a primary requirement for ACI applications to ensure a strict uncertainty characterisation of the ACI estimates. The availability of multiple independent datasets partly mitigates this limitation, because inter-dataset spread provides a useful proxy for structural uncertainty.

Overall, this assessment identifies dataset combinations that are sufficiently mature to support targeted ACI process studies and the first steps towards an aerosol–cloud climate indicator. Nevertheless, further progress will depend on more systematic validation of derived variables, better treatment of uncertainty correlations in gridded products, and continued efforts to harmonise retrieval definitions across sensors and algorithms.

## 6 Conclusions

This paper presents a fit-for-purpose assessment of satellite aerosol and cloud datasets for three classes of aerosol–cloud interaction applications addressed within SATACI: aerosol indirect effects on liquid clouds, dust impacts on cloud glaciation temperature, and the feasibility of a new aerosol–cloud climate indicator. The assessment is structured around application-specific scientific requirements, validation evidence, and the availability and traceability of uncertainty information.

A central outcome of this work is that fit-for-purpose thinking is essential for aerosol–cloud interaction studies. The suitability of a dataset cannot be judged solely from its general maturity or from its performance in a different application, because the observational requirements differ substantially across process studies and climate-monitoring objectives. High-frequency, km-scale, co-located observations are needed to investigate rapid aerosol–cloud adjustments, whereas long-term stability, continuity are more critical for climate indicators. More generally, this assessment shows that the most appropriate configuration for an ACI application may require combining aerosol and cloud variables from different retrieval frameworks, rather than relying on a single product suite.

Existing satellite datasets already provide a strong basis for advancing ACI research, provided that their strengths and limitations are treated explicitly. No single dataset emerges as universally optimal, but the current generation of aerosol and cloud climate data records offers substantial value through its complementarity, its validation heritage, and the possibility of comparing independent retrieval approaches. In this context, inter-dataset consistency checks and multi-dataset analyses are not only useful for robustness testing, but also for characterising structural uncertainty where formal uncertainty information remains incomplete.

Future progress in constraining ACI from space will depend on continued development of retrieval algorithms in order to further improve the accuracy of aerosol and cloud products in the regimes most relevant to ACI, including near-cloud conditions and derived or co-retrieved secondary variables such as FMAOD, CDNC, and ALH. Secondly, uncertainty characterisation should become more complete and more directly usable, including clearer separation of random and systematic components and, where possible, information on correlation structures needed for propagation into aggregated products and derived metrics. These improvements will allow a stricter uncertainty propagation to Level-3 satellite products and ACI estimates. Finally, future data records should place greater emphasis on cross-sensor continuity (e.g. address the gap between AATSR and SLSTR), co-location capability, and retrieval consistency, so that satellite observations can more effectively support both process understanding and long-term monitoring.

While limitations and uncertainties remain, existing satellite aerosol and cloud datasets are sufficiently characterised to allow robust scientific exploitation. This assessment provides a transparent basis for subsequent SATACI analyses and contributes to best practices in the use of satellite climate data records for drawing physically meaningful conclusions from satellite-based ACI analyses.

## 7 Data availability

The datasets described in Section 3 are available as follows:

- CISAR/SEVIRI is available on the CEDA archive at https://catalogue.ceda.ac.uk/uuid/08333ee4a0364756b59cf0810d4c7d59/ (Govaerts and Luffarelli, 2018; Luffarelli et al., 2022)
- ORAC/SEVIRI is available on the CEDA archive at https://catalogue.ceda.ac.uk/uuid/7b2b89836feb4fb3a737106e73016f42/ (Thomas et al., 2009)

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- RAL IMS Scheme Dust product on the CEDA archive at https://catalogue.ceda.ac.uk/uuid/5aa32fb863a048f0b24c541639cfd990/ (Siddans et al., 2021)
- The C3S Aerosol Products (Dual View, GRASP/POLDER, IASI) are available on the Copernicus Climate Data Store at https://cds.climate.copernicus.eu/datasets/satellite-aerosol-properties?tab=overview (Copernicus Climate Change Service (C3S), 2019)
- MODIS/Terra Collection 6.1 Dark Target is available on NASA Near Real-time (NRT) platform at https://nrt3.modaps.eosdis.nasa.gov/archive/FIRMS/modis-c6.1/Global/ (Levy et al., 2015)
- MODIS L3 MCD06 COSP Cloud properties is available on the The Level-1 and Atmosphere Archive and Distribution System Distributed Active Archive Center (LAADS DAAC) at https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MCD06COSP_D3_MODIS/ (MODIS Atmosphere Science Team, 2022)
- C3S/CCI ATSR/SLSTR Cloud Product is available on the Copernicus Climate Data Store at https://cds.climate.copernicus.eu/datasets/satellite-cloud-properties?tab=download (Copernicus Climate Change Service (C3S), 2022)
- CLAAS-3 is available from the Eumetsat Satellite Application Facility on Climate Monitoring (CM SAF) Web User Interface (WUI) at https://doi.org/10.5676/EUM_SAF_CM/CLAAS/V003 (Meirink et al., 2022a)
- Cloud_CCI SEVIRI can be obtained using SEVIRI Level1.5 data available at https://data.eumetsat.int/data/map/EO:EUM:DAT:MSG:HRSEVIRI (EUMETSAT, 2026) and the open-source algorithm repository available at https://github.com/ORAC-CC/orac (Grainger et al., 2024)
- SEVIRI_ML can be obtained using SEVIRI Level1.5 data available at https://data.eumetsat.int/data/map/EO:EUM:DAT:MSG:HRSEVIRI (EUMETSAT, 2026) and the open-source algorithm repository available at https://github.com/danielphilipp/seviri_ml (Philipp, 2024)

*Author contributions.* M.L. coordinated the study, carried out the fit-for-purpose assessment for the liquid cloud application, and prepared the first draft of the manuscript. N.M. reviewed the uncertainty characterisation and developed the uncertainty propagation strategy. T.P., U.S., and S.K. carried out the contribution related to the aerosol–cloud climate indicator. M.S. and S.B. reviewed the datasets and scientific requirements for the study of dust impacts on cloud glaciation temperature. D.R. and G.T. provided the ORAC/SEVIRI dataset. M.E., as ESA Technical Officer, supported the project through coordination and scientific guidance. All authors reviewed and commented on the manuscript.

*Competing interests.* The authors declare that they have no conflict of interest.

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