SATACI

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Executive Summary

This document summarises the science requirements for the derivation of new or improved aerosol-cloud interactions (ACI) constraints and for the development of new tools to monitor the phenomenon.

A comprehensive literature review is conducted to deepen the understanding of existing knowledge gaps identified and to identify strengths and limitations of previous studies using satellite data to address these gaps.

Inputs from external communities, including Aerosat and AeroCom, are also collected to support defining the technical and scientific requirements needed to address the identified knowledge gaps. Additionally, an inventory encompassing all relevant essential climate variables (ECVs) datasets applicable for this purpose is prepared. Datasets obtained during the activities carried out within previous aerosol and cloud CCI studies are included in the inventory, while including selected external, well-established datasets.

Version	Date	Modified Items/Reason for change
V0.0	24/01/2025	Draft version
V1.0	3/04/2025	Includes literature review on climate models, results from the SATACI Scientific Requirements Survey. Identifies project requirements.
V1.1	9/05/2025	The survey results have been updated with the latest responses.

1 Definition and abbreviation

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

Definition/ abbreviation	Explanation
ACI	Aerosol-Cloud Interactions
AE	Ångström Exponent
AI	Aerosol Index (=AOD*AE)
AeroCom	Open international initiative of scientists interested in the advancement of the understanding of the global aerosol and its impact on climate. A large number of observations and results from more than 22 global models have been assembled to document and compare state-of-the-art modeling of the global aerosol.
AERONET	The AERONET (AErosol RObotic NETwork) program is a federation of ground-based remote sensing aerosol networks established by NASA and PHOTONS (PHOtométrie pour le Traitement Opérationnel de Normalisation Satellitaire; Univ. of Lille 1, CNES, and CNRS-INSU).
ALH	Aerosol Layer Height
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).
AR	Assessment Report
C3S	Copernicus Climate Change Service: offers information on climate change and its impacts on many sectors via the Climate Data Store (CDS)
CAMS	The Copernicus Atmosphere Monitoring Service is the successor project of MACC.
CCI	Climate Change Inititative: Generates global, long-term satellite data records of ECVs to track and understand key aspects of Earth's climate system.
CCN	Cloud Condensation Nuclei: subset of atmospheric aerosols on which water vapour condenses for cloud formation.
CER16	Cloud Effective Radius computed from 1.6µm
CER39	Cloud Effective Radius computed from 3.9µm
CMIP	The Coupled Model Intercomparison Project is a WCRP initiative which defines a standard protocol to study the output of coupled general circulation models (which have been strongly used in the IPCC assessments) – it defines the common data / metadata format, also adopted for obs4MIPs which aims to increase the use

	of satellite data by the modelling community (by having a similar data format for both model output and satellite products) .
CMUG	Climate Modelling 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 assess the usefulness of new climate data records produced in CCI for selected ECVs.
CDNC	Cloud Droplet Number Concentration
COD	Cloud Optical Depth
CPH	Cloud Phase
CTP	Cloud Top Pressure
CTT	Cloud Top Temperature
DALH	Dust ALH.
DAOD	Dust AOD.
ECVs	The Essential Climate Variables are geo-physical quantities of the Earth-Atmosphere System that are technically and economically feasible for systematic (climate) observations.
EIS	Estimated Inversion Strength
ERF	Effective Radiative Forcing
ESM	Earth System Model
FCI	Flexible Combined Imager
FMAOD	Fine Mode AOD (also FMAOD) is the part of the total AOD which is contributed by fine mode aerosol particles. This quantity (and its optically defined fraction of the total AOD) depend both on wavelength; usually FMAOD at 550 nm is provided. When AOD at 3 wavelengths is available (e.g. from AERONET or some satellite retrievals), FMAOD can be inferred from it via FMF estimates using the SDA algorithm.
FMF	The 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	The Global Climate Observing System (GCOS) is co-sponsored by the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (IOC-UNESCO), the United Nations Environment Programme (UN Environment), and the International Science Council (ISC). It regularly assesses the status of global climate observations of the atmosphere, land and ocean and produces guidance for its improvement.
ICAP	The 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.
INPs	Ice Nucleating Particles
IPCC	Intergovernmental Panel on Climate Change
IRF	Instantaneous Radiative Forcing
ISCCP	International Satellite Cloud Climatology Project
LTDR	Long Term Data Record
LTS	Lower Tropospheric Stability
LWP	Liquid Water Path
MTG	Meteosat Third Generation
PRP	Partial Radiative Perturbation
RF	Radiative Forcing
SLCFs	Short-Lived Climate Forcers
SSA	The Single Scattering Albedo quantifies the fraction of the attenuation (or extinction) due to scattering at a certain wavelength (usually at 550nm).
SST	Sea Surface Temperature
TOA	Top of Atmosphere

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2 Introduction

The objective of this document is to identify the different sources of uncertainty associated with aerosol-cloud interactions and existing challenges, and to suggest potential ECVs datasets to address these, capitalising on the heritage of the ESA Climate Change Initiative (CCI) projects. The ESA CCI projects contributed to building a large database of Long-Term Data Record (LTDR) Essential Climate Variables (ECVs), obtained through state-of-the-art retrieval algorithms. Data derived from satellite observations have been proven to substantially improve the overall consistency of independent estimates and to ultimately help reduce the uncertainties associated with climate processes and feedbacks.

However, although the 6th IPCC Assessment Report (AR6, Arias et al., 2021) shows large improvements compared to AR5, large uncertainties persist. The IPCC predictions and adaptability strategies rely on the physical understanding of the processes contributing to climate change. The primary metric used to estimate the impact of various drivers on climate is the radiative forcing (RF), which is defined as the net change in the energy balance of the Earth system due to some imposed perturbation (Myhre et al., 2013). The concept of effective radiative forcing (ERF) is introduced, which accounts for rapid adjustments, on top of the instantaneous radiative forcing (IRF), thus representing a better indicator of the eventual global mean temperature response, especially for aerosols.

The latest IPCC technical report (AR6, Arias et al., 2021) shows several improvements in terms of uncertainty reduction in the estimation of the ERF with respect to AR5, thanks to the improvements in observational capabilities, which enabled improved consistency between independent estimates of the drivers of the climate system. The uncertainty ranges for metrics that quantify the response of the climate system to radiative forcing has been strongly decreased, such as in the case of cloud feedback, which is reduced by 50%.
The uncertainty reduction is supported by a combination of increased process-understanding and progress in the consistency between the modelling and observational line of study. However, despite the large uncertainty reduction, clouds remain the largest contribution to the overall uncertainty in climate feedbacks. In particular, the cloud response to aerosol emissions remains poorly constrained. The ERF associated with ACI from observational evidence is currently estimated at -1.0 (-1.7 to – 0.3) Wm-2 (Forster et al., 2021), corresponding to over 30% uncertainty reduction compared to AR5, where the ERF_{ACI} was estimated at -0.45 [-1.2 to 0.0] Wm^{-2} (Boucher et al., 2013; Myhre et al., 2013).
Observation-based evidence on the ERF due to ACI has strongly improved in the latest IPCC report thanks to the increased number of studies assessing statistical relationships obtained from satellite measurements.

Figure 1 summarises the findings of several studies published since IPPC AR5 and reported in Table 7.7 of Arias et al., 2021, considering the IRF. All studies here considered show a common agreement on the sign of the IRF, a large uncertainty persists on its magnitude, with values ranging from -1,75 to 0 Wm^{-2}.

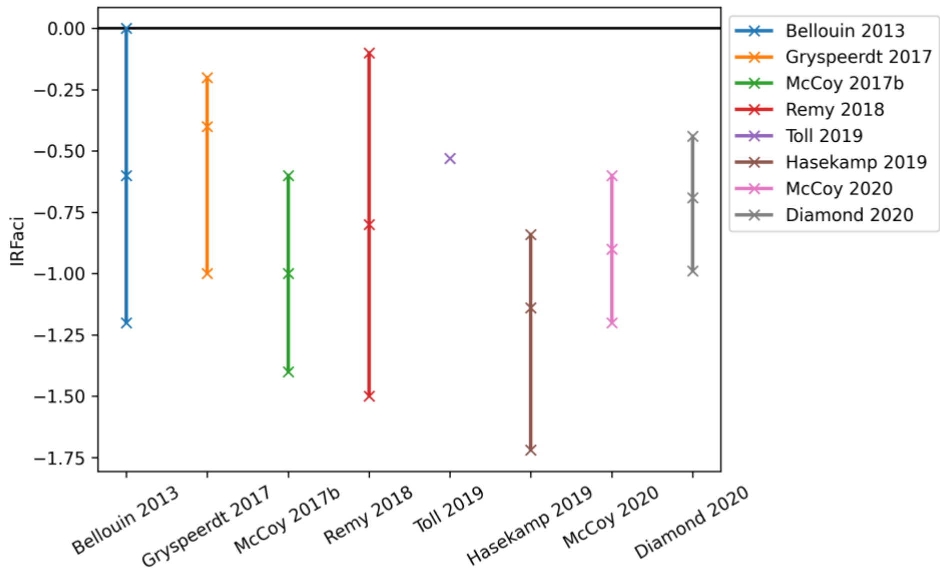

Figure 1 IRFaci observational estimation in Wm^{-2} as in Table 7.7 of Arias et al., 2021.

Furthermore, a large uncertainty persists on the effect of aerosols on cloud liquid water content, cloud fraction and ice clouds (Bellouin et al., 2020).

Several studies suggest that part of the uncertainty in ACI observational studies originates from the use of polar orbiting satellite observations; while providing global observation at a suitable spatial resolution, these only represent a snapshot of the state of the atmosphere, and may not adequately capture the dynamic processes of cloud development and dissipation influenced by aerosols (Christensen et al., 2020, Alexandri et al., 2024, Smalley et al., 2024). Studies based solely on polar observations might underestimate or overestimate ACI effects depending on the timing of the observation relative to the aerosol perturbation. The use of geostationary satellites, with their high temporal resolution, is essential for accurately observing and understanding the transient and evolving nature of aerosol–cloud interactions.

Furthermore, passive remote sensing only allows us to retrieve aerosol properties in clear-sky pixels. In order to co-locate aerosol and cloud retrievals for statistical analysis, many studies use a coarse-resolved grid (usually 1° × 1° grid) to match aerosol to nearby cloud pixels (Quaas et al., 2008, Ma et al., 2014). Jia et al., 2021, highlighted that such coarse resolutions can lead to significant underestimations of radiative forcing by aerosol–cloud interactions, because coarse resolutions fail to capture the spatial variability and localized interactions between aerosols and clouds, which are critical for accurate assessments. On the other hand, local studies near ship tracks overestimate impacts of polluted aerosol on low altitude clouds, as nearby feedbacks/adjustments are ignored. Relying on the latest effort to expand the retrieval of aerosols in the vicinity of clouds, this project will allow better analysis of the impact of including aerosol retrieval in the vicinity of clouds in aerosol-cloud interactions.

Moreover, observational constraints on aerosol-cloud interactions (ACI) at the kilometer scale are often not entirely consistent with those at the 1° × 1° scale. Spatial averaging smooths out localized features, reducing the apparent variability and weakening observed AOD-cloud correlations. For instance, at km-scale, strong, localized relationships between aerosols and cloud droplet number concentration (CDNC) are evident, especially in stratocumulus or polluted environments, whereas at 1º-scale CDNC-AOD relationships are weaker due to the inclusion of clouds unaffected by aerosols within the coarse grid cell. On the other hand, Goren et al., 2023, found that averaging at coarser spatial resolutions leads to an overestimation of about 10% of the radiative forcing, as such coarse resolution could artificially enhance correlations between aerosol proxies and cloud responses by blending affected and unaffected clouds within the same grid cell. This is in contrast with Jia et al., 2021. In order to quantify the impact of different temporal and spatial resolutions, a method to assess the impact of using Level-2 rather than Level-3 data for this exercise will be proposed within this project.

Inconsistency at different spatial scales might also arise from the lack of proper uncertainty quantification and propagation. Inconsistencies in data products can arise from different spatial or temporal resolutions, instrument characteristics or algorithm assumptions. Uncertainties should be considered when assessing the consistency among different datasets, as suggested by (Wildung et al., 2021). Well-characterised uncertainties at the pixel level are also required in data assimilation applications, which need a robust error model for data ingestion into numerical models (Merchant et al., 2017, Benedetti et al., 2018). Scientific requirements on the consistency among the selected dataset will be suggested, to enable the detection of climate trends and provide data suitable for climate model evaluation and climate change attribution (Popp et al. 2020, Ma et al., 2018). Given the above considerations, a dedicated effort will be made to assess the consistency among different datasets and develop a rigorous uncertainty propagation method within this project.

3 Review of previous studies

3.1 Aerosol indirect effect on liquid clouds

Anthropogenic aerosols primarily affect liquid clouds, acting as cloud condensation nuclei (CCN), increasing the cloud droplet number concentration (CDNC) and subsequently affecting the cloud fraction (CF) and liquid water path (LWP).

Several quantities are used in literature as aerosol proxies, such as:

- **AOD**. While it does not directly indicate aerosol size or type, the AOD is widely used due to its global coverage and availability (Liu et al., 2024, Painemal et al., 2020, Quaas et al., 2008).
- **Fine Mode AOD (FAOD)**. For the same AOD, fine mode aerosols are way more numerous than coarse mode aerosols. Thus FAOD, in contrast to AOD, better captures the (optically sensitive) aerosol number concentrations and therefore those aerosols that can act as cloud condensation nuclei (CCN). Jia et al., 2024, demonstrated that using FAOD instead of AOD leads to doubling of RFaci. However, a larger retrieval uncertainty is associated with FAOD (Li et al., 2022, Cheng et al., 2012).
- **Ultraviolett Aerosol Index (UV-AI).** The UV-AI combines spectral information in the ultraviolett to provide qualitative information on the presence of elevated (UV-) absorbing aerosol. Quantitiave estimates (for UV-AOD and UV-SSA) require added information on aerosol altitude. Proxies like UV-AI, relying on statistical correlations with cloud properties which can be confounded by meteorological factors, are insufficient to attribute causality in ACI studies (Jia et al., 2021).
- **Angstrom Exponent (AE)**. Based on two AOD data at different wavelengths, the AE is the negative slope in ln(AOD/ln(wavelength) space. At solar visible wavelengths AOD dominant coarse mode particles have almost no slope (AE <0.5), wheras AOD dominant fine aerosol sizes display strong slopes (AE >1). The smaller the aerosol the larger AE. Its accuracy though depends mainly on the AOD data accuracy, especially that of the smaller AOD (at the longer wavelength). Thus AE-values are less reliable at low AOD.
- Aerosol Index (AI). As the product of AOD and AE, it weighs total AOD with the likelyhood of small aerosol presence (AE), thus is – like FAOD – AI is a good qualitative indicator for aerosol number concentration (and CCN)

Despite being one of the most well characterised contribution to the net forcing associated to ACI, the uncertainty associated to the susceptibility parameter $\beta = \frac{dN_d}{dA}$, where A is an aerosol proxy (e.g. AOD, AI), contributes to 50% of the total uncertainty on ERF_{ACI}; in particular, this is driven by clean conditions (Gryspeerdt et al., 2023, Figure 2). Previous studies have placed the value for β between 0.3 and 0.8, with considerable variation across the globe (Bellouin et al., 2020). More recent studies have found higher values for β and hence more negative values for the RFaci (McCoy et al., 2017; Hasekamp et al., 2019).

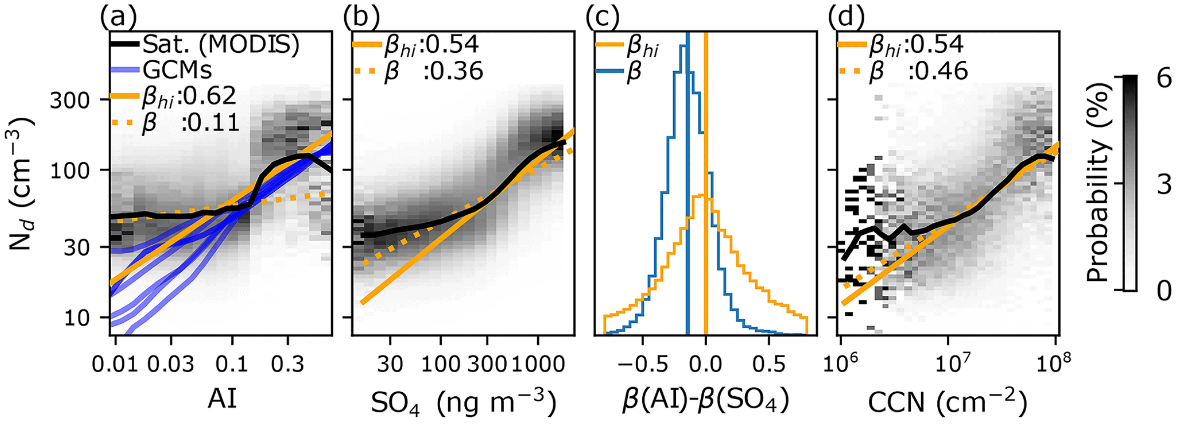

*Figure 2 Figure 1 from Gryspeerdt et al., 2023. "The relationship between MODIS droplet number concentration (N_d) and aerosol index (AI) in the south-east Pacific as a normalised histogram (shading), with the mean value in black. Blue lines are the mean relation for a selection of global aerosol–climate models. The solid orange line is the susceptibility (β; Eq. 1) fit for data with an AI > 0.1, and the dashed line is for all data. Panel **(b)** as **(a)** but for reanalysis SO_4. **(c)** The global distribution of the difference in β for all conditions (blue) and under only polluted conditions (β_{hi}; orange) calculated with AI and reanalysis SO_4, with vertical lines at the global arithmetic mean. Panel **(d)** as **(a)** but a global mean calculated using retrieved cloud condensation nuclei (CCN) column (following Hasekamp et al., 2019; see Methods in Appendix A)".*

While there is high confidence that anthropogenic aerosols lead to an increase in cloud droplet concentrations, the cloud fraction (CF) and LWP adjustments are estimated with medium and low confidence respectively, due to the small availability of studies available (Forster et al., 2021). Modelling studies suggest a uniform increase in the LWP (Quaas et al., 2009, Michibata et al., 2016, Sato et al., 2018, Gryspeerdt et al., 2020), but observational results are much more varied, reporting a negative, weak or positive response depending on the study (e.g. Chen et al., 2014, Toll et al., 2017, Christensen et al., 2022). One of the reasons for such discrepancies is the meteorological conditions in which the study occurred. Tippet et al. (2024) also identified a bias in ship track studies that causes an overestimation of LWP enhancement in ship tracks, leading to a negative radiative forcing due to LWP adjustment, in contrast with the latest IPCC report.

Intense wildfires are known to be a source of aerosols and are capable of producing pyrocumulonimbus (pyroCb) clouds. The aerosols produced by fires with weak intensity have been found to increase cloud droplet radius and reduce liquid water concentration, while also increasing water vapour transport to higher altitudes through aerosol-induced updrafts that lead to an increase in cirrus clouds (Lee et al., 2020). Biomass-burning (BB) aerosols also impact cloud properties and radiation depending on the amount of aerosol produced, with low aerosol loadings leading to increases in LWP and cooling effects, while high aerosol loadings tend to reduce LWP and lead to net heating effects (Liu et al., 2020). Given the high variation in effects of BB aerosols on clouds, as well as wildfires being relatively small-scale, dynamics events, satellite datasets that provide relatively high spatial and temporal resolution information are needed to constrain modelling and validate their results.

Numerous studies have demonstrated a positive correlation between cloud fraction (CF) and aerosol loadings (Bellouin, 2019; Koren et al., 2005; Kaufman et al., 2005; Yuan et al., 2011). However, this relationship is likely confounded by meteorological factors that influence both variables. Meteorological factors such as relative humidity, estimated inversion strength (EIS), and sea surface temperature (SST) (Jia et al., 2023; Gryspeerdt et al., 2016). Notably, adopting cloud droplet number concentration (CDNC) as the causal pathway between AOD and CF has been shown to reduce the strength of this relationship by approximately 80% (Gryspeerdt et al., 2016), highlighting the challenges in establishing a direct causal link between aerosol loadings and CF variability. Furthermore, the AOD–CF relationship is highly dependent on cloud properties and geographical location. In tropical regions, a negative correlation has been observed (Grandey et al., 2013), potentially due to wet scavenging of aerosols. Stratifying regions based on lower tropospheric stability (LTS) may aid in identifying areas with strong or weak AOD–CF correlations (Jia et al., 2023). Additionally, several factors can introduce uncertainty in the AOD–CF relationship, including errors in aerosol and cloud retrievals (Yuan et al., 2008) and methodological differences in cloud fraction calculations (Emde et al., 2024). Addressing these uncertainties is crucial for accurately quantifying the influence of aerosols on cloud fraction.

3.2 Dust impact on cloud glaciation temperature

In liquid clouds colder than 0°C (super-cooled clouds), aerosols can also act as ice nucleating particles (INPs), initiating ice crystal formation (heterogeneous freezing) at warmer sub-zero temperatures compared to pristine environments in which water droplets can remain liquid down to temperatures of about -38°C where homogeneous freezing starts. The phase of the clouds, thus being liquid or ice, is of crucial importance for the clouds' development, and precipitation formation, but very importantly also for the radiative properties of clouds with, for example, liquid clouds reflecting significantly more incoming solar radiation than ice clouds. While laboratory studies could quantify the ability of different aerosol types to "onset" heterogeneous freezing (Hoose et el., 2012), i.e. when super-cooled liquid clouds glaciate, observational-based studies have mostly been limited to Lidar or aircraft observations (e.g. Choi et al., 2010) which by construction provide only small spatial representativeness and context. Examples of Choi et al. (2010) results are shown in Figure 3 (right panel). A large-scale (ideally global) and observation-based quantitative impact of aerosols on cloud glaciation is still missing Foster et al., 2021. This can only be done with satellite data with the requirement that the satellite data provide relevant cloud and aerosol properties with sufficient accuracy Foster et al., 2021. In atmospheric models, the treatment of aerosols acting as INPs is very diverse, ranging from not considering (in ECMWF models) to prognostic aerosols and linking them INP numbers and cloud glaciation through parametrizations in some GCMs. Han et al., 2023, has demonstrated the impact of INP concentration on modelled cloud glaciation temperatures for convective clouds using the ICON model. They highlighted that glaciation temperature shifted towards warmer temperatures by as much as 8°C for increasing INP concentrations (Figure 3 left panel).
Given the enormous importance of the cloud phase on, for example, the cloud's radiative properties it becomes clear that cloud glaciation processes and the role of aerosols therein need to be understood better. Satellite datasets will here provide additional insights if they accurately provide necessary cloud properties, primarily cloud top temperature and cloud

phase, and aerosols information, primarily on mineral dust aerosol as dust can be assumed to be dominating cloud glaciation at temperatures colder than −15°C Han et al., 2023.

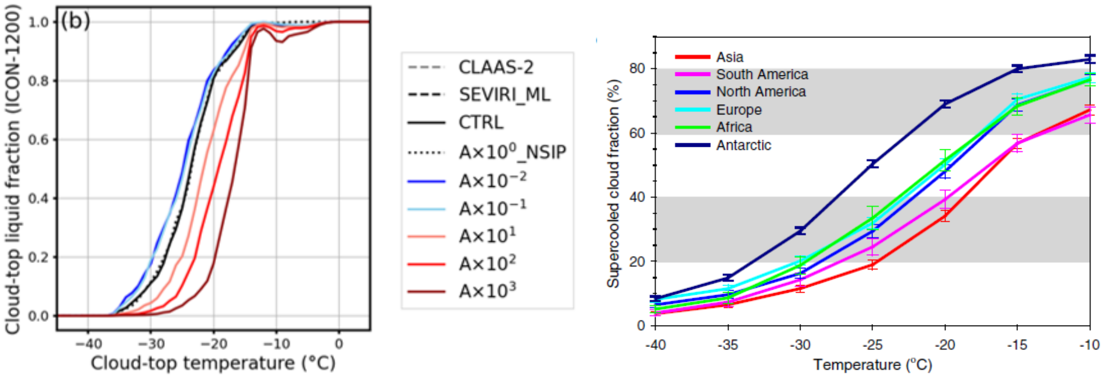

Figure 3: Left: Liquid cloud pixel fraction as a function of temperature from INP sensitivity experiments for convective clouds using ICON, Figure adopted from Han et al., 2023. Right: Annual mean super-cooled cloud fraction with respect to temperature over the selected geographical regions. Figure adopted from Choi et al., 2010.

3.3 Aerosol-cloud interactions in climate models

A range of Earth system models (ESM) is in use to simulate aerosol-cloud interactions and the impact of these on climate evolution. Models show consistently the importance of aerosol-cloud interactions for radiative forcing, but the results vary considerably when it comes to quantification. Recently the concept of the effective radiative forcing (ERF) has been used to characterise the sum of the instantaneous forcing and the fast adjustments in clouds and temperature structure of the atmosphere. In an ESM the ERF can be retrieved by performing a reference and a perturbation experiment, assuming that the change of the radiative balance at the top of the atmosphere is due to the perturbation, e.g. anthropogenic aerosols or dust loading. Because of internal variability in the climate system, such as the fluctuation in cloud and aerosol fields, the retrieved ERF value cannot be obtained with very short simulations. To retrieve with confidence an ERF of 0.1 W m-2, model simulations need to be 5 years long, if the sea surface temperatures are fixed and the atmospheric circulation is controlled by nudging. 30 year long simulations are needed if only the sea surface temperatures are fixed (Kooperman et al., 2012, Forster et al., 2016).

Different aspects of the effective radiative forcing due to aerosol-cloud interactions may be constrained or evaluated with satellite observations. Here we review aspects which relate to the SATACI project goals, review some model concepts in use and what requirements for satellite products and their quality emerge for model evaluation purposes.

3.3.1 ESM model structure and model diagnostics

An earth system model (ESM) contains a complex suite of components. Of most relevance here is the atmospheric component, in which one can find process formulations of the formation of clouds, atmospheric circulation, mixing processes, the life cycle and transport of gases and aerosols and the microphysics of clouds and aerosols. An exemplary descriptions of such a model can be found in Seland et al. 2020 (NorESM) and Danabasoglu et al. 2020 (CESM).

An ESM is typically solving a forcing problem and not an initial value problem, the latter being the case in weather forecasting. The forcing may consist of emissions of greenhouse gases, reactive gases, land properties, land-use changes, and what concerns the atmospheric component of an ESM also observed sea surface temperatures. The forcings applied in a given ESM simulation should be close to those apparent in e.g. the time period when satellite observations are available. Recently significant trends in aerosol loads are regionally visible and require to be taken into account (Quaas et al., 2022).

A typical time stepping for solving equations in the atmospheric physics component is 30 minutes and a typical horizontal resolution of the Coupled Model Intercomparison Project (CMIP) class models is 1x1 degree. The computational resources for simulating multi-annual and decadal climate evolution require supercomputers. A simulation of the historical period from 1850 to 2020 can easily take one month wall clock time. The number of simulations of decadal scale is thus limited to small and medium ensembles. The exploration of new satellite products requires therefore a careful coordination of the periods under study.

By forcing the ESM winds and temperature to adjust to reanalysis fields (nudging) it is possible to obtain rather realistic spatio-temporal distributions of the aerosol. Reanalysis fields are typically available every 6 hours. The model time stepping, the diagnostics and the nudging limits the comparison to observations with a high temporal resolution. While diurnal cycles may be evaluated, the noise and uncertainty increases when going from daily to 3-hourly time scales. A specific investigation of the impact of these limitations for the model evaluation is needed.

In addition to the prognostic variables, the model also contains a module to produce diagnostic output, which can be specifically designed to allow for an optimal comparison to observations. There is a large variety of 3-hourly, daily and monthly output of 2d and 3d fields at the resolution of the model stored in netCDF files. A specific case are satellite simulators, such as the International Satellite Cloud Climatology Project (ISCCP) simulator (Klein and Jakob 1999; Webb et al. 2001). It uses the model representation of cloudiness to derive cloud-top pressure and optical thickness that would be seen by a particular satellite instrument. The simulator accounts for effects at the pixel scale, including the screening of clouds low in the atmosphere by clouds above them, the interpretation of measurements as if they arise from clouds in a single homogeneous layer, and the estimation of cloud-top pressure based on infrared brightness temperatures. The simulator also adopts the averaging strategies from the processing of ISCCP observations. Pincus et al., 2012, point to the limitations of the use of simulators and recommend to compare cases where cloud optical thickness is larger than 1.3.

3.3.2 Background state and aerosol activation

Constructs such as the albedo susceptibility (Platnick & Twomey, 1994) or precipitation susceptibility (Sorooshian et al., 2009) are useful in that they survey globally the regions of the Earth that have the potential to generate large responses to aerosol perturbations while controlling for key meteorologically driven variables.

Christensen et al., 2022, point out that the background cloud state (namely, aerosol Nd) determines the specific sensitivities of scene albedo and cloud processes to aerosol perturbations. Twomey (1974) showed that cloud albedo sensitivity to a change in Nd is largest at low Nd and cloud albedo of 0.5 (Eq. S4), where the background Nd and α set the strength of the cloud albedo susceptibility. This has been confirmed in many field campaigns (Ackerman et al., 2000; Durkee et al., 2000; Ferek et al., 2000; Lu et al., 2009). While Nd changes at constant LWP can occur, i.e., the LWP in the polluted clouds is the same as the unpolluted clouds on either side of a ship track, it is a relatively rare occurrence (roughly 10 %) in satellite-derived ship track databases (Segrin et al., 2007; Christensen and Stephens, 2012). In the majority of ship tracks, the LWP actually decreases, and in roughly 30 % of the tracks, the decreases are so large that the cloud albedo becomes dimmer in the polluted clouds (Chen et al., 2012). Similar behaviour has been observed in volcanoes, industry, and fire tracks (Toll et al., 2019). Nevertheless, cloud susceptibility is a useful construct and could be even more useful with an improved understanding of the relationship between meteorological controlling factors and the timescales for LWP adjustments (Glassmeier et al., 2021).

The concept of cloud susceptibility points to the problem that it is relevant to identify where the aerosol perturbation in time and space perturbs the clouds. Regional findings need to be extrapolated to global estimates of ERF, a process that is not yet state-of-the-art. The non-linearity of the aerosol-cloud interaction as a function of Nd implies also that the natural background from biogenic precursors, DMS and sea salt has to be characterised and known when aerosol ERFaci due to anthropogenic aerosol shall be retrieved (Carslaw et al. 2013).

3.3.3 Dust and ice cloud cover

Mineral dust particles have been shown to exhibit as good ice nucleating particles and dust-cloud interactions have thus been incorporated in some, but not all, climate models. For instance, NorESM2 includes heterogeneous ice nucleation by dust aerosols following classical nucleation theory (Hoose et al., 2010) and has a separate scheme for heterogeneous nucleation via immersion freezing within cirrus clouds as described by Liu et al. (2007). A recent analysis of historical dust loading changes by Kok et al. 2023 revealed that climate feedbacks or land-use changes on dust emissions may have been underestimated in ESMs to a considerable degree. Changes of dust loadings are practically constant in the CMIP6 models in the historical period from 1850 to 2014. Significant changes of dust loadings would imply considerable radiative forcing through the dust direct effect and dust-cloud interactions.

To explore how dust perturbations would exert climate feedbacks a dust perturbation experiment was suggested in the AerChemMIP framework under CMIP6 (Collins et al. 2017), where dust emissions were doubled. The initial workup from Thornhill et al 2021 suggested a small dust TOA ERF of -0.05 Wm2 on average from doubling dust. A recent analysis by Haugvaldstad et al (submitted to ACP, 2025) decomposed the dust forcing data from that experiment further, and explained a large part of the inter model diversity by some few models incorporating dust-ice cloud interactions. The analysis showed also that considerable changes in high cirrus clouds appear in NorESM, which both have a considerable LW and SW radiative impact, nearly cancelling each other.

Dust cloud interactions of course depend also on the presence of dust at high cloud levels. Other properties of the dust cycle, such as amount of dust emission, vertical mixing of dust clouds, longevity of dust particles, and co-location of dust and humidity fields are becoming important. How dust and cirrus cloud climatologies and observations from satellite sensors constrain such properties is largely unresolved.

3.3.4 Decomposition of direct and indirect forcing and their components

An important aspect of the quantification of the aerosol ERF is the ability to differentiate the direct from the indirect forcing, or the aerosol radiation interaction term from the aerosol cloud interaction one. Ghan (2013) proposed to perform a second diagnostic radiation call where scattering and absorption by aerosols is set to zero. If done both for the preindustrial and the anthropogenic – or dust perturbed – simulation, one is able to decompose ERF into direct and indirect effect. Often a small residual is left which can be attributed to surface albedo changes due to either aerosol deposition on snow or snow cover changes in the perturbed experiments. If total aerosol ERF is retrieved as a diagnostic from satellite measurements it would be beneficial to also provide a decomposition of the ERF, to allow for apple-to-apple comparison with models.

Finally it is useful to decompose in a climate model the ERFaci into a radiative forcing by anthropogenic cloud droplet number change and adjustments of the liquid water path and cloud fraction. This allows also to use different satellite observations of e.g. droplet radius, cloud liquid water path and cloud cover to constrain model derived ERFaci. The decomposition in the model is possible by using the method of offline radiative transfer modeling and the partial radiative perturbation (PRP) approach (Mülmenstädt et al., 2019). In ECHAM-HAMMOZ they show that the simulated radiative forcing by anthropogenic cloud droplet number change and liquid water path adjustment are of approximately equal magnitude at−0.52 and−0.53 W m−2, respectively, while the cloud-fraction adjustment is somewhat weaker at−0.31 W m−2. Spatial correlations indicate that the temporal-mean liquid water path adjustment is proportional to the temporal-mean radiative forcing, while the relationship between cloud-fraction adjustment and radiative forcing is less direct. They also that using low-frequency (daily or monthly) time-averaged model output of the cloud property fields underestimates the ERF, but that 3-hourly mean output from the model is sufficiently frequent. Such requirements are currently incorporated into the AeroCom phase 4 experiment protocol, where particular emphasis is put on the study of ERFaci.

3.4 WMO Climate Indicators

The ERF contribution due to ACI (ERFaci) is estimated at -1.3 [-2.0 to -0.6] 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] Wm^{-2} (Forster, et al., 2021). Despite the ACI contribution to the total anthropogenic aerosol 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] and [https://climatedata-catalogue-wmo.org/climate_indicators], likely due to the large uncertainty and the resulting challenges in satisfying traceability and data adequacy requirements. So far, WMO uses a list of 7 state-of-the-climate indicators that are based on the 54 Global Climate Observing System (GCOS) Essential Climate Variables, including surface temperature, ocean heat content, atmospheric carbon dioxide (CO2), ocean acidification, sea level, glacier, and Arctic & Antarctic sea ice extent. Those climate indicators are visualized as (mostly global) temporal records or as global annual maps. Additional indicators are usually assessed to allow a more detailed picture of the changes in the respective domain. Aerosols and clouds are not included in the panel of the current WMO climate indicators.

Trewin, et al., 2021, summarize the requirements for a climate indicator. Their primary objective is to provide a range of indicators which gives a more comprehensive picture of the overall state of the global climate system than surface temperature alone. Those indicators should be scientifically robust and cover the atmosphere, ocean, and cryosphere, while still being sufficiently simple and few in number (ideally between 5 and 10) to be suitable for widespread public communication. Those indicators are targeted particularly at high-level policy events such as the activities of the UNFCCC, but it is expected that they will also be valuable for broader reporting of the state of the global climate. The desired characteristics for the headline climate indicators as specified by Williams and Eggleston 2017 are as follows:

- Relevance*:* Each headline indicator should be a clear, understandable indicator of the state of the climate system, with broad relevance for a range of audiences, whose value can be expressed as a single number. Some such global indicators may also have value at the national and regional levels.
- Representativeness: The indicators as a package should provide a representative picture of a broad range of changes to the Earth system related to climate change.
- Traceability: Each indicator should be calculated using an internationally agreed upon (and published) method and accessible and verifiable data.
- Timeliness: Each indicator should be calculated regularly (at least annually), with the minimum possible time between the end of the period and publication of the data.
- Data adequacy: The available data needed for the indicator calculation must be sufficiently robust, reliable, and valid.

Another similar initiative is the “Indicators of Global Climate Change” (IGCC) initiative which is providing updates of several key global climate indicators reported by the Intergovernmental Panel on Climate Change (IPCC) that can help to understand the state of the climate system and how it is changing. The methodologies used to update the indicators are directly traceable back to the IPCC Sixth Assessment Report (AR6). These methodologies are described in Forster, et al., 2024. The methodology is mostly model-based and supported with some additional satellite information (.e.g.: the statement that “even though trends over recent years are uncertain, the general decline in some Short-Lived Climate Forcers (SLCFs) emissions derived from inventories punctuated by temporary anomalous years with high biomass burning emissions including 2023 is supported by MODIS Terra and Aqua aerosol optical depth measurements”. In addition to IPCC AR6, this report contains recent updates for 2022 and 2023.

Their visualization is presented in the Climate Change Tracker which comprises temperature records, emission records and bulk quantities (e.g. remaining carbon budget to the 1.5 °C target). Radiative effects of changes in sulfate and biomass burning aerosols but not of changes in sea salt and dust aerosols are included there in the total effective radiative forcing (ERF); aerosol-cloud radiative effects (Twomey effect only) are also included.

Forster, et al., 2024, state that "the total aerosol ERF (sum of the ERF from aerosol–radiation interactions (ERFari) and aerosol–cloud interactions (ERFaci)) for 1750–2023 is -1:18 [-2:10 to -0:49] W m-2." Furthermore, they state that "this counters a recent trend of reductions in aerosol forcing and is related in most part to 2023 being an extremely active biomass burning season. Most of this reduction is from ERFaci, which is determined to be -0:91 [-1:80 to -0:27] W m-2 in 2023." In the paper they summarize the main radiative forcing results in Table 3 (for 2019 as in IPCC AR6, 2022 and 2023) and a time evolution of total global ERF and its components (including "tropospheric aerosols) (Figure 4). The comparison of forcing values for 2023 with earlier years shows significant increases due to due to "biomass burning, continued COVID-19 recovery and drop in sulfur from shipping." In their conclusion they state that "Human induced warming is increasing at the unprecedented rate of over 0.2 °C per decade, the result of greenhouse gas emissions being at an all-time high over the last decade, as well as reductions in the strength of aerosol cooling."

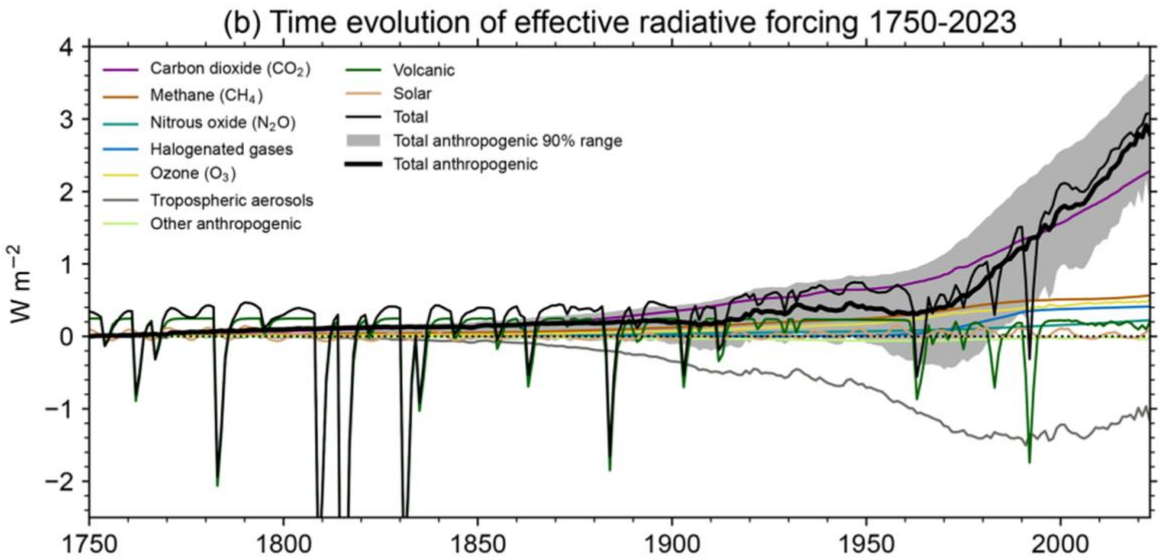

Figure 4 [Figure 3b from Forster, et al., 2024]: The grey line below zero shows the radiative forcing due to "Tropospheric aerosols".

Exactly, the last half sentence shows the importance of aerosol (and their effect on clouds) to understanding climate change and in particular their radiative forcing. This is the basis for the intended work to assess the feasibility of a new climate indicator "Cooling offset by aerosols and clouds" . This will include aerosol direct radiative forcing and radiative forcing changes due to aerosol-induced cloud changes. The focus will be on testing the use of satellite data records to prescribe the temporal and spatial changes as far as feasible. The use of satellite data will include direct observational records (e. G. aerosol: AOD, FM-AOD, D-AOD) but also regional multi-annual statistical associations of cloud properties (e.g. CDNC, cloud fraction, cloud liquid water) with aerosol properties (FM-AOD, DAOD). The visualization of the new indicator shall be as time records similar to Figure 3b in Forster, et al., 2024, (but global and regional) and as global maps (in 5-year intervals matching the frequency of the Global Stocktake).

4 Scientific Requirements Survey

To complement the literature review and ensure that the SATACI project aligns with the current needs of the scientific community, a targeted survey was conducted among experts working in the field of aerosol-cloud interactions (ACI). The aim of the survey was to gather perspectives from a broad range of stakeholders—including data users, modellers, and observational scientists—on the primary challenges, priorities, and requirements related to the use of satellite-based ACI datasets.

The survey was distributed across relevant scientific networks, including the AeroCom and AeroSat communities, and collected responses from researchers with diverse professional backgrounds and areas of expertise. Respondents were invited to share their experience with ACI-related data, highlight key limitations of existing datasets, rank the usefulness of various aerosol proxies and metrics, and provide guidance on how to shape future data products and visualisations.

The insights from 24 respondents collected through this survey serve as an essential input for defining the scientific and technical requirements of the SATACI project. They help ensure that the project outcomes will be relevant, targeted, and beneficial for the broader ACI research and policy communities.

The full summary of the survey results is added in Annex 1.

4.1 Respondents Background

To ensure that the requirements captured through the survey reflect a diversity of scientific perspectives, respondents were asked to describe their professional background, domain of expertise, and current use of ACI-related datasets.
The majority of respondents identified as senior scientists (79%), with additional input from junior and mid-career researchers, ensuring both depth of experience and operational insights into ACI-related data usage.

In terms of domain expertise, responses were well-distributed across relevant fields, as shown in Figure 5. This disciplinary spread supports a comprehensive view of both observational and modelling requirements.

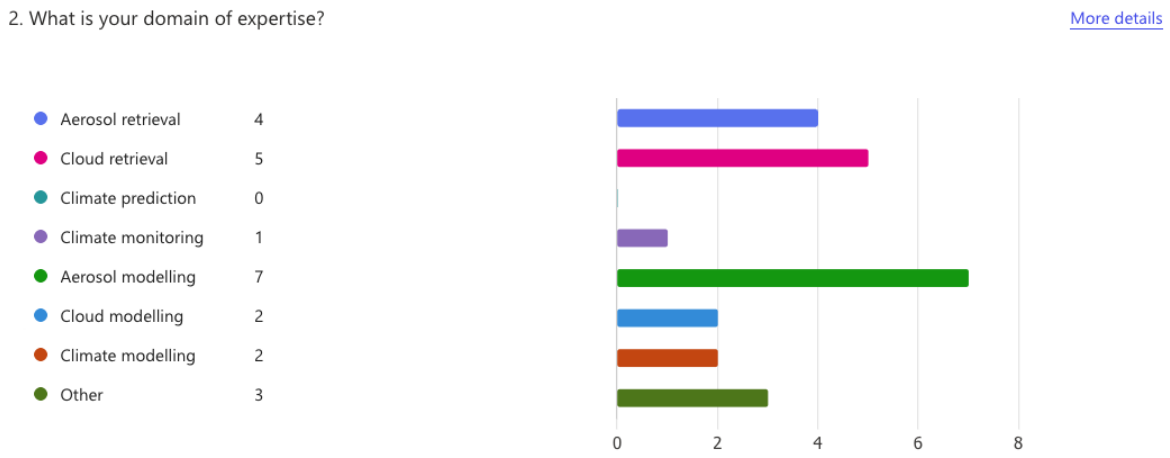

Figure 5 Domain of expertise of the survey's respondents.

Observational studies were the most frequently cited use case (58%), followed by climate modelling (36%). This highlights the dual importance of ACI datasets in both understanding underlying physical processes and integrating them into large-scale climate simulations. Notably, there was limited mention of forecasting applications, suggesting the main focus remains on research and long-term assessment rather than operational prediction systems. Relevance to policy or decision-making appears limited: respondents only occasionally use ACI studies in indirect support of climate policy, typically via modelling outputs or in collaboration with colleagues involved in assessment and planning.

4.1.1 Methodological Approaches and Data Practices

This subsection summarises the practical aspects of how respondents currently study aerosol–cloud interactions, including their spatial resolution preferences, treatment of uncertainties, and climate modelling approaches.

4.1.1.1 Climate models

Respondents reported employing a wide range of global and regional models, including ECHAM-HAM, UKESM1, ICON, CESM2, NorESM, and EC-Earth. Notably, only a subset of these models explicitly represent the role of dust as an ice-nucleating particle (INP) — a process increasingly recognised as important for understanding mixed-phase and ice cloud formation. On a total of 19 responses on this topic, 37% of the participants stated that the climate model takes into account the impact of dust on ice clouds, 31.5% answered that this is only partially done. The remaining 31.5% confirmed that dust-ice cloud interactions are not explicitly accounted for.

4.1.1.2 Spatial Resolution

Respondents reported using resolutions ranging from coarse model grids (1–3°) to km-scale satellite data. Roughly half indicated they use or prefer high-resolution data (e.g., 7×7 km), particularly for studies involving cloud dynamics and localised aerosol effects. The impact of using fine or coarse resolution hasn't been strictly quantified by the respondent, although they confirmed the relevance of this approach.

4.1.1.3 Time offset

When considering time offsets, responses were split: some assumed instantaneous correlation, while others preferred short delays (0–6 hours) or case-dependent offsets. This reflects a recognition of the time-lagged nature of cloud response to aerosol perturbations, which geostationary observations could help constrain. However, the lack of high-temporal and spatial resolution combined aerosol and cloud retrievals is considered a challenge by 65% of the respondents (see Section 4.2.1).

4.1.1.4 Uncertainty estimates

When asked whether their datasets include uncertainty estimates, 17% of the participants indicated that no uncertainty was provided with the aerosol and cloud dataset used in their study. 43% report a pixel-level uncertainty, while the remaining 39% indicates an overall uncertainty.

However, even among those with access to uncertainties, only half propagate these through to ACI metrics. Open comments suggest this is often due to the uncertainties being either too imprecise or not well-characterised enough to be meaningful.

4.2 Key Findings from the Survey

4.2.1 Dataset Limitations

Participants were asked to identify the primary limitations of current datasets in studying ACI. As seen in Figure 6, the three main identified limitations are the lack of aerosol measurements in the vicinity of clouds, inconsistencies across instruments and uncertainty quantification. These findings are aligned with 65% of the participants agreeing that the lack of high-temporal and high-spatial resolution (e.g., 10-minute, 1 km) combined aerosol and cloud retrievals poses a challenge for assessing ACI. This highlights a critical need for better-resolved, co-located observations to capture dynamic processes such as cloud formation, growth, and dissipation in response to aerosol perturbation.

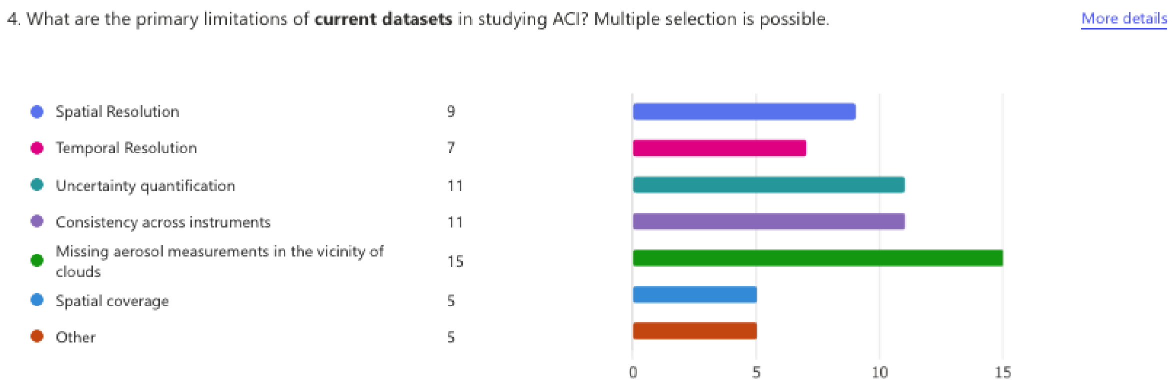

Figure 6 Identified limitations of current datasets for ACI studies.

These responses reinforce findings from the literature (e.g. Jia et al., 2021), confirming the need for co-located aerosol-cloud retrievals at high resolution and with pixel-level uncertainty estimates. These insights directly align with SATACI's objectives to exploit high-temporal-resolution geostationary satellite data (e.g., SEVIRI) and develop consistent retrievals of aerosol and cloud properties within the same pixel footprint. SATACI also aims to address limitations in uncertainty propagation, dataset consistency, and temporal/spatial sampling strategies — all issues raised by the survey participants. In particular, these insight support the proposal of processing Meteosat Third Generation (MTG) Flexible Combined Imager (FCI) to provide co-located aerosol and cloud properties at 1 km spatial resolution. This alignment ensures that the project's scientific developments are tightly coupled to community needs and will ultimately support more reliable quantification of ACI processes.

4.2.2 Aerosol Proxies

Figure 7 shows the ranked preferences of respondents for various aerosol proxies used in ACI studies. The Fine Mode AOD emerged as the most consistently favoured option, receiving the highest number of first-choice rankings. It was followed closely by Aerosol Index (AI) and Total AOD, both of which were also well-regarded. Interestingly, while Ångström Exponent (AE) and Absorbing AOD were considered useful by some, they were more frequently placed lower in the rankings, suggesting more variable confidence or applicability across different use cases.

This pattern reflects a shared view among users that AI and fine-mode aerosol properties are particularly informative for understanding cloud susceptibility and indirect effects. These preferences also align with the scientific strategy of SATACI to focus on well-characterised aerosol indicators that can be reliably retrieved in conjunction with cloud properties.

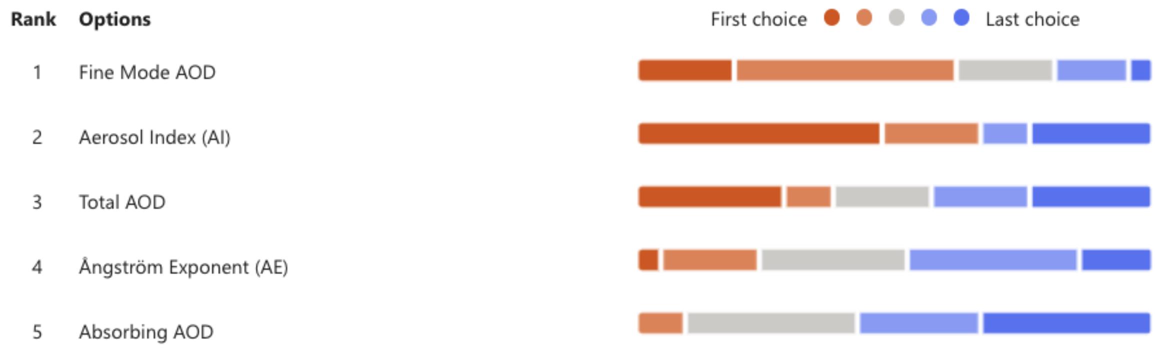

Figure 7 Ranked preferences of respondents for various aerosol proxies used in ACI studies.

4.2.3 Prioritised Metrics

When asked which ACI metrics are most critical, half of the respondents indicated dCDNC/dAerosol, reflecting focus on cloud microphysical responses (

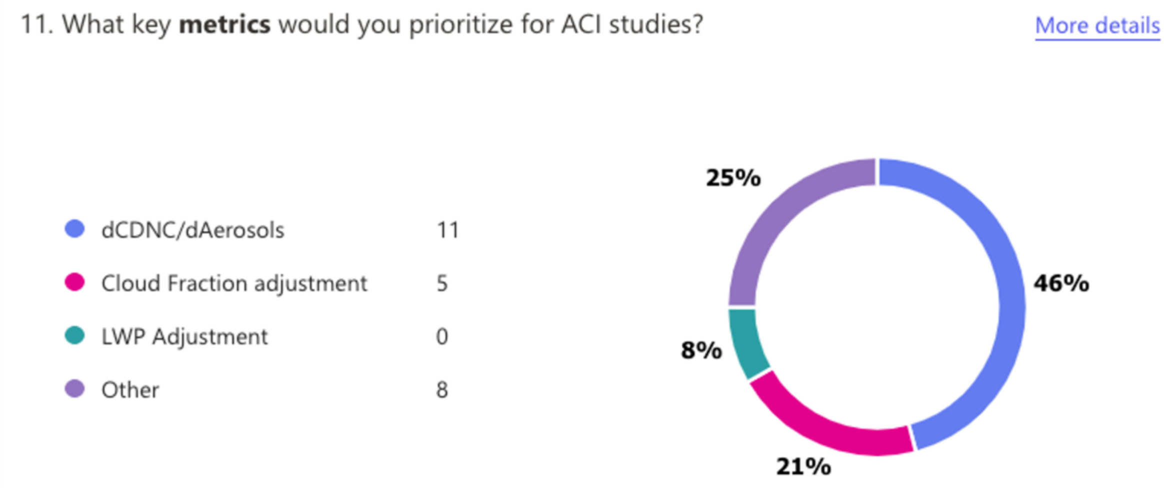

Figure 8). Participants recognised this quantity as "the start of all ACI processes", with the advantage of being more easily observable than LWP or CF adjustments. However, CF adjustments are prioritised by 21% of the participants, being the largest contribution of the total aerosol forcing uncertainty based on Bellouin et al., 2020.

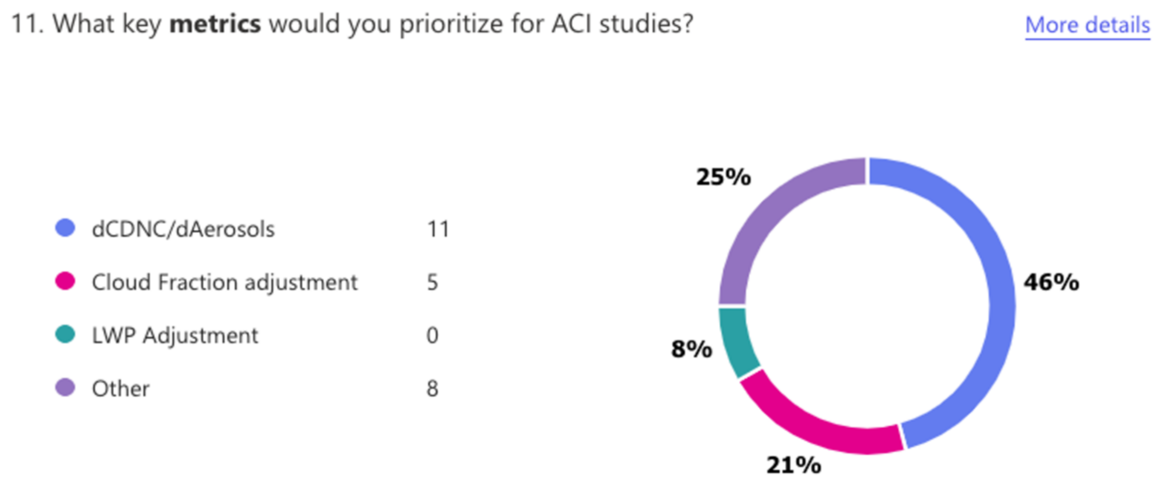

Figure 8 Prioritised metrics according to the survey's respondents.

4.2.4 Stratifications

The respondents' preferences regarding stratifications to be considered when analysing aerosol–cloud interactions are quite varied, as shown in Figure 9. The most commonly selected option was liquid versus ice clouds, chosen by nearly all respondents. This highlights a strong consensus on the importance of cloud phase in modulating ACI processes, particularly given the distinct microphysical pathways and radiative properties of liquid and ice clouds.

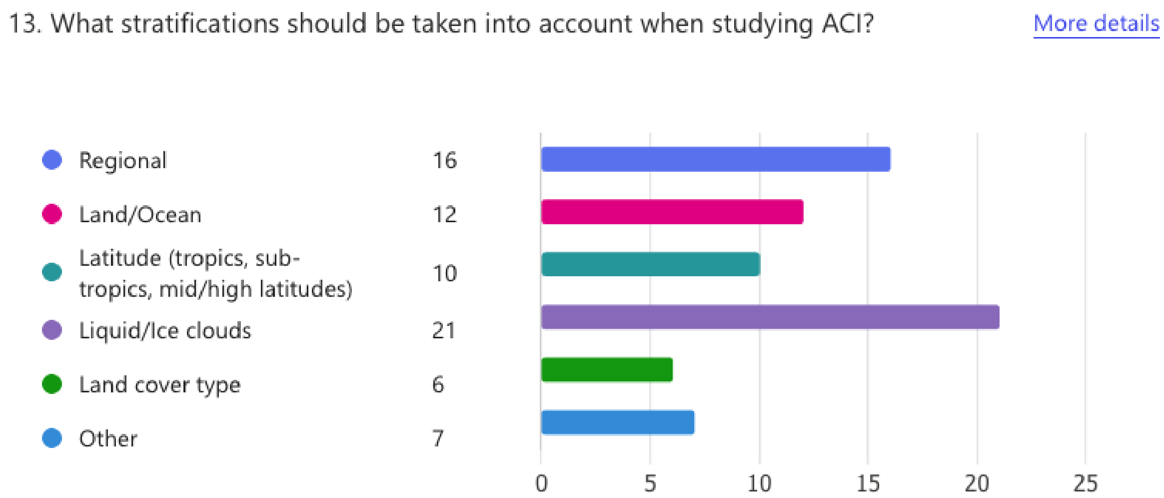

Figure 9 Preferred stratifications to consider when studying aerosol–cloud interactions, based on responses to the SATACI survey.

Other highly recommended stratifications included regional differences and land/ocean separation, both of which reflect the well-known geographic variability in aerosol sources, cloud regimes, and meteorological conditions. Stratifying by latitude (e.g., tropics, subtropics, mid- or high-latitudes) also received notable support, recognising that ACI sensitivities may differ across climatic zones.

Less emphasis was placed on land cover type, although a few responses suggested it could still play a role in defining aerosol regimes or boundary layer characteristics. These preferences are consistent with previous modelling and observational studies and will guide the SATACI project's stratification strategies when producing regional and global ACI diagnostics.

4.2.5 Visualisation and Climate Indicator Preferences

This section summarises user feedback on how ACI datasets should be visualised and interpreted to support scientific and policy applications.

When asked about regional definitions for data visualisation, such as in Figure 4, respondents expressed strong support for breaking down outputs by continental-scale regions. These preferences reflect a recognition that ACI processes and their radiative impacts can vary substantially depending on aerosol sources, meteorology, and cloud regimes.

Regarding the proposed development of a new climate indicator, respondents supported a wide range of essential characteristics (Figure 10). These included relative temporal consistency, consistency across regions and absolute accuracy. A third of respondents selected "All of the above," highlighting a general demand for robust and traceable indicators that support both scientific and policy relevance.

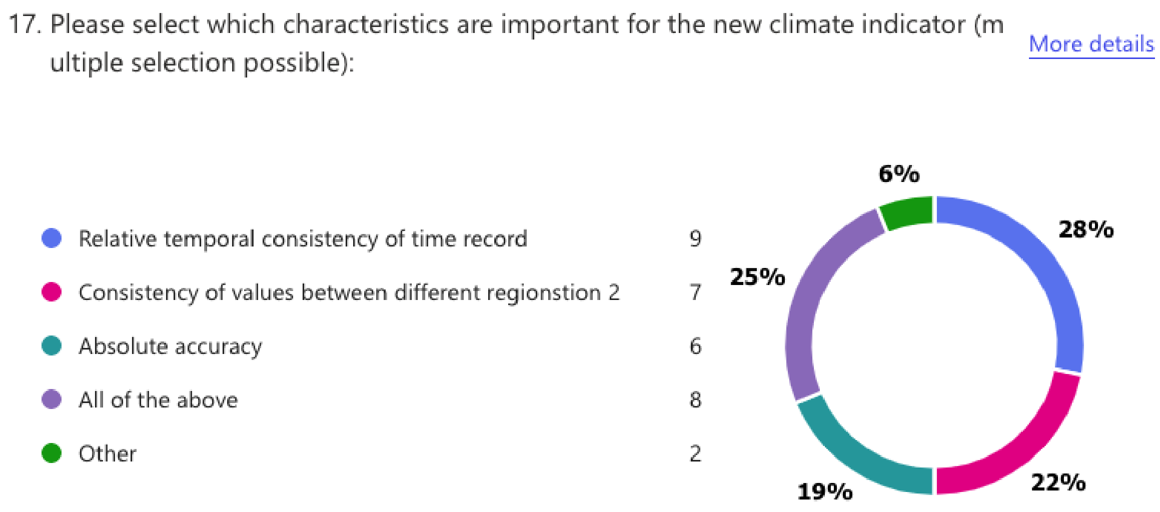

Figure 10 Selection of characteristics important for the new climate indicator.

Finally, the decision of translating radiative forcing (in W/m^2) into a simplified estimate of temperature change, following the IPCC AR6 methodology, is largely supported by 65% of the participants.

4.3 Envisaged Synergies

Participants expressed the interest of following up on the progress and outcome of the SATACI project. In particular, some users expressed enthusiasm for obtaining simultaneous cloud and aerosol parameters around the vicinity of clouds, as well as drawing conclusions on the use of CF adjustment as a valid ACI metric.

5 Identified Requirements

The SATACI project builds on the findings of the literature review and the community survey to define the following scientific and technical requirements. These requirements are designed to address key limitations in current datasets and methods, and to support both advanced scientific analysis and the development of climate indicators.

1. **Assessment of dataset consistency and fitness-for-purpose**
   Evaluate the consistency and suitability of selected satellite-derived aerosol and cloud products. This includes checking their temporal and spatial coverage, retrieval assumptions, and internal consistency, with the aim of establishing whether they are appropriate for quantifying aerosol–cloud interactions at the required resolution and accuracy, depending on the targeted application.
2. **Development of an uncertainty propagation framework**
   Establish a rigorous approach for quantifying and propagating uncertainties in aerosol and cloud retrievals through to ACI metrics. This includes assessing pixel-level uncertainties where available and exploring the effect of aggregated or instrument-level uncertainties on statistical analyses. Within SATACI, a dedicated method for uncertainty propagation will be developed for each study (aerosol indirect effect on liquid clouds, dust impact on cloud glaciation temperature and climate indicator)
3. **Adopt preferred aerosol proxies**
   In line with survey results and literature review, the Scientific Study I (aerosol indirect effect on liquid clouds) and the study on the feasibility of a new climate indicator will prioritise the use of the following proxies in the derivation of ACI metrics, especially susceptibility-type parameters:
   - Fine Mode Aerosol Optical Depth (FMAOD)
   - Aerosol Index (AI)
   - Total AOD
4. **Selection of key ACI metrics**
   For liquid clouds (Scientific Study I), the following quantities will be prioritised, which reflect the most supported metrics in the community survey and are directly linked to the radiative effects of aerosol–cloud interactions:
   - dCDNC/dAerosols (as a primary measure of cloud microphysical susceptibility)
   - Cloud fraction adjustment (majour source of uncertainty according to Bellouin et al., 2020)
5. **Improved characterisation of dust–ice interactions**
   Provide observational constraints on the role of mineral dust as ice-nucleating particles (INPs) in super-cooled cloud regimes. This will support better

representation of dust–ice processes in models by combining aerosol and cloud phase data over regions and seasons with high dust occurrence.

6. **Assessment of the impact of time offsets**
   Quantify how different assumptions about time lags between aerosol perturbation and liquid cloud response influence the derived ACI signals within Scientific Study I. This includes comparisons of instantaneous, short-delay (0–6 h), and case-dependent approaches using high-temporal-resolution geostationary data.

7. **Assessment of the impact of spatial resolution**
   Evaluate the influence of spatial resolution by comparing ACI metrics derived from Level-2 (native resolution) and Level-3 (gridded) data products. This is necessary to understand how spatial averaging affects the strength and sign of aerosol–cloud relationships. This analysis will be performed within WP530, aiming at assesing the consistency between observational constraints and climate indicator.
8. **Relevant stratifications**
   Implement appropriate stratifications in the implementation of the climate indicator, based on the survey findings, and discuss possible differences and discrepancies resulting from such stratifications. These include:
   - Cloud phase (liquid vs. ice)
   - Regional areas
   - Land/ocean separation
   - Latitude zones (e.g., tropics, subtropics, mid-latitudes)
   - Additional factors such as land cover or meteorological regime where appropriate
9. **Development of a climate indicator with community-informed design**
   In support of broader communication and policy relevance, radiative forcing estimates in W/m² are to be converted into estimated temperature change using IPCC AR6 methodology. The climate indicator shall be provided at a continental scale and shall satisfy characteristics such as consistency, temporal stability, and interpretability, as prioritised in the survey.
10. **Dissemination of SATACI progress to the community**
    Maintain visibility of project outcomes and intermediate findings through regular communication. This includes presentations at relevant community meetings and publications.
11. **Establish a community-facing communication channel**
    Set up a monthly newsletter or similar mechanism to share updates, datasets, and early results with interested stakeholders across the ACI research and modelling communities.

6 Conclusion

The SATACI SRD outlines the current knowledge gaps and community needs in the study of ACI, synthesising insights from a detailed literature review and a targeted survey of domain experts.

Despite progress in recent years, major limitations persist in the ability to quantify ACI effects using satellite observations. These include the lack of co-located aerosol and cloud retrievals, insufficient spatial and temporal resolution, and limited uncertainty characterisation. The survey confirmed that these challenges are widely experienced by the community and provided clear guidance on methodological preferences, data practices, and metric prioritisation.

Based on these findings, SATACI will include the use of high-resolution, uncertainty-aware satellite products that enable the derivation of ACI-relevant metrics. The project will prioritise the use of well-supported aerosol proxies (FMAOD, AI, AOD), focus on microphysical and radiative cloud responses (dCDNC/dAerosols, cloud fraction), and support an improved characterisation of dust–ice interactions. Methodological components such as stratifications, resolution sensitivity, and time-offset analysis are also integral to the project's design.

In addition, SATACI will explore the feasibility of a new climate indicator that captures the radiative effect of aerosols and aerosol-induced cloud changes. This indicator will be designed to meet the requirements of traceability, regional relevance, and interpretability, as identified by the scientific community.

Overall, the project is well-aligned with community priorities and is expected to deliver tools and datasets that are directly relevant to both scientific research and policy-driven climate monitoring initiatives.

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Annex 1

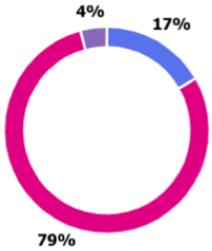
Responses Overview

Active

Responses	Average Time	Duration
24	20:43	166 Days

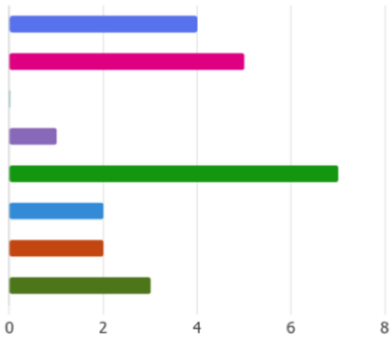
1. How would you categorize your professional background ? Please select from the following categories:

Junior scientist	4
Senior scientist	19
Student	0
Other	1



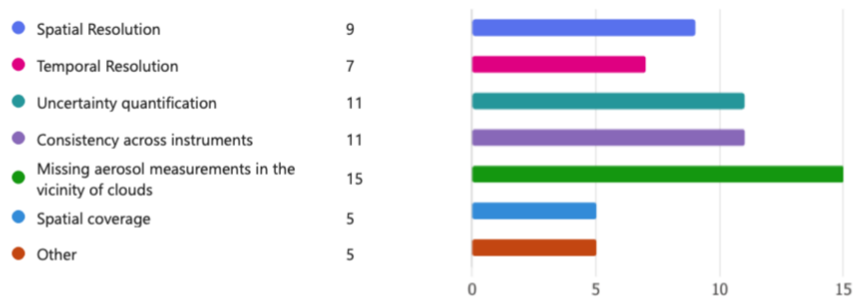
2. What is your domain of expertise?

Aerosol retrieval	4
Cloud retrieval	5
Climate prediction	0
Climate monitoring	1
Aerosol modelling	7
Cloud modelling	2
Climate modelling	2
Other	3



3. How do you currently use ACI-related data (e.g., climate modeling, observational studies, forecasting)?

4. What are the primary limitations of **current datasets** in studying ACI? Multiple selection is possible.



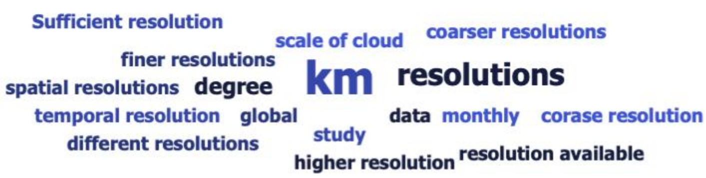
5. How would you rate the following quantities to use as aerosol proxies in ACI studies (e.g. susceptibility paramete r)?

6. (If applicable) What spatial resolution do you use in your ACI study? Why? Have you estimated the impact of coarser or finer resolutions?

21
Responses

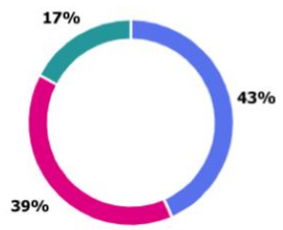
Latest Responses
"10 km"
"For the puropse of climate impacts I like to work with corase resolu... "
"1-3km (GEO nadir, so often worse res at study site)"
...

10 respondents (48%) answered km for this question.



7. Do the aerosol and cloud datasets included in your study provide uncertainty?

Yes, at pixel level	10
Yes, as an overall uncertainty	9
No	4



8. If you answered yes to the previous question, is this uncertainty taken into account and propagated to ACI estimat es?

19
Responses

Latest Responses
"Yes"
"I do not care too much about uncertainty as I like to example relati... "
"No"
...

5 respondents (26%) answered uncertainty for this question.

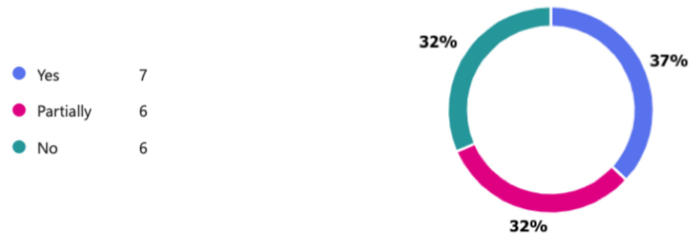
9. (If applicable) What climate model do you use in your ACI study?

18
Responses

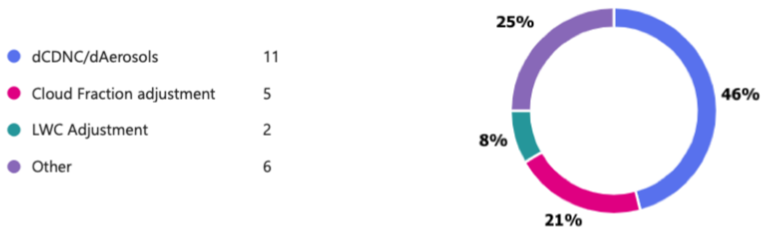
Latest Responses
"None"
"a proxi climate model: globally applied offline radiative transfer wit... "
...

3 respondents (17%) answered Echam ham for this question.

10. (If applicable) Does this model take into account the dust effect on ice clouds?



11. What key **metrics** would you prioritize for ACI studies?



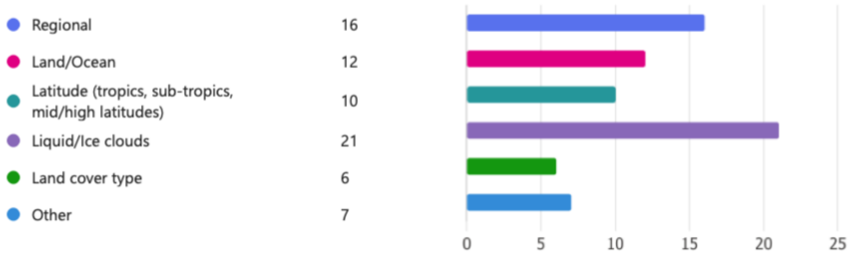
12. Please justify your answer to the previous question.

18
Responses

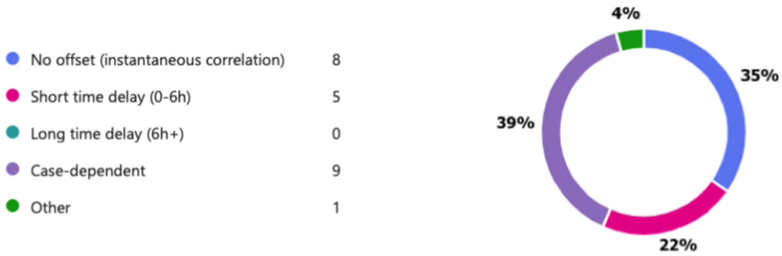
Latest Responses
"Because it is retrievable"
"reductions of the cloud drop radius (dCDNC-AODf) are well docum... "
"The effects of aerosol on convective initiation, lightning production... "
...

5 respondents (28%) answered adjustments for this question.

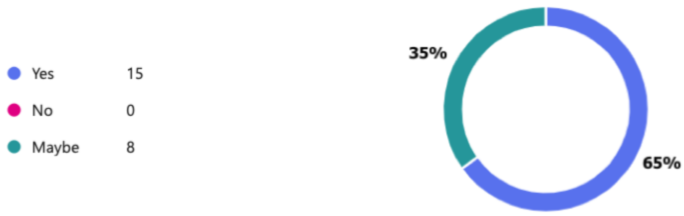
13. What stratifications should be taken into account when studying ACI?



14. Do you consider any **time offsets** when analyzing aerosol-cloud interactions?

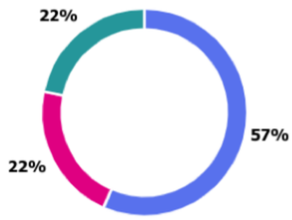


15. Does the lack of high-temporal and spatial resolution (e.g., 10-minute, 1 km) **combined** aerosol and cloud retrievals pose a challenge for studying cloud lifetime adjustments?



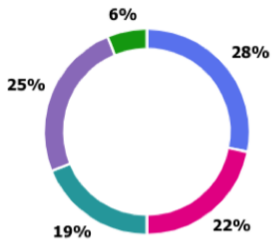
16. Visualization such as in Figure 3b of Forster et al., 2024 (https://doi.org/10.5194/essd-16-2625-2024) will be prov ided both globally and regionally. What regions should be defined for such visualization?

North/South America, North/South Africa, Europe, Australia, SouthEast Asia, Siberia	13
Land/Ocean	5
Other	5



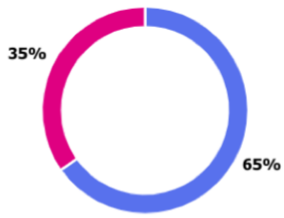
17. Please select which characteristics are important for the new climate indicator (multiple selection possible):

Relative temporal consistency of time record	9
Consistency of values between different regionstion 2	7
Absolute accuracy	6
All of the above	8
Other	2



18. We plan to convert W/m2 into a simple estimate of temperature change (following IPCC AR6). Do you support th is post-processing for easier understanding?

Yes	15
No	8



19. Do you use ACI data for **climate policy or decision-making applications**? If so, how?

19
Responses

Latest Responses
"No"
"... do we trust future emission scenarios ? (with obs we can only ad... "
...

4 respondents (21%) answered climate for this question.

20. How could the **SATACI project** best support your research?

11
Responses

Latest Responses
"Being innovative and thinking out of the box"
"... let me travel (haha)"
...

4 respondents (36%) answered cloud for this question.

[End of document]