



Validation of EarthCARE Surface Irradiance Products Against Ground-Based Observations and Geostationary Satellite Estimates

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Abstract. The Earth Cloud Aerosol and Radiation Explorer (EarthCARE) satellite, launched in 2024, is the most complete cloud, aerosol, and precipitation observing satellite to date. Now in its second year of operation, EarthCARE provides a continuous stream of high-resolution data essential for refining weather and climate models. However, due to the advanced technologies and retrieval approaches used in EarthCARE, the credibility of each instrument and of their synergistic products must be verified. In this study, ground-based radiation observations from the Baseline Surface Radiation Network (BSRN) are used to validate surface global horizontal irradiance (GHI) computed using one-dimensional (1D) and three-dimensional (3D) radiative transfer models (RTMs) and reported in the EarthCARE ACM-RT product. To optimize collocation, EarthCARE's 1D fluxes are extended across-track utilizing EarthCARE's scene construction algorithm (SCA). In addition to the BSRN validation, EarthCARE irradiances are compared with gridded solar estimates from the Copernicus Atmospheric Monitoring Service (CAMS) radiation service, which infers high-resolution cloud information from geostationary satellites. Due to limited availability of the CAMS radiation service gridded dataset, this comparison is restricted to September-December 2024.

The results indicate that EarthCARE's 1D RTM systematically underestimates GHI relative to both BSRN and CAMS, with Mean Bias Errors (MBEs) of -9.8 W m^{-2} (-2.1%) and -20.1 W m^{-2} (-3.9%), respectively. Intercomparison of EarthCARE's 1D and 3D RTMs revealed that the 3D RTM exhibits lower GHI bias against BSRN observations (-4.6 W m^{-2} compared to -19.5 W m^{-2}). However, the 3D RTM substantially underestimates beam (direct) horizontal irradiance (BHI) ($\text{MBE} = -51.4 \text{ W m}^{-2}$) while overestimating diffuse horizontal irradiance (DHI) ($\text{MBE} = 47.1 \text{ W m}^{-2}$), leading to the near-zero GHI bias. Spatial analysis demonstrates that EarthCARE GHI is generally lower than CAMS values across most regions, particularly in Oceania, Central Africa, and Europe, while parts of South America, Northern Africa, and Western Asia are notable exceptions where EarthCARE GHI exceeds CAMS. Approximately 65 % of EarthCARE's GHI bias against CAMS can be attributed to differences in cloud estimation, while the remaining 35 % stems from differences in the clear-sky GHI. Future data releases from BSRN and CAMS will expand the dataset, enabling a more robust assessment. These findings offer a critical early assessment of EarthCARE's performance and provide valuable benchmarks for the solar energy and atmospheric science communities.



1 Introduction

25 The goal of climate science is to understand the structure and dynamics of Earth's climate system. It seeks to address challenges such as global warming and extreme weather for a sustainable future. An important factor in the Earth's climate system is the radiation budget which affects atmospheric circulation patterns (Forster et al., 2021; Loeb et al., 2021). Radiative forcing induced by clouds and aerosols plays a critical role in modulating the radiation budget, resulting in atmospheric energy imbalances (Wild, 2020). These energy imbalances can shift atmospheric circulation and alter the transport of water vapour (Bony et al., 2015). While significant effort has been devoted to aerosol and cloud radiative forcing both currently and in the past, their quantitative estimates remain uncertain. The level of radiative forcing is ultimately governed by the top of atmosphere (TOA) solar (global) irradiance, which is defined as the incoming solar radiation in the 0.2–4.0 μm wavelength region, typically averaging around 1361 W m^{-2} (Prša et al., 2016; Schmutz, 2021). While passing through the atmosphere, this radiation is subject to scattering and absorption by clouds, aerosols, gases, and water vapour, leaving only a fraction of the initial energy to reach the Earth's surface (Wild, 2020). The resulting surface solar irradiance can be estimated using radiative transfer models (RTMs). Conversely, radiometer irradiance observations can be used to evaluate the accuracy of RTMs (Urraca et al., 2018). Therefore, having precise measurements of surface irradiance would considerably constrain RTMs, reducing the associated uncertainty in climate and weather models. Beyond climate science, other fields would also benefit from highly accurate surface irradiance measurements. For example, the solar energy community could improve their estimation of solar energy potential, thereby ensuring more reliable performance of their tools (Papachristopoulou et al., 2024).

Different methods are used to evaluate surface irradiance. Ground-based stations provide direct, high-precision observations of global horizontal irradiance (GHI) (e.g. Augustine et al., 2000; Driemel et al., 2018a). However, logistical and financial constraints prevent global coverage (e.g. Yuan et al., 2021). In contrast, satellite-based retrievals generally lack the precision of ground-based measurements, but provide broader coverage. Satellite-based retrievals can be subdivided into different methodologies. Satellites on near-polar orbits provide global data by measuring atmospheric input parameters needed by RTMs, potentially using active sensors capable of capturing detailed vertical profiles of clouds and aerosols. Alternatively, imagers on geostationary satellites provide high-temporal-resolution horizontal information about clouds that can be used as input alongside assimilated atmospheric composition data in RTMs. An example of the former is the Earth Cloud, Aerosol and Radiation Explorer (EarthCARE, ECA) satellite (Illingworth et al., 2015; Wehr et al., 2023), jointly developed by the European Space Agency (ESA) and the Japanese Aerospace Exploration Agency (JAXA) to advance the observation of clouds, aerosols, and radiation. The satellite was launched in 2024, building on the success of the previous Earth-observing satellites CloudSAT and CALIPSO (Stephens et al., 2008; Winker et al., 2010). The four instruments used by EarthCARE are designed to characterize profiles of clouds, aerosols and precipitation as well as TOA radiation. Specifically, synergistic retrievals of vertical cloud, aerosol and precipitation profiles are derived using the ATmospheric Lidar (ATLID), Cloud Profiling Radar (CPR), and Multispectral Imager (MSI) (Mason et al., 2023; Sato et al., 2025), while the Broad-Band Radiometer (BBR) observes radiances at three fixed viewing angles to estimate TOA solar and thermal fluxes (Velázquez Blázquez et al., 2024a, b). The synergistic



retrievals are used to calculate flux and heating rate profiles and radiative fluxes at the TOA and surface (Cole et al., 2023; Yamauchi et al., 2024). The comparison of the BBR fluxes at TOA with the simulated TOA fluxes serves as a continuous radiative closure for EarthCARE, with the mission aiming to achieve consistency within 10 W m^{-2} (ESA, 2001; Barker et al., 2025). While internal closure with the BBR is a key objective, it must be complemented by validation against independent external measurements to ensure the absolute accuracy of EarthCARE products (Koopman et al., 2019). EarthCARE data products are released in successive baselines, with each version offering improved accuracy. The BA baseline provides the longest continuous data stream of the mission, featuring a complete reprocessing of all measurements for the period from July 2024 to July 2025. Following the BA baseline, baseline BC is the mission's most recent version of the data products starting in November 2025.

The validation of EarthCARE products is a collaborative, global effort that integrates a wide range of instruments and methodologies. It includes retrievals from ground stations, airborne research flights, and other satellite missions. Despite the short duration since the satellite's launch in 2024, a significant body of results has been published. For example, Feuillard et al. (2026) validated EarthCARE's CPR Level 2a reflectivity against ground-based radars, reporting a near-zero mean bias error (MBE) of $-0.2 \pm 0.4 \text{ dB}$ in baseline BA. Baars et al. (2026) utilized ground-based lidar observations to demonstrate that ATLID's Level 2a products provide backscatter and extinction profiles that generally align with the ground-based reference. However, significant discrepancies were identified in the depolarization ratios within the aerosol regime for baselines BA and BB. Furthermore, transitions from particle layers to clean air seem to be problematic. Consequently, the authors emphasized the necessity of rigorous quality checks for EarthCARE ATLID data prior to their use in scientific analysis. Yamauchi et al. (2024) performed a pre-launch test of their Japanese radiative flux algorithm using A-Train satellite (CloudSat, CALIPSO, and MODIS) data as input. Estimated 20 km along-track TOA radiative flux was compared against $20 \times 20 \text{ km}$ data from the Clouds and the Earth's Radiant Energy System (CERES), resulting in an MBE of 24.4 W m^{-2} and a root mean square error (RMSE) of 36.3 W m^{-2} for short wave (SW) fluxes. In addition, simulated downward surface fluxes were validated against ground-based observations from BSRN stations within $\pm 0.1^\circ$ of the CloudSat footprint. The MBE and RMSE for SW fluxes are -17.6 W m^{-2} and 172.0 W m^{-2} , respectively. Long wave (LW) fluxes exhibit lower MBE (-5.6 W m^{-2}) and RMSE (19.0 W m^{-2}) at the surface.

By comparing radiative estimates derived from EarthCARE's sensors with other products and ground-based observations, their uncertainties can be assessed. If EarthCARE's sensors provide reliable radiative flux estimates, partitioned into surface and atmosphere, they will considerably constrain and thus improve climate models. The present study aims to investigate this performance of the synergistic ATLID, CPR, and MSI irradiance product. Consequently, the evaluation of this synergistic product provides an implicit assessment of the retrievals from each instrument. To validate EarthCARE surface radiation estimates against ground-based observations, we utilize measurements from the Baseline Surface Radiation Network (BSRN) (Driemel et al., 2018b). In addition, EarthCARE surface GHI is intercompared with state of the art satellite-based irradiance estimates from the Copernicus Atmospheric Monitoring Service (CAMS) radiation service, which utilizes high-resolution cloud



information from the Meteosat Second Generation (MSG) and Himawari 8 geostationary satellites to infer gridded surface GHI (Lefèvre et al., 2013; Qu et al., 2016). Given that the CAMS datasets rely on satellite-based retrievals, their associated uncertainties must be considered within the context of this intercomparison. CAMS radiation services validate their product in a three-month cycle against ground-based observations. For September–November 2024, they find an all-sky GHI MBE of 8.2 W m^{-2} with an RMSE of 71 W m^{-2} (Lefèvre, 2024). The MBE is particularly pronounced within the Himawari field of view (eastern Asia and Oceania), reaching 25.7 W m^{-2} , whereas it is notably lower (4.5 W m^{-2}) within the MSG field of view (Europe and Africa). Under cloud-free conditions, the MBE increases to 21.5 W m^{-2} , while the RMSE decreases to 31 W m^{-2} . Utilizing the BSRN and CAMS validation datasets, alongside additional information from EarthCARE’s BBR instrument, this study addresses the following objectives:

- 1) Validate downwelling SW and LW EarthCARE surface irradiance products against ground-based observations from BSRN stations, including a partition of SW irradiance into direct/diffuse components.
- 2) Intercompare EarthCARE’s surface solar irradiance estimates with geostationary satellite-based products, specifically the CAMS solar radiation product.
- 3) Differentiate between cloud-free, partly cloudy and overcast conditions using the cloud modification factor approach.
- 4) Investigate clear-sky GHI discrepancies between CAMS and EarthCARE by comparing their respective aerosol inputs.
- 5) Evaluate differences between EarthCARE’s one-dimensional and three-dimensional models, and quantify the across-track extension algorithm’s performance.
- 6) Assess whether surface irradiance discrepancies (relative to BSRN/CAMS) correlate with differences observed at the TOA by the BBR instrument.

The remainder of this paper is organized as follows: Section 2 describes the data products and the collocation methodology used in the analysis. In Section 3, the validation results are presented, including a connection to TOA differences relative to the BBR instrument. Section 4 summarizes the conclusions of this study.

2 Data and methods

2.1 EarthCARE radiative transfer products

EarthCARE derives cloud, aerosol, and precipitation geophysical parameters by combining measurements from ATLID, CPR, and MSI. These parameters are used as input, alongside auxiliary meteorological data provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) and information about the surface properties, as input for RTMs in the ACM-RT (ACM: ATLID, CPR, and MSI) algorithm and resulting product. The ACM-RT product represents the last step in EarthCARE’s data processing chain before radiative closure assessment against BBR flux measurements (Eisinger et al., 2024).



2.1.1 The ACM-RT product inputs: ACM-CAP and ACM-COM

Inputs for ACM-RT are largely reported in ACM-COM (COM: composite), where cloud, aerosol, and precipitation profiles are gathered from two sources. ACM-CAP (CAP: clouds, aerosols, and precipitation) applies the Cloud, Aerosol and Precipitation from mulTiple Instruments using a VArational TEchnique (CAPTIVATE) algorithm to estimate aerosol, cloud, and precipitation properties. This algorithm uses a classic variational approach that is highly adaptable, allowing users to configure assimilated observations, atmospheric constituents, state variables, and constraints at runtime (Mason et al., 2023). Subsequently, CAPTIVATE can be applied to both ground-based and satellite-based platforms. Aerosol retrieval is based on a uniform EarthCARE classification that distinguishes between fine (pollution and fresh smoke) and coarse (dust and salt) particles (Wandinger et al., 2023). The ACM-CAP retrievals are EarthCARE's "best estimates", representing synergistic use of the observations made by CPR, MSI, and ATLID. In ACM-COM, an alternative set of cloud, aerosol, and precipitation profiles is provided, which is derived by combining single-sensor Level 2a products.

2.1.2 The ACM-RT product

The ACM-RT processor uses both 1D and 3D RTMs to compute vertical profiles of solar (SW) and thermal (LW) fluxes, along with corresponding heating rates (HRs) (Cole et al., 2023). The Rapid Radiative Transfer Model for General Circulation (RRTMG) model (Iacono et al., 2008; Morcrette et al., 2008) is used as the 1D RTM, which is applied along the nadir curtain with a spatial resolution of approximately 1 km along-track and fixed 1 km across-track. Fluxes and heating rates are computed for three different conditions: all-sky (including clouds, aerosols, and molecules), clear-sky (excluding clouds), and pristine-sky (excluding clouds and aerosols). Three-dimensional all-sky radiances and fluxes are calculated using Monte Carlo algorithms for a 5 km across-track by 21 km along-track domain, referred to as the assessment domain. For solar 3D fluxes, a forward algorithm injects photons over the computational domain (assessment domain with buffer zone) and evaluates their paths and energies. For thermal 3D fluxes, a backward algorithm traces photons from the top of their domain back to their emission source. At the source, their radiance contribution is calculated using local temperature and optical properties.

2.1.3 Extending geophysical properties across-track: The ACMB-3D product

A significant challenge for 3D RTMs arises because synergistic Level 2 cloud and aerosol retrievals are restricted to narrow nadir curtains (~ 1 km width). At this horizontal scale, lateral radiative transport (which can be neglected in 1D RTMs) becomes an important factor, leading to significant energy leakage or biases if the computational domain is confined strictly to this nadir curtain. Consequently, the surface-atmosphere system must be extended across-track. EarthCARE employs a scene construction algorithm (SCA) to infer aerosol and cloud profiles of each column in the 3D assessment domain (5×21 km) (Qu et al., 2023). The results of this algorithm are provided in the ACMB-3D (ACMB: ATLID, CPR, MSI, BBR) product. The SCA algorithm utilizes spectral MSI radiances to match across-track with along-track pixels (Barker et al., 2011). The latter serve as the donor, replicating their geophysical profiles to the across-track pixels (the receivers). There exist some constraints on pixel matching: the surface types (land, sea, and snow/ice) must be the same and the cosine of solar zenith angles and azimuth



angles between sun and satellite tracking direction should not exceed a certain amount. If those conditions are met, the SCA identifies along-track pixels that best resemble the radiances of the across-track pixel and selects the spatially closest match. The reach of this algorithm corresponds to the swath width of the MSI instrument (115 km to the left of the nadir and 35 km to the right).

2.2 EarthCARE radiative closure assessment: the BBR instrument

To quantify the uncertainties in synergistic radiative flux estimates from ATLID, CPR, and MSI, it is crucial to validate these products against independent observations. Consequently, the EarthCARE satellite houses an additional instrument, the BBR, which derives TOA fluxes from radiometric measurements. Because BBR observations are not used in the synergistic retrieval of the other three instruments, they enable an assessment of radiative closure (Barker et al., 2025). The primary objective of EarthCARE is to ensure that the difference between simulated and observed TOA fluxes stays within 10 W m^{-2} for a scene size of $5 \times 21 \text{ km}$ (3D assessment domain).

The BBR estimates TOA fluxes by measuring co-located reflected and emitted radiation with three telescopes. It is able to measure at three fixed viewing directions called fore, nadir, and aft, with respective ground zenith angles of $\pm 55^\circ$ forward, 0° , and $\pm 55^\circ$ backward. The BBR utilizes two channels: SW (0.25 to $4 \mu\text{m}$) and total wave (TW, 0.25 to $>50 \mu\text{m}$). By periodically switching between these filters, the instrument determines the LW component through subtraction of the SW radiance from the TW measurement. The resulting filtered radiances depend on the spectral response of the instrument and consequently, the radiances must be unfiltered (Velázquez Blázquez et al., 2024a). Correlation with MSI data can be used in the unfiltering process to improve performance. Radiances are co-registered either at the surface or in the presence of clouds at the radiatively most significant vertical layer of the atmosphere (reference level). Cloud identification is supported by information from ATLID and MSI (Velázquez Blázquez et al., 2024b). For each BBR viewing direction, fluxes are determined independently and combined into a single flux which is provided in the BMA-FLX product as the best estimate for a given scene. While the standard spatial resolution is $10 \times 10 \text{ km}$, the product can be configured to match the $5 \times 21 \text{ km}$ assessment domain of the 3D RTM, allowing radiative closure assessment.

2.3 Ground-based surface irradiance observations: BSRN

BSRN is a project conducted by the World Climate Research Programme (WCRP) Radiative Fluxes Working Group as part of the Global Climate Observing System (GCOS) (Ohmura et al., 1998; Driemel et al., 2018b). Its primary objective is to identify trends in surface radiative fluxes that may be correlated to climate change. In addition, BSRN provides essential observations for the validation of satellite and numerical model estimates. The BSRN database is hosted at the Alfred Wegener Institute (AWI) in Bremerhaven, Germany, containing more than 14,000 months of data since 1992. The network currently comprises 78 stations (43 active, 12 declared as inactive, 23 closed) that measure thermal and solar (global, direct, and diffuse) downward radiation with uniform instruments. These measurements are sampled at a high temporal resolution ($\sim 1 \text{ Hz}$), with quality-controlled 1-minute averages being subsequently provided to the public. Global horizontal downward radiation is



observed with pyranometers while direct and diffuse components are measured using pyrhemometers and pyranometers with sun-tracking shading ring, respectively. For thermal radiation, pyrgeometers are used.

190 BSRN data are uploaded as monthly files, containing both SW (including direct/diffuse partition) and LW surface irradiance, along with their respective time stamps. However, the reporting frequency can vary significantly from station to station. At the time of writing, 27 stations have provided data since September 2024. To increase the volume of available observations and expand the geographical coverage, measurements from an independent station in Thessaloniki (Laboratory of Atmospheric Physics), Greece, were integrated into the dataset. Although this station is not part of the BSRN network, its pyranometer and
195 pyrhemometer undergo regular calibration, and the irradiance measurements were subjected to quality control before being used in the study. Additional information about this station can be found in Bais et al. (2013). The global distribution of the ground stations can be seen in Figure 1. Europe has a dense distribution of stations, while central Asia lacks stations. A summary of the stations, including data volume and details on the spatial proximity to the satellite overpasses, can be found in Appendix A (Tab. A1). A total of 591 EarthCARE overpasses (descending trajectories) occurred within a 50 km radius to these stations.

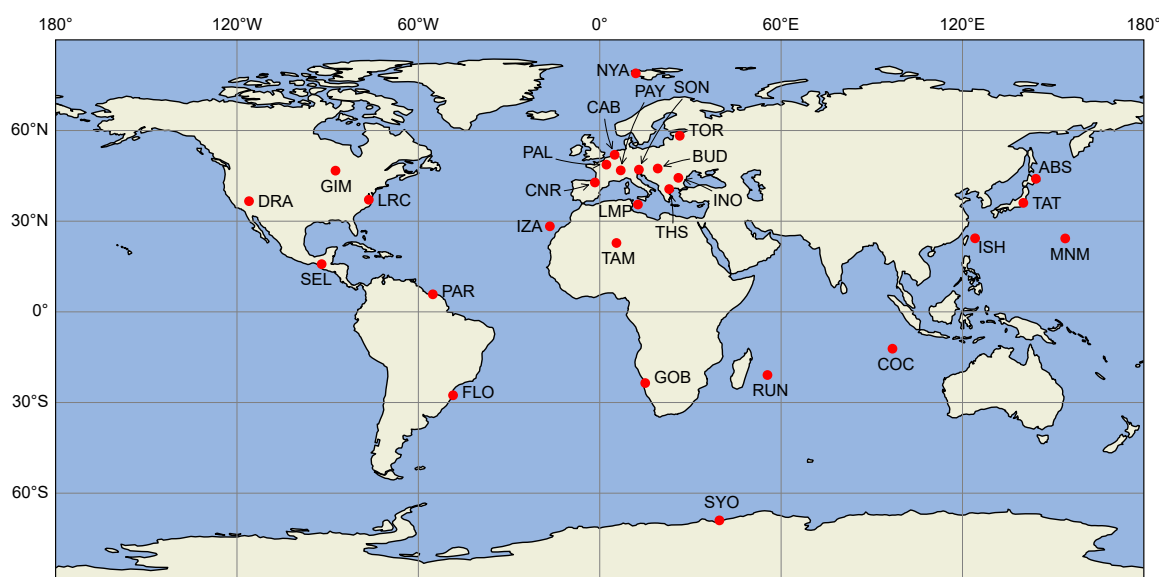


Figure 1. Map of the 28 ground stations used in the analysis. Stations belonging to BSRN have uploaded at least one monthly dataset since September 2024.

200 2.4 Surface solar irradiance estimates: CAMS radiation services

CAMS is one of six services within Copernicus, the European Union's Earth Observation programme. It uses satellite observations, in-situ measurements and modelling to provide information about the Earth and its atmosphere (CAMS, 2026). CAMS radiation services focus on solar energy products. They compute global horizontal, diffuse horizontal, direct horizontal, and



direct normal irradiation on the surface using measurements from geostationary satellites and data from the CAMS global forecasting system. By providing these parameters, the service aims to address the requirements of European and national policy development while supporting the solar energy community with critical data. CAMS radiation services distinguish between two different conditions: clear-sky and all-sky. Clear-sky irradiance is modeled via the McClear algorithm (Lefèvre et al., 2013; Gschwind et al., 2019), which incorporates aerosol optical depth (AOD), aerosol type, and total column water vapor and ozone from the CAMS global forecasting system. For all-sky conditions, CAMS employs the Heliosat-4 method (Qu et al., 2016). This approach integrates McClear's clear-sky estimates with a cloud correction factor derived from the McCloud model. This cloud correction factor is computed using observations from geostationary satellites. Specifically, McCloud leverages the SEVIRI (Spinning Enhanced Visible and Infrared Imager) instrument onboard the series of MSG satellites (Aminou, 2002) and the AHI (Advanced Himawari Imager) onboard the Himawari 8 satellite (Da, 2015). The combined field of view of these imagers includes Europe, Africa, the Middle East, eastern South America, eastern Asia, and Oceania (Fig. 2). By deriving essential cloud parameters such as coverage, height, optical depth, and type, McCloud determines the cloud correction factor necessary to compute all-sky GHI. Both McClear and McCloud are based on LUTs and have been realized by using the libRadtran radiative transfer model (Mayer and Kylling, 2005).

The clear-sky and all-sky irradiances derived in McClear and McCloud are provided in $0.1^\circ \times 0.1^\circ$ latitude/longitude grids with a temporal resolution of 15 minutes. The corresponding datasets are publicly archived and accessible via Copernicus Atmosphere Monitoring Service (2022). As mentioned earlier, due to the MSG and Himawari-8 satellites being on geostationary orbits, only part of the globe is covered (Fig. 2). In addition, oceanic regions are omitted from the retrieval algorithm, limiting the available results to landmasses. For zenith angles above 75° , satellite retrievals become inaccurate due to pixel distortion, Earth's curvature, and increased optical path length (Qu et al., 2016; Schroedter-Homscheidt et al., 2022).

Beyond its role in solar radiation estimation, CAMS also provides daily forecasts of pollutants, aerosols and greenhouse gases across the globe. A detailed computer simulation of the atmosphere is initialized twice a day, assimilating satellite-based observations of the atmospheric composition to produce hourly forecasts of various atmospheric constituents. The forecasted parameters are provided in $0.4^\circ \times 0.4^\circ$ latitude/longitude grids. AOD is determined at several different wavelengths, including the 355 nm wavelength used for ATLID. The respective dataset is publicly archived and accessible via Copernicus Atmosphere Monitoring Service (2021).

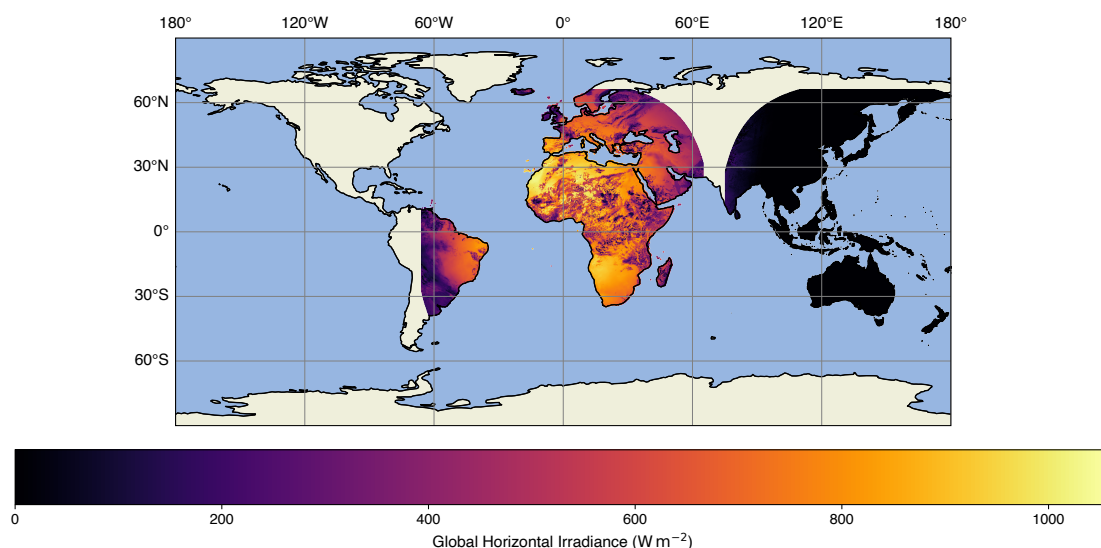


Figure 2. Spatial coverage of the surface GHI product estimated by CAMS radiation services. The data corresponds to the integrated radiation from 12:00 to 12:15 UTC on 01.09.2024. The map is shown as a Plate Carrée projection.

2.5 Ground-based AOD observations: AERONET

AERONET (AErosol RObotic NETwork) is a network of ground-based remote sensing stations established by NASA (National Aeronautics and Space Administration) and PHOTONS (PHOtométrie pour le Traitement Opérationnel de Normalisation Satellitaire). The stations (1659 total, 578 currently active) are globally distributed and have the primary objective of measuring aerosol properties. They are equipped with Cimel Electronique Sun–sky radiometers that measure direct solar radiation under clear-sky conditions. In those conditions, most of the solar extinction stems from aerosol attenuation. By using specific wavelength bands, the influence of trace gas absorption is minimized (Giles et al., 2019). AERONET stations provide observations with an accuracy of 0.01 to 0.02 in the mid-visible wavelengths, offering three to five times lower uncertainty than satellite-based retrievals (Chin et al., 2009). Aerosol properties are observed with high temporal resolution (15 min) over a wide spectral range (340 – 1640 nm). AERONET distinguishes between three different data quality levels: Level 1.0, Level 1.5, and Level 2.0 (Smirnov et al., 2000). The first level, Level 1.0, represents unscreened data that may lack final calibration. Level 1.5 introduces automatic cloud screening and instrument anomaly quality controls. The final data level, Level 2.0, applies pre- and post-field calibration and is manually inspected for quality assurance.

2.6 Cloud modification factor

Given the significant influence of clouds on surface irradiance, it is crucial to isolate these effects in the validation procedure. This can be achieved using the cloud modification factor (CMF). The CMF describes the cloudiness above a certain location



and is defined as:

$$\text{CMF} = \frac{G_{\text{all_sky}}}{G_{\text{clear_sky}}}, \quad (1)$$

250 where $G_{\text{all_sky}}$ is the measured value under all-sky conditions and $G_{\text{clear_sky}}$ is the modelled value assuming clear-sky conditions. Theoretically, the CMF ranges from 0 to 1, where 0 denotes a completely overcast sky with zero surface solar irradiance, and 1 signifies a cloudless sky with no cloud-induced attenuation. However, in practice, the CMF can exceed 1 due to three-dimensional effects such as cloud enhancement. While both EarthCARE and CAMS derive clear-sky irradiance using atmospheric parameter values from their own products (CAPTIVATE/composite for EarthCARE and global forecasting system
255 for CAMS), BSRN does not provide information about the clear-sky irradiance. Therefore, clear-sky irradiance at the BSRN station was independently calculated using the Ineichen-Perez model (Ineichen and Perez, 2002; Richard et al., 2002). This model estimates clear-sky irradiance by leveraging the local Linke turbidity factor alongside the site's altitude and solar geometry. Although the Ineichen-Perez model yields robust estimates, it cannot capture atmospheric conditions at the exact time of the BSRN observation. Hence, an uncertainty is introduced when using this method, which can also cause the calculated
260 CMF to exceed 1. Beyond its role in quantifying cloud-induced impact on the surface radiation, the CMF also serves as a metric to categorize atmospheric conditions into different cloudiness regimes. In this study, three distinct cloudiness regimes are considered: overcast, partly cloudy, and cloud-free. Satellite overpasses are classified as cloud-free when the EarthCARE CMF equals 1 and the BSRN CMF exceeds 0.95. However, because ground-based measurements are point observations, their corresponding CMF provides a spatially limited view of the cloud field during an overpass. To address this limitation, cloud-
265 free conditions are additionally constrained using the variability index (VI) (Stein et al., 2012). The VI is computed from BSRN observations within a 60-minute window centered on the EarthCARE overpass. To filter out periods with broken cloud fields, overpasses exhibiting large irradiance fluctuations ($\text{VI}_{\text{BSRN}} > 2$) are excluded from the cloud-free category. Similarly, overpasses are classified as overcast if they meet the following joint criteria: $\text{CMF}_{\text{ECA}} < 0.4$, $\text{CMF}_{\text{BSRN}} < 0.4$, and $\text{VI}_{\text{BSRN}} < 5$. Any overpass that satisfies neither the cloud-free nor the overcast threshold is defined as partly cloudy. Despite these thresh-
270 olds, some classification uncertainty remains unavoidable, as BSRN measurements represent single point observations and the satellite's spatial resolution may fail to resolve localized, small-scale cloud features.

2.7 Collocation approach between EarthCARE and BSRN

Following the satellite's launch, EarthCARE products underwent an initial commissioning phase. In mid-August 2024, the first Level 2 datasets were released to Cal/Val teams. Consequently, this study focuses on the period from September 2024 on-
275 ward, with September marking the first full month of available Level 2 Cal/Val activities. During this time frame, EarthCARE products were primarily processed under baseline BA (ESA/JAXA, 2025a, b, c, d, e). In mid-November 2025, the subsequent baseline BC was released. However, the inherent reporting latency of BSRN results in an insufficient volume of coincident ground observations, leading to a sparse comparison. Consequently, this study will focus only on the baseline BA, covering the time period from September 2024 to November 2025.

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To compare surface GHI between EarthCARE and BSRN, the EarthCARE ACM-RT product was used (see Sect. 2.1.2), which provides along-track 1D all-sky and clear-sky irradiance over a pixel size of 1×1 km as well as 3D all-sky irradiance as an average value over the assessment domain (5×21 km). In the analysis, only data with either 0 or 1 quality index were utilized, corresponding to "good" input quality for the RTMs. GHI was calculated as the sum of surface BHI and DHI reported in ACM-RT. To validate 1D EarthCARE GHI, the collocation process began by identifying the spatially closest EarthCARE pixel to the BSRN station. Then, a 21-pixel sample (along-track length of 3D assessment domain) was created by appending the ten preceding and subsequent pixels. From this sample, the mean all-sky GHI, clear-sky GHI, and time were calculated (Fig. 3a). In this study, averaging was generally only performed for EarthCARE domains where at least 80% of the constituent data points were valid. Finally, the two temporally closest measurements from the BSRN station were linearly interpolated to this EarthCARE time stamp. To ensure temporal representativeness, a constraint was applied requiring at least one BSRN observation within a ± 1 min window of the EarthCARE timestamp. In instances where only one measurement fell within this radius, that specific value was utilized directly. In the analysis, a SZA threshold of 75° was applied to exclude twilight conditions. This filtering step is necessary for maintaining the accuracy of CMF calculations, which can become unstable at high zenith angles. For the analysis of irradiances computed by the 3D RTMs, an overpass was included if the center pixel of the assessment domain fell within a ± 10 pixel along-track radius of the EarthCARE pixel spatially closest to the BSRN station (Fig. 3b). As the 3D RTM was not configured to compute clear-sky irradiance, a representative reference was derived by spatially averaging the along-track 1D clear-sky irradiances over the corresponding 3D assessment domain. Similarly, to compare 1D with 3D irradiances, the along-track 1D all-sky irradiance was spatially averaged over the 3D assessment domain. Due to the spatiotemporal variability of the radiation field, surface GHI measurements can drastically change according to their location. Therefore, only EarthCARE overpasses with a maximum separation distance of 50 km from a BSRN station were included in the analysis. In addition to the general evaluation, the analysis focused on cases with high spatial proximity (< 25 km) where both instruments exhibited cloud-free conditions ($CMF_{ECA} = 1$, $CMF_{BSRN} > 0.95$, and $VI_{BSRN} < 2$). The combination of stationary BSRN sites and fixed satellite overpasses significantly restricts the number of available validation samples, despite the generous 50 km spatial matching limit.

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In addition to using 1D irradiances for the 1×1 km pixels under the nadir track, the SCA algorithm is used to assign 1D along-track radiative flux profiles and surface fluxes to across-track pixels, following the independent pixel approximation (IPA). When comparing 1D GHI with those from the 3D RTM, 1D GHI are averaged over each 3D assessment domain (5×21 km) (Fig. 3b). These values are subsequently validated by nearby BSRN observations within a 50 km radius of the EarthCARE overpass. The SCA algorithm also allows constructing fluxes for small domains over BSRN stations (Fig. 3c) due to the broader across-track swath width of the MSI instrument (115 km to the left of the nadir and 35 km to the right). To assess the sensitivity of the results to the spatial aggregation scale, 1×1 , 3×3 , 5×5 pixel averages centered on the BSRN station are compared. Only collocations featuring a valid EarthCARE value at the center pixel are included. While this across-track approach is a good alternative to the along-track estimates, especially due to the improved collocation, not all constructed SCA indices exhibit optimal quality. In this study, only SCA indices with quality index of either 0, 1, or 2 were selected,

315



corresponding to "good construction quality", "limited search distance due to frame edge", and "limited search distance due to large variability of solar zenith angle", respectively. The reliability of the SCA algorithm tends to decrease with increasing across-track distance from EarthCARE's nadir track (Qu et al., 2023, 2025). Therefore, this distance dependence is investigated to characterize its impact on the validation results. Beyond the GHI validation, EarthCARE's BHI and DHI estimates are
320 evaluated against corresponding BSRN observations.

In addition to the validation of SW fluxes using BSRN observations, LW surface irradiances from EarthCARE were compared with BSRN measurements. This was limited to 1D irradiances since downward 3D LW fluxes are not reported in the ACM-RT product. Consequently, the collocation approach follows the same methodology as the 1D nadir-only evaluation
325 (Fig. 3a).

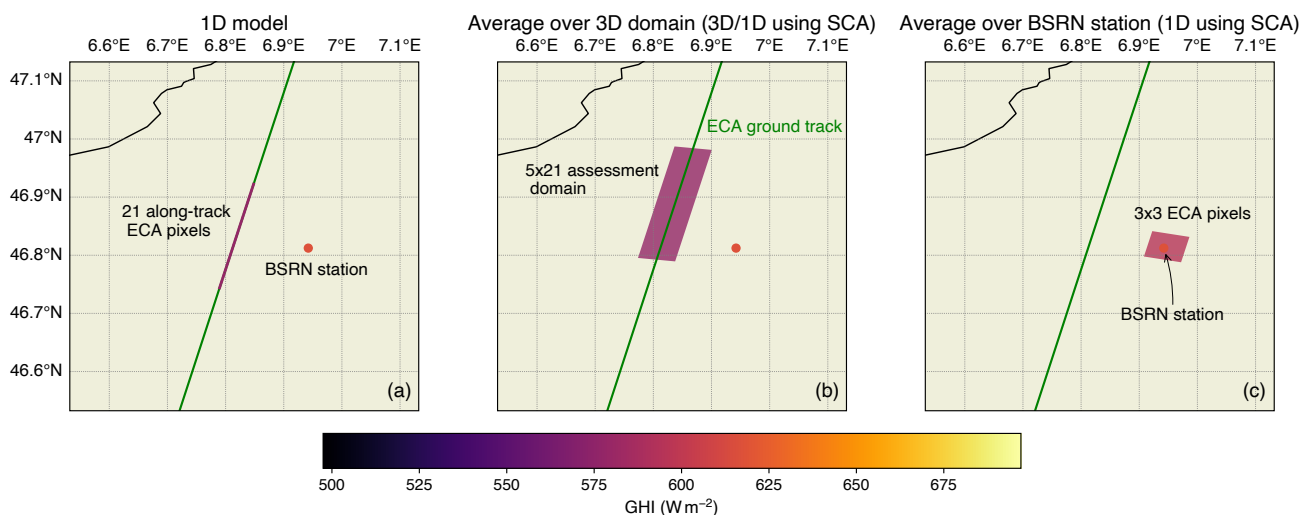


Figure 3. Collocation methodology between BSRN and EarthCARE. In this example, the BSRN station is located in Payerne, Switzerland and EarthCARE overpass 1581D on 07.09.2024 is used. Panel (a) illustrates the methodology for the 1D RTM, which is evaluated across a linear transect of 21 along-track ECA pixels. Panel (b) depicts the approach for the 3D assessment domain (5×21 km). The domain average is either computed natively by the 3D RTM or derived via 1D across-track extension using the SCA algorithm. Panel (c) represents the sampling domain for the SCA Algorithm, where a localized 3×3 ECA pixel grid is centered directly on the BSRN station.

2.8 Collocation approach between EarthCARE and CAMS

CAMS gridded solar radiation datasets are released to the public on an annual basis. At the time of writing, data for 2025 had not yet been released so the analysis is limited to the period from September to December 2024. EarthCARE orbits with descending (sunlit) frames covering the CAMS domain (see Fig. 2) were utilized, resulting in 2286 frames. While CAMS
330 data do not replace absolute ground truth, this enormous amount of collocation data and comparison possibilities are highly beneficial for assessing EarthCARE retrieval quality and detecting systematic errors in the mission products.



As noted in Sect. 2.4, CAMS radiation services provide surface GHI at a spatial resolution of $0.1^\circ \times 0.1^\circ$ latitude/longitude and a temporal resolution of 15 minutes. To compare EarthCARE irradiance products with CAMS, the analysis was again
335 partitioned into three components: a nadir-only along-track assessment utilizing the 1D ACM-RT RTM, an assessment of the 3D RTM based on a weighted-average approach, and an expanded evaluation incorporating across-track 1D irradiance values derived from the SCA algorithm. For the along- and across-track 1D assessments, all EarthCARE measurements within a given CAMS cell were averaged. In the nadir-only analysis, the EarthCARE pixels form a narrow (1 km) transect through the CAMS cell ($\sim 10 \times 10$ km) (Fig. 4a). Conversely, the SCA-based analysis populates the entire CAMS cell with pixels, offering superior spatial representativeness. While the nadir-restricted assessment was confined to CAMS cells directly intersected by the
340 satellite ground track, the SCA evaluation incorporates all EarthCARE pixels within a 15 km across-track radius (Fig. 4c). This expansion, aligning with the computational domain used in EarthCARE's 3D RTM, effectively triples the number of sampled CAMS cells. To compare CAMS irradiance with three-dimensional GHI from EarthCARE, a weighted-average approach was implemented. The weights are assigned based on the number of EarthCARE pixels within each CAMS cell that intersects the
345 5×21 km 3D assessment domain (Fig. 4b). In all three assessments, the two temporally closest CAMS measurements were linearly interpolated to the mean EarthCARE timestamp. In alignment with the BSRN comparison, an SZA limit of 75° was applied which also excludes McCloud retrievals that are inaccurate due to pixel distortion of the geostationary satellite imager.

To assess the sensitivity of the results to different averaging scales, EarthCARE and CAMS fluxes were spatially averaged
350 along-track over 100 km (1/500 frame), 500 km (1/10 frame), and 2500 km (1/2 frame). Given the orbital velocity of EarthCARE, these time lengths correspond to temporal scales of 14 s, 70 s, and 350 s, respectively. In addition, CMFs from both datasets were compared to characterize the difference in retrieved cloudiness from McCloud and ACM-RT. The data were subsequently categorized into different cloudiness regimes to identify the conditions under which the largest discrepancies occur. Furthermore, clear-sky irradiances of both datasets were compared, and the spatial distributions of all-sky, cloud-induced, and
355 clear-sky differences were evaluated. To obtain a cloud-induced GHI value, the CMFs of both datasets were multiplied by the clear-sky irradiance of CAMS.

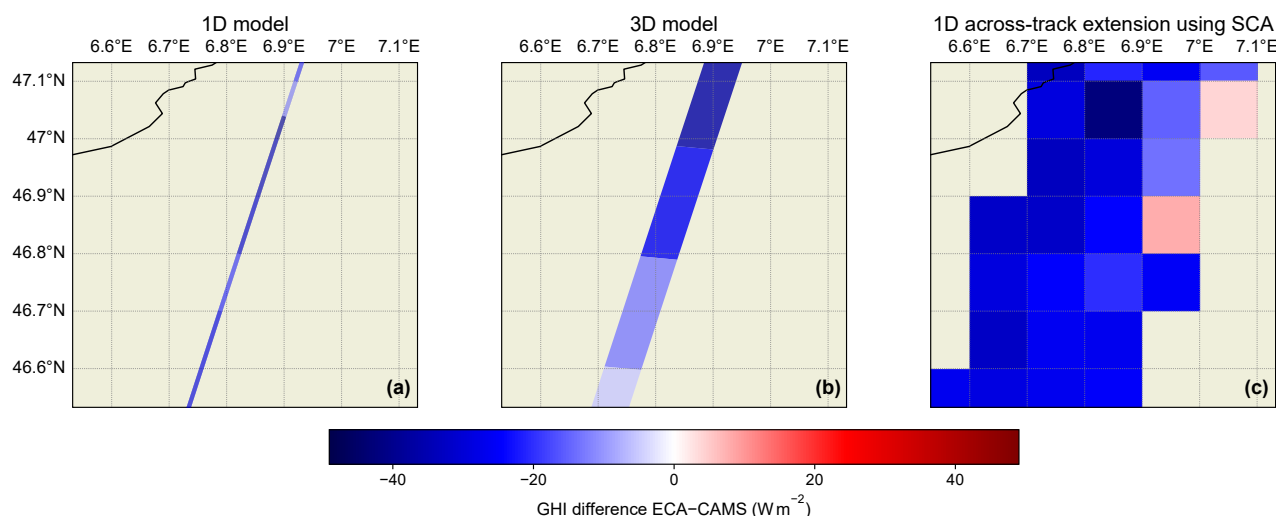


Figure 4. Collocation methodology between CAMS and EarthCARE. In this example, EarthCARE overpass 1581D on 07.09.2024 is used, passing through Switzerland. Panel (a) illustrates the methodology for the along-track 1D RTM, which is averaged over each CAMS cell. Panel (b) depicts the approach for the 3D RTM, where CAMS values are collocated with the EarthCARE assessment domain based on a weighted-average approach. Panel (c) represents the methodology utilizing the SCA Algorithm, in which EarthCARE 1D results are spatially averaged to the resolution of the CAMS grid and compared with their corresponding CAMS cells.

Complementing the dual-dataset evaluations, a comparison of all three datasets was conducted. This comparison utilizes precise, ground-based BSRN observations to identify which satellite-based surface GHI estimation is more accurate. Due to the CAMS data availability, this assessment is restricted to the period of September-December 2024. The analysis employed the same EarthCARE overpasses as in the CAMS-only evaluation. Twenty ground stations are within this CAMS domain (see Fig. 2 and 1). Ground-based observations were included if the station was within a 50 km radius of the EarthCARE overpass. EarthCARE values were derived using the 1D across-track extension methodology established in the EarthCARE–CAMS comparison (Fig. 4c). To ensure a fair comparison, EarthCARE pixels were spatially aggregated over the CAMS cell encompassing the BSRN station, rather than directly collocated with BSRN.

365

In addition to the evaluation of downwelling surface GHI from EarthCARE, discrepancies observed at the surface (relative to BSRN/CAMS) were compared with upwelling radiative flux differences at the TOA, validated against internal BBR observations. The TOA radiative flux differences offer a complementary boundary perspective, providing helpful diagnostic context about potential surface irradiance differences. In this assessment, EarthCARE's 1D and 3D RTM results were separately analyzed over the assessment domain, utilizing their corresponding averaged surface downwelling and TOA upwelling fluxes. The combined flux from the three BBR views served as the benchmark, with data retained only if the quality index was zero or one. These values correspond to "good quality input of both ACM-RT and BMA-FLX" and "potentially reduced status for ACM-RT or BMA-FLX", respectively (ESA/JAXA, 2025b). Results were categorized into different cloud phases using the ice

370



and liquid effective radii in the ACM-COM product. Profiles were assigned to a given phase if at least one vertical layer exhibited a corresponding effective radius greater than zero. Profiles containing both liquid and ice components were designated as mixed. Data points with an EarthCARE CMF exceeding 0.8 were filtered as cloud-free.

2.9 Comparative analysis of EarthCARE AOD retrieval

Given that AOD is a primary factor in clear-sky irradiance modelling, a comparison of the AOD inputs between EarthCARE and CAMS is crucial for gaining insight into potential irradiance differences. In case of EarthCARE, both the CAPTIVATE and composite algorithm products (see Sect. 2.1.1) were used for the assessment, and their differences were evaluated. To ensure the reliability of the comparison, EarthCARE AOD retrieval was filtered to include only data points designated as "good" (quality index of zero) according to the quality assurance of its product. The collocation methodology is consistent with the surface GHI intercomparison of EarthCARE and CAMS utilizing the SCA algorithm (Sect. 2.8). The primary deviations are the coarsened resolutions: the temporal window is one hour (instead of 15 minutes) and the spatial resolution is $0.4^\circ \times 0.4^\circ$ (instead of $0.1^\circ \times 0.1^\circ$). CAMS forecasting services provide global AOD values, including retrievals over the ocean. Therefore, to maintain an identical spatial and temporal sample across both the surface GHI and AOD comparison, the AOD analysis is restricted to cells which are provided in the CAMS radiation services dataset. For the same reason, the exact EarthCARE frames and orbits employed in the surface GHI comparison were utilized in this analysis. Consequently, only orbits from September to December 2024 were studied. In addition, the SZA was again limited to a maximum of 75° .

To identify which of the two satellite-based retrievals more accurately represents the physical reality, high-resolution ground-based measurements from AERONET were used. AERONET stations provide AOD across a wide spectral range. For the validation of the EarthCARE AOD product, the AERONET channel at 340 nm was utilized due to its close spectral proximity to the ATLID wavelength of 355 nm. To account for the spectral shift between those two wavelengths, the AERONET measurements were adjusted using the Angstrom power law:

$$\tau_{\lambda_{355}} = \tau_{\lambda_{340}} \left(\frac{355 \text{ nm}}{340 \text{ nm}} \right)^{-\alpha}, \quad (2)$$

where $\tau_{\lambda_{355}}$ represents the desired AOD at 355 nm, $\tau_{\lambda_{340}}$ denotes the observed AERONET AOD at 340 nm, and α signifies the Angstrom exponent. For this AOD extrapolation, the AERONET Angstrom exponent from 340 nm to 440 nm was used. In the analysis, AERONET Level 2.0 data were utilized. The collocation methodology with AERONET is similar to the procedure introduced in the BSRN comparison (see Sect. 2.7). AERONET observations were used if the EarthCARE overpass was within a radius of 50 km. Due to AERONET AOD observations typically exhibiting lower frequency, more frequent data gaps and less variability compared to BSRN surface GHI measurements, a maximum window of ± 2 hours around the overpass was applied. If data were available on only one side of the overpass within this window, the temporally closest value was selected. If measurements existed both before and after the overpass, the temporally closest value on each side was selected to linearly interpolate the AERONET AOD to the exact time of the overpass. To ensure a consistent comparison between the two satellite-based datasets, EarthCARE pixels are collocated with the CAMS cell rather than the AERONET station. AERONET stations



that are located in the CAMS domain and do not exhibit significant Level 2.0 data gaps in the months from September to December 2024 were selected, resulting in 19 stations. Their geographic distribution is shown in Figure 5. A summary of the stations can be found in Appendix B (Tab. B1).

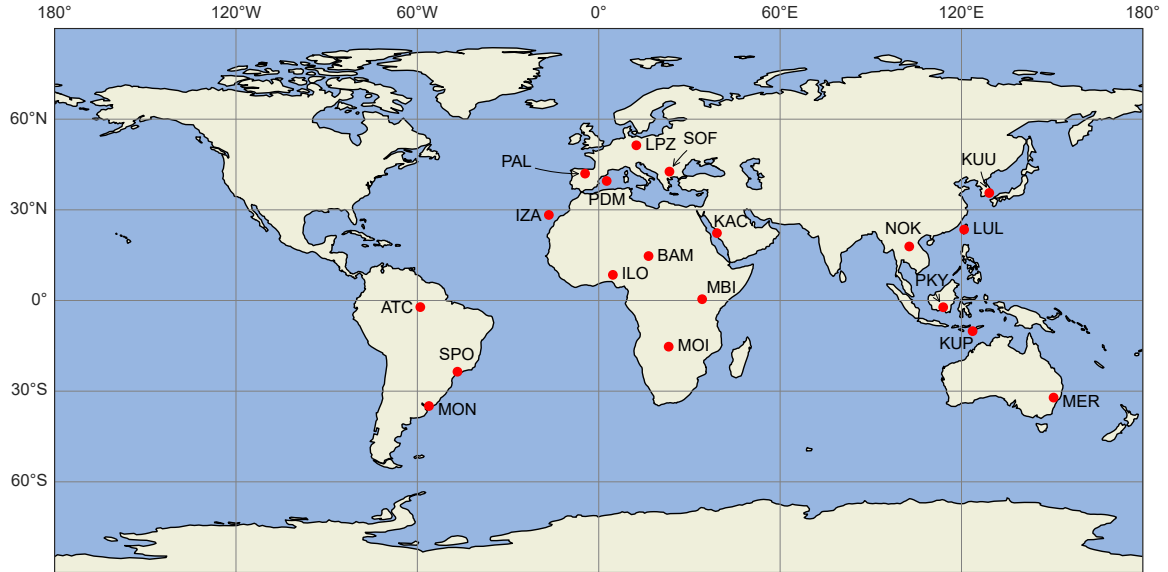


Figure 5. Map of the 19 AERONET stations used in the analysis.

410 2.10 Evaluation metrics

To quantitatively estimate the accuracy and uncertainty of EarthCARE’s radiative flux products, the MBE and the RMSE were utilized as the primary performance metrics. Their respective definitions, as well as their corresponding relative metrics (rMBE and rRMSE) are provided in Eqs. (3), (4), (5), and (6), where N denotes the sample size, P_i represents the predicted value (in this study mainly by EarthCARE), and O_i signifies the observed value from the validation datasets.

$$415 \quad \text{MBE} = \frac{1}{N} \sum_{i=1}^N (P_i - O_i) \quad (3)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^N (P_i - O_i)^2}{N}} \quad (4)$$

$$\text{rMBE} = \frac{\text{MBE}}{\frac{1}{N} \sum_{i=1}^N O_i} \quad (5)$$



$$\text{rRMSE} = \frac{\text{RMSE}}{\frac{1}{N} \sum_{i=1}^N O_i} \quad (6)$$

3 Results

420 3.1 EarthCARE surface irradiance validation against BSRN

3.1.1 Solar irradiance

As a first step in the validation of EarthCARE's surface irradiance products, 1D along-track ACM-RT surface GHI is benchmarked against BSRN observations (Fig. 6). In general, BSRN measured slightly higher irradiance than EarthCARE, with an MBE of -13.9 W m^{-2} and a rMBE of -2.7% . The RMSE exhibits a high value with 162.5 W m^{-2} (31.0 %), reflecting the

425 challenges in comparing the two data sets due to the spatiotemporal variability of the radiation field, especially in the case of cloud presence. The data are then classified according to cloud regime, with the regime performance metrics shown in Table 1. Under partly cloudy conditions, substantial discrepancies can occur ($\text{RMSE} = 173.5 \text{ W m}^{-2}$). Overcast cases also exhibit high discrepancies, particularly in relation to the mean BSRN GHI ($\text{rRMSE} = 72.0 \%$). Under these two conditions, the spatiotemporal distance between the measurements plays a major role. While lowering the maximum spatial distance threshold could

430 mitigate these artifacts, it would simultaneously reduce the sample size, decreasing the quality of the comparison. Furthermore, during partly cloudy conditions, the uncertainty in the comparison increases drastically. Under these conditions, even a strict distance threshold may fail to exclude data points with extreme GHI differences. This is further evidenced by the distance dependence of the GHI differences (Fig. 6c). Even for distances below 5 km, differences up to 400 W m^{-2} can occur under partly cloudy conditions. Such extreme GHI deviations cannot be primarily attributed to potential discrepancies in the Earth-

435 CARE algorithm, but are instead artifacts of high spatiotemporal variability and fluctuating sun visibility at the BSRN station (e.g. Kazadzis et al., 2009; Carpentieri et al., 2023; Papachristopoulou et al., 2024). Figure 6d illustrates the variation of GHI difference categorized into five distinct distance bins. At smaller distances, the GHI difference between EarthCARE and BSRN varies less, establishing once again that significant discrepancies are primarily driven by the spatiotemporal variability of the radiation field, rather than systematic biases between the sources. Across all bins, the median difference remains consistently

440 negative, indicating a systematic EarthCARE GHI underestimation regardless of the distance to the BSRN station. To further investigate the differences in cloud estimation, the CMF is utilized (Fig. 6b). Overall, BSRN stations retrieve slightly higher CMF than EarthCARE ($\text{MBE} = -0.027$). EarthCARE's CMF is capped at 1 due to the one-dimensional RTM used in this comparison. On the other hand, the CMF of BSRN regularly exceeds 1, with the highest values being around 1.3. Many data points are in a regime where both systems classify the conditions as cloud-free. There exist also data points with high BSRN CMF

445 (> 1.2) and moderate EarthCARE CMF (around 0.6). These points likely stem from cloud enhancement, a three-dimensional radiative process which the 1D RTM used in EarthCARE is not able to capture. Furthermore, significant scatter is observed where EarthCARE identifies clear-sky conditions while BSRN detects cloud cover. These cases were detected under partly



cloudy conditions, leading to significant differences in CMF. BSRN stations also exhibit an unusually high number of data points slightly above 1. These results suggest that the Ineichen-Perez model overestimates atmospheric attenuation, leading to a decreased clear-sky irradiance. As a result, the actual CMF MBE might be closer to zero, if not positive.

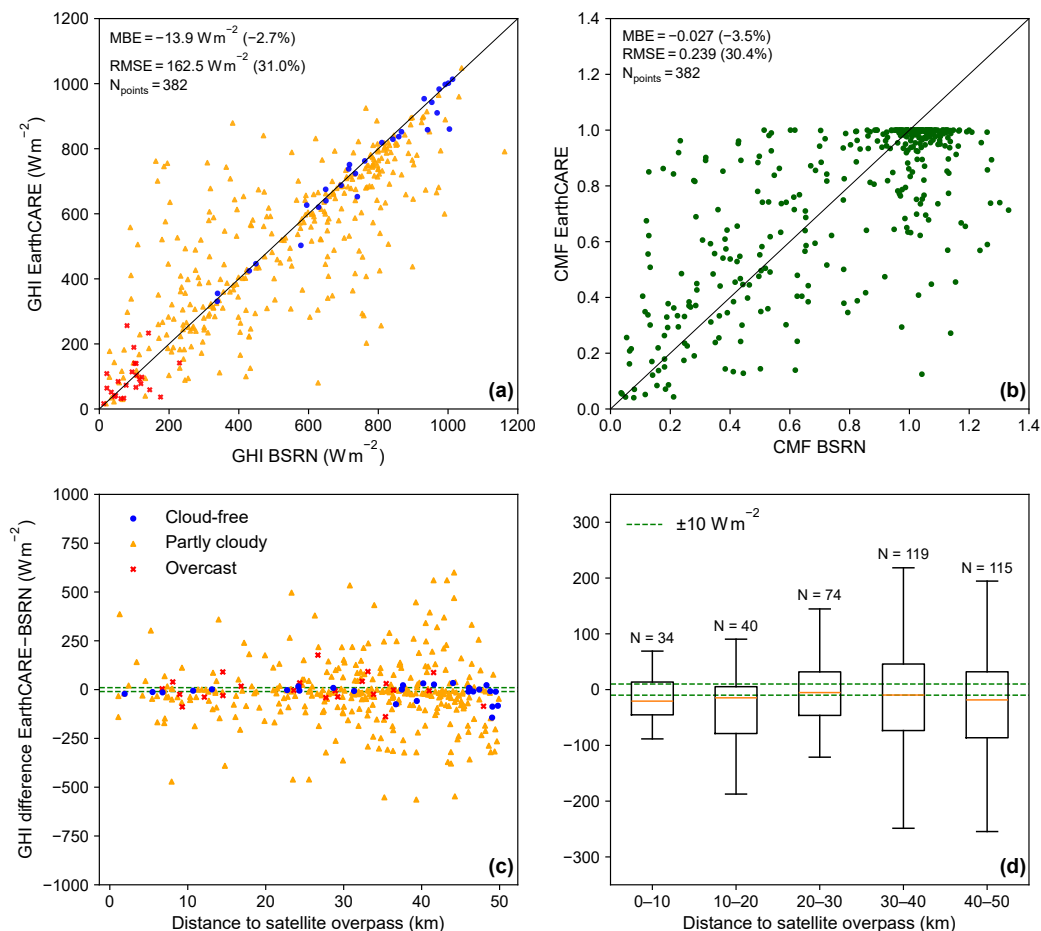


Figure 6. Validation of the 1D along-track ACM-RT surface irradiance product against BSRN observations. Panels (a) and (b) illustrate the GHI and CMF comparison, respectively. Panels (c) and (d) display the dependence on the distance. Two green lines depict EarthCARE's desired radiative closure agreement of $\pm 10 \text{ W m}^{-2}$ with the BBR. In panels (a) and (c), data points are classified according to their cloud regime (see Sect. 2.6).



Table 1. Performance metrics of EarthCARE GHI relative to BSRN for different cloud regimes.

Condition	MBE (W m^{-2})	rMBE (%)	RMSE (W m^{-2})	rRMSE (%)
Cloud-free	−13.5	−1.8	42.2	5.6
Partly cloudy	−15.2	−2.9	173.5	32.4
Overcast	4.6	5.0	65.5	72.0

To improve the spatial collocation with the BSRN stations, EarthCARE’s 1D across-track extension ACMB-3D is utilized (Fig. 7). While significant irradiance differences persist for individual overpasses, the RMSE exhibits a notable decrease compared to the along-track assessment. Especially for increased spatial aggregation scales, the RMSE is significantly lower than before. This trend suggests that evaluating EarthCARE pixels ($\sim 1 \times 1 \text{ km}$) in isolation is inherently prone to localized noise.

455 By averaging over a larger domain, these surface GHI discrepancies are reduced. For all spatial aggregation scales, the MBE is negative with values around -10 W m^{-2} . Therefore, EarthCARE values derived from the SCA algorithm slightly underestimate surface GHI relative to BSRN. EarthCARE estimates under cloud-free conditions exhibit again a negative MBE (-17.4 W m^{-2} , -17.9 W m^{-2} , and -14.1 W m^{-2} for 1×1 , 3×3 , and 5×5 pixel averages, respectively). Furthermore, the distance dependence of GHI differences (Fig.7d, e, f) confirms that the combined effects of retrieval and SCA on computed 1D
460 irradiances are smallest when in close proximity to EarthCARE’s nadir ground track.

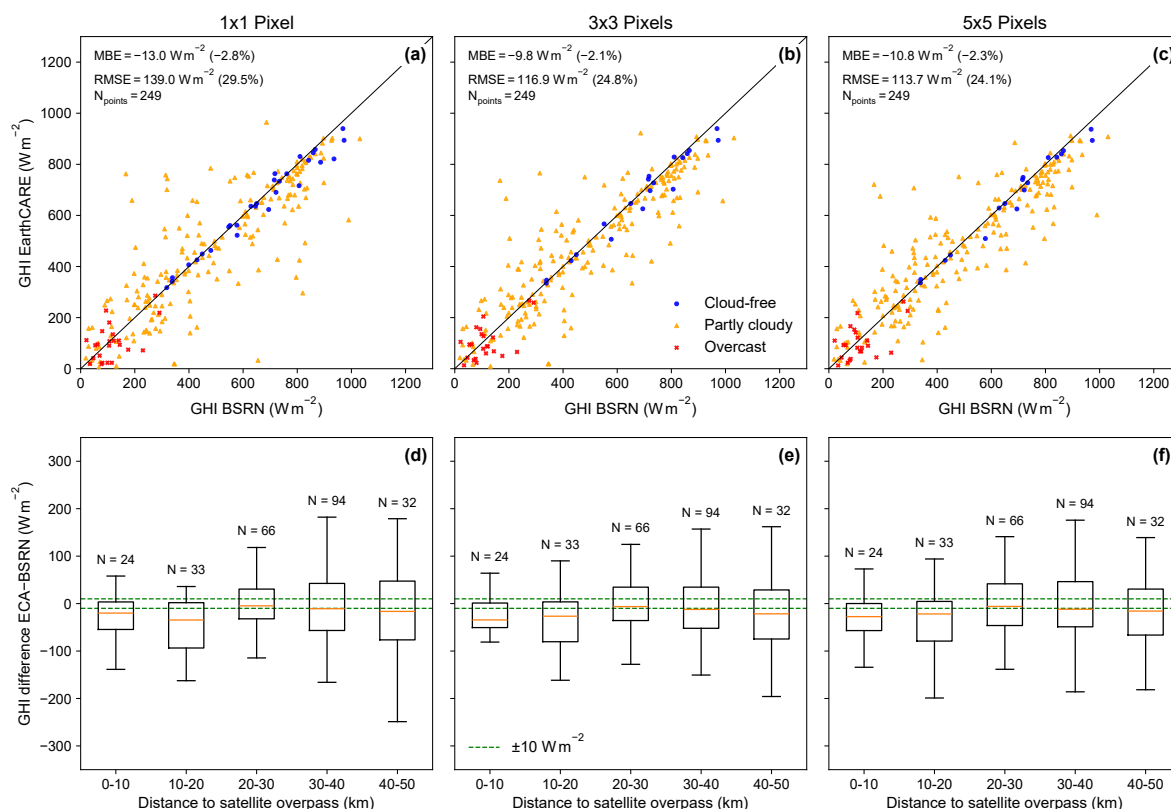


Figure 7. Validation of EarthCARE across-track surface irradiance (derived from ACMB-3D indices) against BSRN observations. Panels (a), (b), and (c) illustrate the GHI comparison for 1×1 , 3×3 , and 5×5 pixel averages, respectively. Data points are classified according to their cloud regime. Panels (d), (e), and (f) present boxplots of GHI differences as a function of distance to the satellite overpass.

Figure 8a illustrates that EarthCARE's 3D RTM exhibits significant GHI discrepancies relative to BSRN under all-sky conditions ($\text{RMSE} = 168.4 \text{ W m}^{-2}$, $\text{rRMSE} = 33.7\%$). This discrepancy is largely attributable to the suboptimal spatial collocation, with the 3D assessment domain across-track length (5 km) being significantly narrower than the 50 km distance threshold set in the analysis. The MBE is rather close to zero (-4.6 W m^{-2}). Taking the other two methodologies into account (1D RTM along-track average and across-track extension), the 3D RTM produces the highest RMSE while displaying the lowest negative MBE. Theoretically, EarthCARE's 3D RTM should yield closer agreement with BSRN observations than the 1D RTM due to the inherent 3D nature of ground-based measurements. However, the larger RMSE contradicts this expectation. This discrepancy most likely stems from the spatial averaging of the EarthCARE 3D simulations over a $5 \times 21 \text{ km}$ domain, contrasted with the single-point nature of the BSRN measurements. For instance, localized cloud enhancement that elevates surface GHI at the BSRN station may be smoothed out across the wider EarthCARE domain by adjacent cloud shadows. Consequently, despite the 3D nature of ground-based observations, a superior performance from the 3D RTM over the 1D RTM is not guaranteed. Although it has the lowest GHI MBE, the 3D RTM significantly overestimates DHI ($\text{MBE} = 47.1 \text{ W m}^{-2}$) and underestimates



BHI ($\text{MBE} = -51.4 \text{ W m}^{-2}$), leading to the near-zero global bias. This suggests either a mismatch between the direct/diffuse definition of BSRN (pyrheliometer) and EarthCARE's 3D RTM or a systematic error within the 3D algorithm, as both the 1D RTM along-track average and its extension over the assessment domain (using the SCA algorithm) do not produce such significant deviations from the BSRN observations despite having the same cloud and aerosol retrievals as input. To minimize the artifacts related to spatial collocation, broken cloud fields, and sun visibility over the BSRN station, a subset of the data is analyzed including only overpasses with cloud-free conditions ($\text{CMF}_{\text{ECA}} = 1$, $\text{CMF}_{\text{BSRN}} > 0.95$, and $\text{VI}_{\text{BSRN}} < 2$) and distances below 25 km from the ground site (Fig. 8d,e,f). The GHI RMSE (Fig. 8d) decreases substantially for all three methods, dropping from approximately 33 % in all-sky conditions to below 3 % in this subset. This showcases the significantly enhanced validation quality attainable under stable, cloud-free conditions, particularly when supported by strong spatial collocation due to the close proximity of the stations to the overpass. The GHI MBE is close to zero, with the along-track 1D RTM and its across-track extension slightly underestimating surface GHI by -4.9 W m^{-2} , while the 3D RTM slightly overestimates it by 6.5 W m^{-2} . While these results suggest that EarthCARE performs well under cloud-free conditions when evaluated over the assessment domain against BSRN, the statistical significance of these findings remains limited by the small sample size of 7.

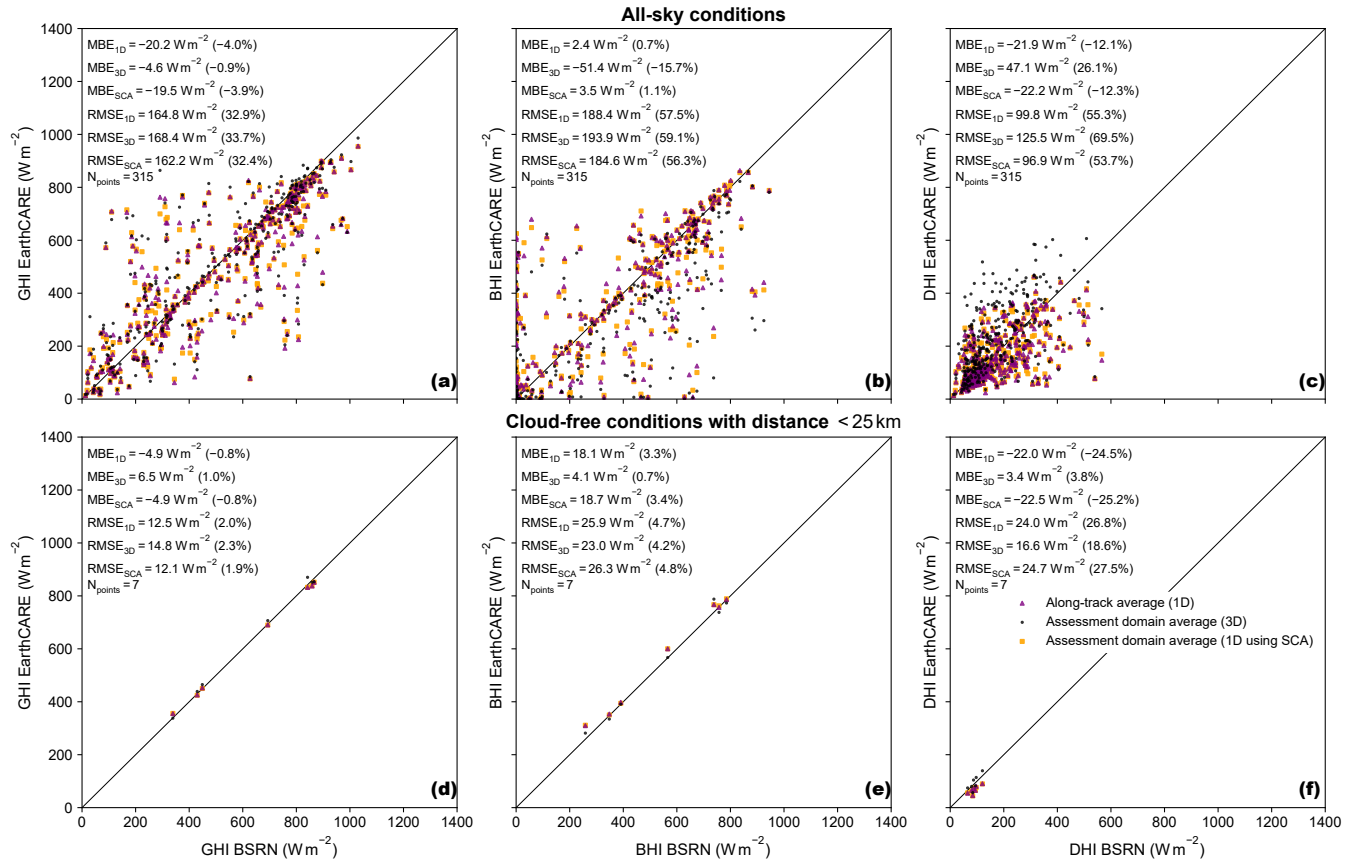


Figure 8. Intercomparison of surface GHI, BHI, and DHI derived from EarthCARE's 1D (along-track average and across-track extension using the SCA algorithm) and 3D RTMs against BSRN ground observations. Panels (a), (b), and (c) illustrate the respective comparisons under all-sky conditions, while panels (d), (e), and (f) present overpasses with cloud-free conditions ($CMF_{ECA} = 1$, $CMF_{BSRN} > 0.95$, and $VI_{BSRN} < 2$) and distances below 25 km from the ground site.

3.1.2 Thermal irradiance

Figure 9 demonstrates that LW irradiance differences between EarthCARE's 1D RTM and BSRN exhibit significantly lower values in the performance metrics ($MBE = -4.1 \text{ W m}^{-2}$ and $RMSE = 34.9 \text{ W m}^{-2}$) than in the SW regime. This improvement is also reflected in the relative metrics, with the rMBE and rRMSE being reduced to -1.2% and 10.0% , respectively. This diminished variance stems from the different physical behaviour of clouds in the thermal spectrum. In this regime, clouds increase the surface radiation by absorbing the emitted upward radiation from the earth and returning part of it isotropically. As a result, surface LW irradiance is characterized by lower spatiotemporal variability in response to cloud cover compared to SW irradiance, leading to diminished variance in the BSRN validation. This inherent stability is further evidenced by the distance dependence of LW discrepancies (Fig. 9b), where deviations at large spatial separations remain comparable to those observed in close proximity to the BSRN station. The results indicate that EarthCARE and BSRN maintain relatively high



agreement in the thermal regime, even under partly cloudy conditions. This contrast to the SW validation arises because the direct component, which represents the primary portion of SW radiation, decreases exponentially with cloud optical thickness according to the Lambert-Beer law. Consequently, the SW signal is dominated by this attenuation, whereas LW variance is primarily governed by temperature fluctuations rather than cloud geometry.

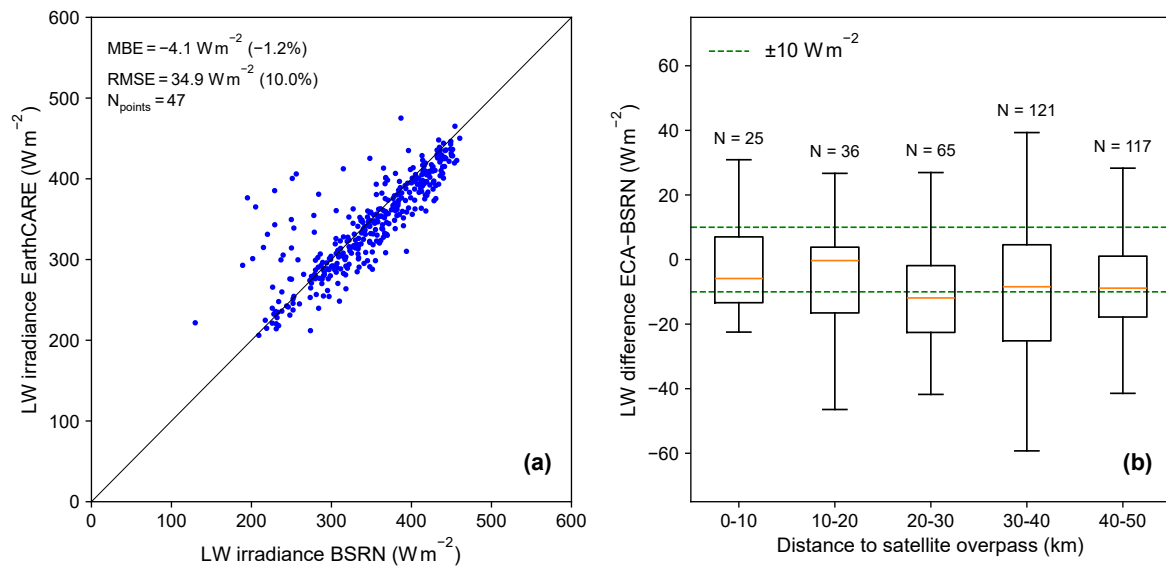


Figure 9. Validation of ACM-RT 1D LW surface irradiance against BSRN observations. Panel (a) illustrates the comparison of their respective irradiances, while panel (b) displays the dependence on the distance.

500 3.2 Surface solar irradiance intercomparison against CAMS radiation services

By evaluating EarthCARE surface GHI measurements against CAMS, the amount of comparison points increases drastically. However, it should be noted that CAMS itself produces satellite-based GHI estimates, which can introduce uncertainties. Consequently, we utilized CAMS not for a direct definitive evaluation, but as a secondary dataset to leverage its superior spatial coverage for identifying EarthCARE's spatiotemporal features. Nonetheless, CAMS radiation services are a well-established resource which has long provided surface GHI, constantly validating and improving their models through evaluation with ground-based measurements (Lefèvre, 2024). Therefore, benchmarking EarthCARE observations against these models remains highly valuable.

Table 2 displays the resulting performance metrics of the three different EarthCARE methodologies relative to CAMS. Their corresponding density distributions can be found in Appendix C (Fig. C4). The 3D RTM achieves the lowest rRMSE (16.5 %), which may be attributed to the larger along-track averaging window (21 km vs. ~ 11 km). Furthermore, the 3D model's MBE (-7.6 W m^{-2}) represents a significant improvement over the other two methodologies. Notably, when considering the docu-



mented positive bias of CAMS against ground-based observations (8.2 W m^{-2} , Lefèvre, 2024), these results suggest that the EarthCARE 3D RTM operates with a nearly negligible absolute GHI bias. However, this result stems from mutually offsetting errors in the direct and diffuse irradiance (see Fig. C1, C2, and C3). EarthCARE's 1D RTM produces results with a larger negative bias, indicating a systematic underestimation of GHI. While the 3D RTM yields the lowest relative RMSE, the 1D across-track extension achieves the lowest absolute RMSE, reflecting the 3D model's strength in high-irradiance conditions versus the overall consistency of the 1D across-track extension. In addition, the ability of the across-track extension to minimize RMSE across a significantly larger sample size than the other two methodologies suggests superior reliability in its collocation with CAMS. As CAMS' McCloud and McClear models utilize 1D RTMs, EarthCARE's 1D RTM is expected to give more comparable results than its 3D counterpart. Given this consistency and the 1D model's superior agreement with the validation datasets in terms of direct/diffuse irradiance, the subsequent analysis focuses exclusively on results from the 1D across-track extension. The corresponding partition into direct/diffuse irradiance can be found in Appendix C (Fig. C5).

Figure C4 illustrates a trend in which EarthCARE estimates irradiances below 100 W m^{-2} while CAMS retrieves higher values. These cases primarily originate from assessment domains at higher latitudes, where absolute irradiance levels are inherently lower. At these latitudes, the geostationary satellites providing cloud information to CAMS operate at the edges of their field of view. Consequently, they encounter geometric and radiometric challenges such as pixel distortion and increased optical path lengths (Papachristopoulou et al., 2024 and references therein). This leads to an uncertainty in the GHI estimation, likely explaining the observed discrepancy with EarthCARE.

Table 2. Performance metrics of EarthCARE GHI relative to CAMS using different methodologies.

Methodology	MBE (W m^{-2})	rMBE (%)	RMSE (W m^{-2})	rRMSE (%)	N_{points}
1D RTM	−21.5	−3.9	102.8	18.7	378'352
3D RTM	−7.6	−1.4	91.3	16.5	149'431
1D across-track extension using SCA	−20.1	−3.9	88.4	17.0	805'439

To evaluate cloud-induced impacts on the validation, the CMF was calculated. The corresponding relationship between EarthCARE and CAMS (Fig. 10) displays a substantial amount of data points at CMFs of 1, where both EarthCARE and CAMS detect clear-sky conditions (approximately 15 % of the sample). A divergent trend is also observed, characterized by EarthCARE retrieving CMF values near zero while CAMS estimates remain higher. This trend suggests discrepancies in the detection of optically thick cloud layers. While EarthCARE likely detects these optically thick cloud layers, observations from geostationary satellites are susceptible to subpixel inhomogeneity and insufficient spatial resolution, leading to an underestimation of optical thickness. The overall MBE of the CMF differences is -0.024 (-3.0%), indicating that CAMS systematically estimates higher CMF values than EarthCARE. Physically, this implies that CAMS predicts less cloud cover or lower cloud optical thickness than EarthCARE. This discrepancy is a primary driver of the GHI bias ($\text{MBE} = -20.1 \text{ W m}^{-2}$). By using CAMS



540 clear-sky irradiance as a baseline to calculate EarthCARE all-sky GHI (weighted by EarthCARE's CMF), the cloud-induced MBE component is isolated at -13.1 W m^{-2} , accounting for 65 % of the total GHI MBE.

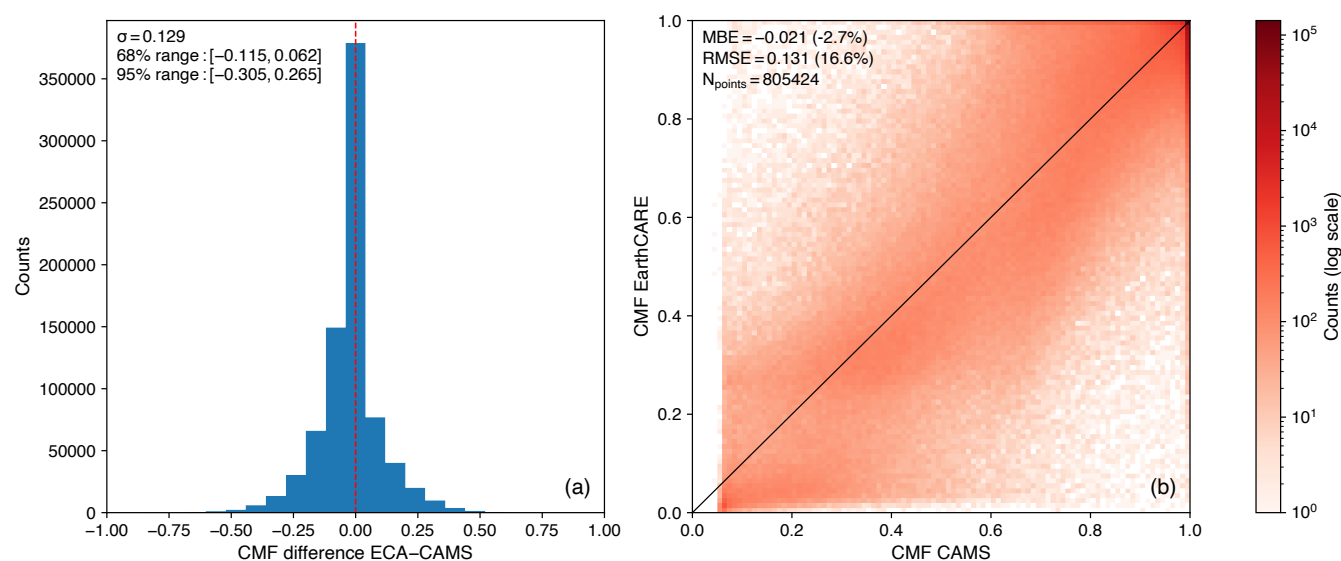


Figure 10. Comparison of CMF derived from the EarthCARE SCA algorithm and CAMS. Panel (a) presents the 1D histogram of CMF differences, while panel (b) displays the corresponding 2D scatter density distribution. The color bar in panel (b) utilizes a logarithmic count scale.

Figure 11 illustrates the GHI MBE and RMSE for different cloudiness regimes. The RMSE reaches its peak under partly cloudy conditions (CMF 0.4-0.8), showcasing the difficulty in collocating the two datasets when spatial heterogeneity is high. The smallest RMSE is found under clear-sky conditions, where the role of clouds is negligible. This is likely due to the fundamentally different physical principles underlying the cloud retrieval algorithms used by the two satellite sensors. The MBE exhibits a negative trend, transitioning from positive values under overcast conditions ($\text{CMF} \leq 0.2$) to negative values as the sky clears. This trend is likely a statistical artifact of the CMF boundaries under conditions of high random noise: because collocation difficulties and fundamentally different measurement techniques introduce significant random variation between the datasets when clouds are present, the probability of EarthCARE recording a higher value is statistically greater for low CAMS CMF bins, while the opposite is true at the high end of the scale. Under partly cloudy conditions, EarthCARE seems to encounter either more extensive cloud cover than CAMS or higher cloud optical thickness, resulting in the negative MBE. Similar to the BSRN validation results, the MBE of the 1D RTM under cloud-free conditions (both CMFs = 1) is slightly negative (-5.5 W m^{-2} , -0.8%).

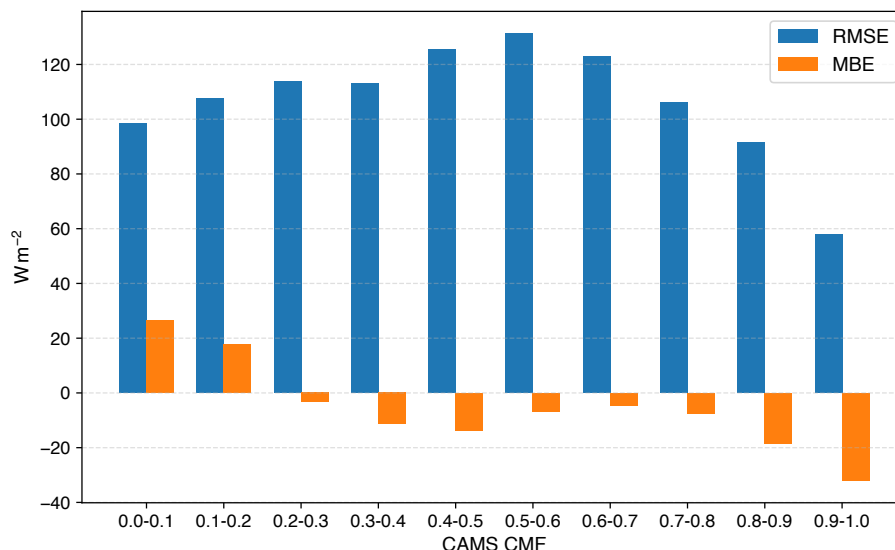


Figure 11. MBE and RMSE of EarthCARE–CAMS GHI difference in ten CMF bins, representing various cloudiness regimes. The data was classified according to CMF estimated by CAMS. Blue bars represent the RMSE, while orange bars indicate the corresponding MBE.

So far, the comparison with CAMS has been focused on cloud-related effects and their impact on the radiation. However, different estimations of the clear-sky irradiance can also result in discrepancies between the corresponding all-sky GHI. Consequently, the clear-sky components of both datasets were evaluated. As shown in Figure 12b, the RMSE decreases under these conditions, reaching a value of 30.4 W m^{-2} (4.7 %). This can be attributed to the inherently low variance of the radiation field in this regime, allowing for a better comparison quality between the two datasets. A slight negative MBE of -6.5 W m^{-2} (–1.0 %) persists. The 1D histogram (Fig. 12a) shows a distribution peak between -30 W m^{-2} and 0 W m^{-2} , with only 28% of comparison points exhibiting positive differences. These instances, where EarthCARE’s clear-sky irradiance exceeds that of CAMS, lead to more pronounced discrepancies. Quantifying these effects reveals that clear-sky irradiance bias accounts for approximately 35 % of the total all-sky MBE, while the remaining 65 % originates from the previously discussed cloud-induced effects. Although the observed MBE is negative, the significant cloud-free bias of 21.5 W m^{-2} (3.0 %) identified in CAMS’s internal validation (Lefèvre, 2024) suggests that the true EarthCARE MBE may be near zero or potentially positive.

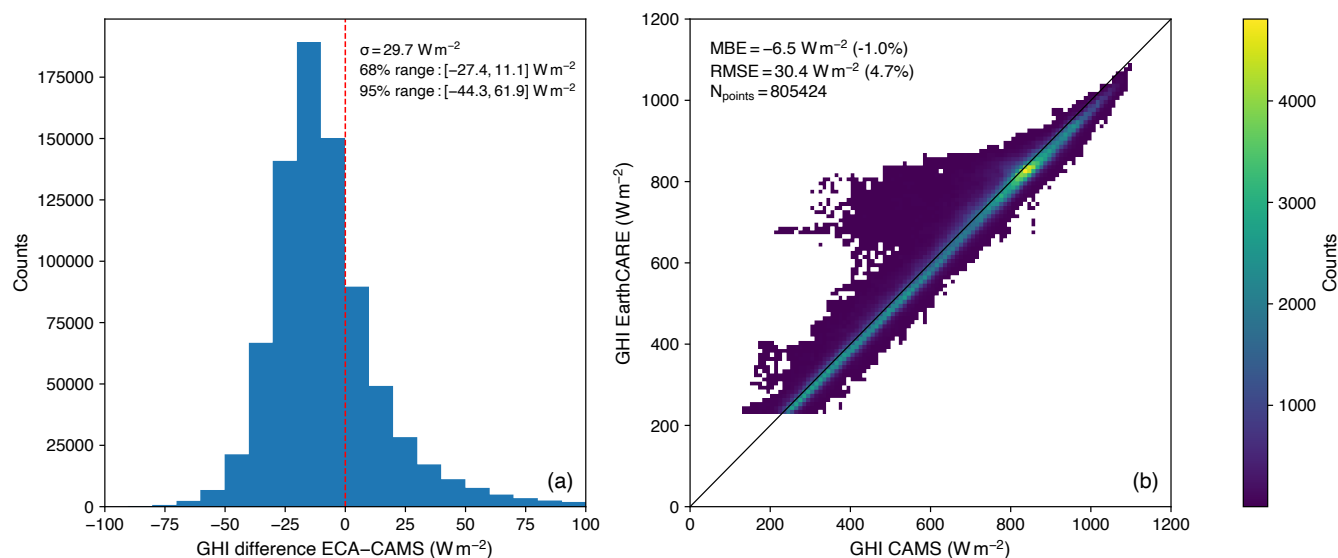


Figure 12. Comparison between EarthCARE and CAMS clear-sky irradiance. Panel (a) presents the 1D histogram of CMF differences, while panel (b) displays the corresponding 2D scatter density distribution.

565 While evaluating EarthCARE measurements over single CAMS grid cells (~ 10 km) is essential for product validation, as-
 sessments over larger spatiotemporal scales are equally vital for a wide range of communities (e.g. atmospheric science, solar
 energy). Consequently, the sensitivity of the results according to different averaging scales is illustrated in Figure 13. Averaging
 over larger spatial scales smoothens the effects of clouds and aerosols, leading to less variability as seen in the reduced RMSE.
 While small-scale comparisons are susceptible to stochastic noise and sub-grid resolution differences between the respective
 570 instruments, these localized discrepancies effectively cancel out as the averaging window increases to 1/2 frame (~ 2500 km).
 In addition, the coarser resolution of CAMS, which relies on geostationary satellite data, may fail to fully resolve the intricate
 structure of broken cloud fields, further contributing to small-scale divergence. In contrast, the MBE remains scale-invariant
 and approximately constant across all resolutions. This stability confirms that the discrepancy between EarthCARE and CAMS
 surface GHI estimates is not a stochastic artifact, but rather a systematic difference between the sources.

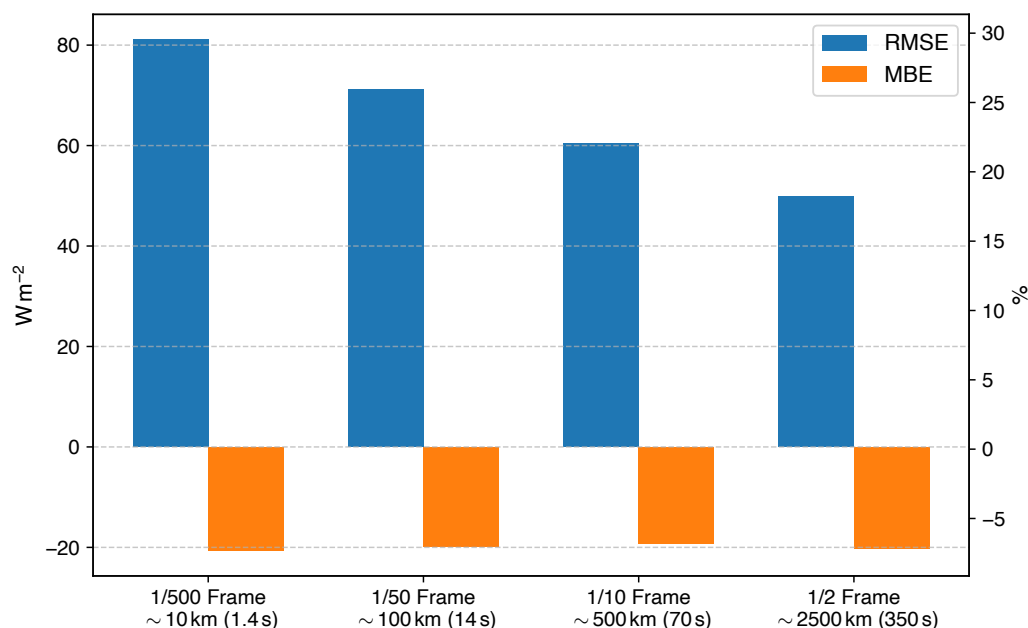


Figure 13. RMSE and MBE as a function of spatiotemporal averaging scales. Aggregation is performed over increasing fractions of an EarthCARE frame (defined as 1/8 of an orbit), ranging from 1/500 (~ 10 km, size of one CAMS cell) to 1/2 (~ 2500 km). Blue bars represent the RMSE, while orange bars indicate the corresponding MBE.

575 Following the assessment of increased spatial scales, regional differences in GHI were evaluated. Under all-sky conditions (Fig. 14a), parts of South America, Northern Africa and Western Asia tend to have higher EarthCARE GHI. However, most of the available regions display higher CAMS GHI. This is especially the case in Oceania, Central Africa, East Asia, and Europe. Regional GHI residuals exhibit substantial spatial variability, with differences ranging from $-89 W m^{-2}$ to $+63 W m^{-2}$ across the global domain. To isolate the potential origins of this variability, the MBE is again decomposed into cloud-related effects and clear-sky irradiance differences. Cloud-induced GHI residuals (Fig. 14b) closely mirror those observed under all-sky conditions, confirming that cloud estimation is a dominant source of the discrepancies between the datasets. The highest positive differences occur in Western Asia. These regions correspond to the edges of the MSG satellites' field of view, where increased pixel distortion and atmospheric path length introduce greater measurement uncertainty. Consequently, this bias should be interpreted with caution. While Europe and Central Africa exhibit a consistent negative MBE, Northern Africa shows values near zero. This region corresponds to the Sahara desert, indicating better agreement between EarthCARE and CAMS in predominantly clear-sky, arid regions. There also seems to exist a correlation between negative MBE values and the Intertropical Convergence Zone (ITCZ). This correlation likely stems from deep tropical clouds which are difficult to simulate due to the complex physical processes involved (Sassen et al., 2009). EarthCARE's high-resolution, along-track sensors may provide a more accurate characterization of these cloud structures than CAMS, resulting in a more realistic, lower GHI estimate. The ITCZ migrates with the thermal equator. Because the data were recorded from September to December, most of these clouds

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appear around the equator, in the process of migrating from North to South. Finally, while CAMS GHI estimates using the MSG satellites (covering Europe, Africa, the Middle East) do not exhibit any significant bias according to their own validation, estimates based on the Himawari 8 satellite (covering eastern Asia and Oceania) exhibit a documented positive MBE of 25.7 W m^{-2} (Lefèvre, 2024). Consequently, the -31.4 W m^{-2} MBE observed in this region can be primarily attributed to the
595 known overestimation inherent in the CAMS Himawari 8 retrievals rather than to an EarthCARE deficiency.

The range of clear-sky irradiance differences (-32 W m^{-2} to $+66 \text{ W m}^{-2}$) is significantly narrower than the all-sky GHI range, confirming that clear-sky modelling is not the primary driver of the overall GHI discrepancies. However, the maximum positive residuals in the clear-sky case are noteworthy, as they exceed the highest observed positive all-sky differences.
600 These residuals are concentrated over the Amazon rain forest in South America. They may be attributed to different AOD retrievals during the deforestation and wildfire events that occur in Autumn. These events lead to a significant increase in AOD and its spatial variability. Consequently, CAMS appears to capture the impact of these events more comprehensively, while EarthCARE likely underestimates the associated aerosol attenuation. Another notable region is the Western Sahara, where EarthCARE detects higher clear-sky irradiance than CAMS. This implies that EarthCARE retrieves a lower AOD, which is
605 primarily driven by dust particles in this region. However, existing literature suggests that CAMS already tends to underestimate AOD of dust aerosols in the Sahara (O’Sullivan et al., 2020). Therefore, it is possible that EarthCARE significantly underestimates the actual AOD in this area. A more detailed analysis of the AOD discrepancies between EarthCARE and CAMS is provided in the subsequent section.

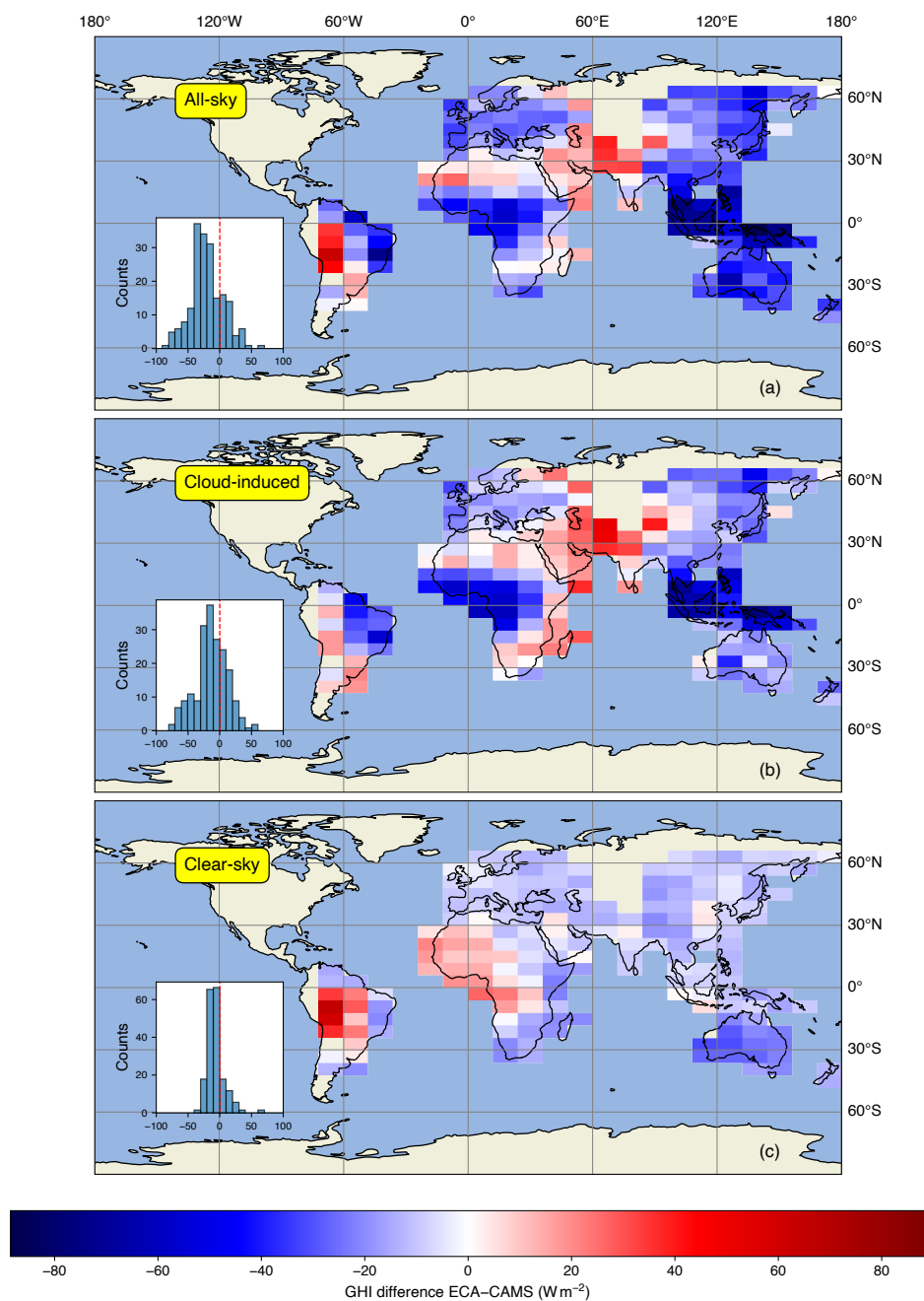


Figure 14. Global spatial distribution of surface GHI differences ECA–CAMS. Panel (a) depicts all-sky, panel (b) cloud-induced, and panel (c) clear-sky GHI differences. Values are averaged on a $6^\circ \times 12^\circ$ latitude/longitude grid, excluding cells with fewer than 1000 comparison points. All panels utilize the shared color scale at the bottom (W m^{-2}).



To conclude the irradiance validation, BSRN observations were used as a reference to evaluate the performance of both Earth-
 610 CARE and CAMS (Fig. 15). Due to the limited temporal overlap between BSRN and CAMS, the validation is constrained to
 a sample size of 73. Both EarthCARE and CAMS exhibit relatively high GHI RMSE, illustrating that estimates remain highly
 sensitive to the spatiotemporal variability of the radiation field. EarthCARE generally underestimates GHI, yielding an MBE
 of -10.3 W m^{-2} (-2.8%), while CAMS tends toward overestimation with an MBE of 15.2 W m^{-2} (4.2%). Consequently,
 BSRN observations typically fall in between the two estimates. Although slightly higher, the positive CAMS bias against
 615 BSRN in this study aligns with the literature value of 8.2 W m^{-2} . While EarthCARE exhibits a lower systematic bias than
 CAMS across global and direct irradiance components, its higher RMSE and rRMSE suggest greater overall variance from
 ground-based observations. In the case of diffuse irradiance, CAMS maintains superior precision with a near-zero MBE and
 lower RMSE. However, the limited sample size makes it difficult to generalize these assumptions on a broader scale.

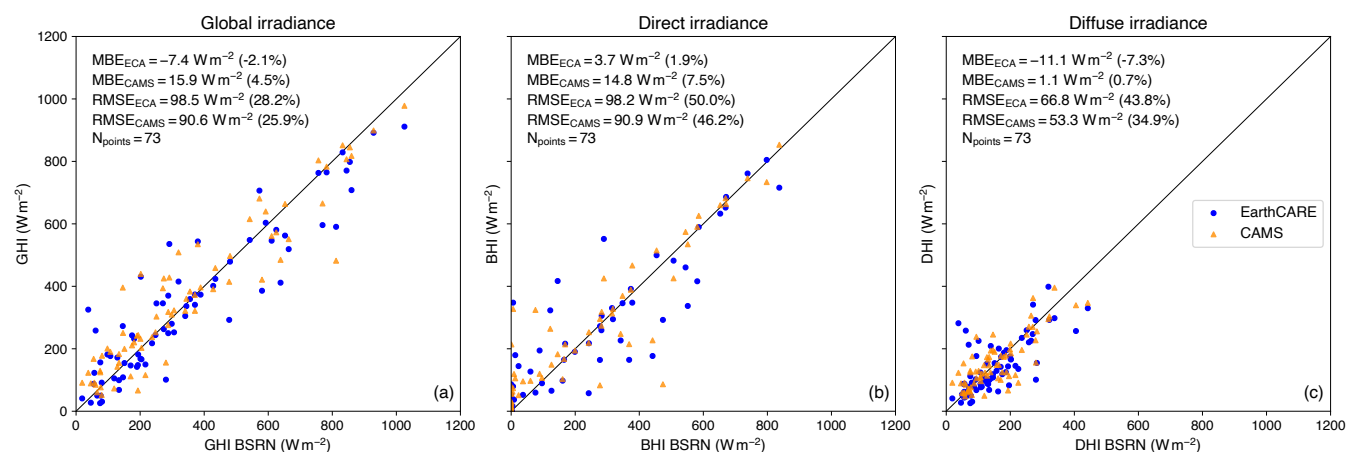


Figure 15. Comparison between EarthCARE (blue circles) and CAMS (orange triangles) GHI, BHI, and DHI, validated by BSRN observations.

3.3 EarthCARE AOD intercomparison against CAMS atmospheric monitoring services and AERONET

As mentioned in the surface GHI validation of EarthCARE, differences in aerosol retrievals are a key cause of discrepancies
 620 in the clear-sky irradiance estimation. One parameter that strongly influences the outcome is AOD, which represents the inte-
 grated optical extinction of the aerosol load within the atmospheric column. Therefore, a detailed analysis of the EarthCARE
 AOD retrievals and CAMS forecast values was conducted. EarthCARE can utilize either results from the CAPTIVATE or the
 composite algorithm as input to the RT models. Their respective performance metrics relative to CAMS are illustrated in Ta-
 625 ble 3, evaluated over 50'634 comparison points (Fig. C6). The sample size is smaller than that of the surface GHI comparison,
 primarily due to the coarser CAMS resolution and the exclusion of numerous data points recorded under suboptimal measure-
 ment conditions. In general, EarthCARE CAPTIVATE AOD seems to be significantly lower than CAMS, while EarthCARE
 composite achieves an MBE much closer to zero. In baseline BA, EarthCARE RT simulations were configured to only use
 CAPTIVATE aerosol and cloud retrievals. This methodology was subsequently revised for baseline BC, where the composite



product became the primary aerosol input due to discontinuities in the aerosol classification of CAPTIVATE (ESA/JAXA, 2025c, e). This transition is supported by the results of this study. Given that the present analysis relies exclusively on baseline BA, the systemic underestimation of AOD would theoretically suggest a positive bias in EarthCARE clear-sky irradiance. However, the absence of such a positive bias relative to both BSRN ($\text{MBE} = -17.9 \text{ W m}^{-2}$) and CAMS ($\text{MBE} = -6.5 \text{ W m}^{-2}$) suggests that the inherent clear-sky bias of EarthCARE is likely more negative than our results indicate. A future analysis of baseline BC is therefore critical to disentangle these biases. While the composite product performs better than CAPTIVATE, the substantial RMSE underscores the inherent challenges in comparing EarthCARE AOD retrievals and CAMS forecast values.

Table 3. Performance metrics of EarthCARE CAPTIVATE/composite AOD relative to CAMS.

Algorithm	MBE	rMBE (%)	RMSE	rRMSE (%)
CAPTIVATE	-0.108	-35	0.347	111
composite	0.017	5	0.279	90

As mentioned before, EarthCARE's clear-sky irradiance is calculated with aerosol properties derived from the CAPTIVATE processor (ESA/JAXA, 2025e). While this allows for a comparison with the clear-sky irradiance differences shown in Figure 14c, a direct evaluation is hindered by the reduced sample size of the AOD dataset. To ensure a consistent comparison, an updated clear-sky irradiance bias map is shown in Appendix C (Fig. C7), which was filtered to match the AOD data availability. The lower EarthCARE AOD in South America and Central Africa (Fig. 16) correlates with a positive clear-sky irradiance bias in those regions. Australia is the only major region where EarthCARE AOD values exceed those of CAMS, a discrepancy that aligns with the negative clear-sky irradiance bias observed in this area. Across the rest of the assessed domain, the AOD bias is close to zero. Therefore, the negative clear-sky irradiance bias observed in most regions cannot be explained by AOD differences alone, as CAMS' higher aerosol levels should theoretically result in lower irradiances. Other tendencies, such as the increase in EarthCARE clear-sky irradiance over the Western Sahara, are absent in the AOD map.

Overall, while some common trends exist, the AOD comparison shows a more pronounced shift towards higher CAMS values than the clear-sky irradiance comparison suggests. Although AOD is a primary driver of clear-sky irradiance attenuation, it is not the sole determinant. Irradiance levels are also significantly influenced by additional aerosol optical properties (such as the single scattering albedo), surface albedo, columnar water vapour, and the varying concentrations of trace gases (e.g. O_3 , NO_2).

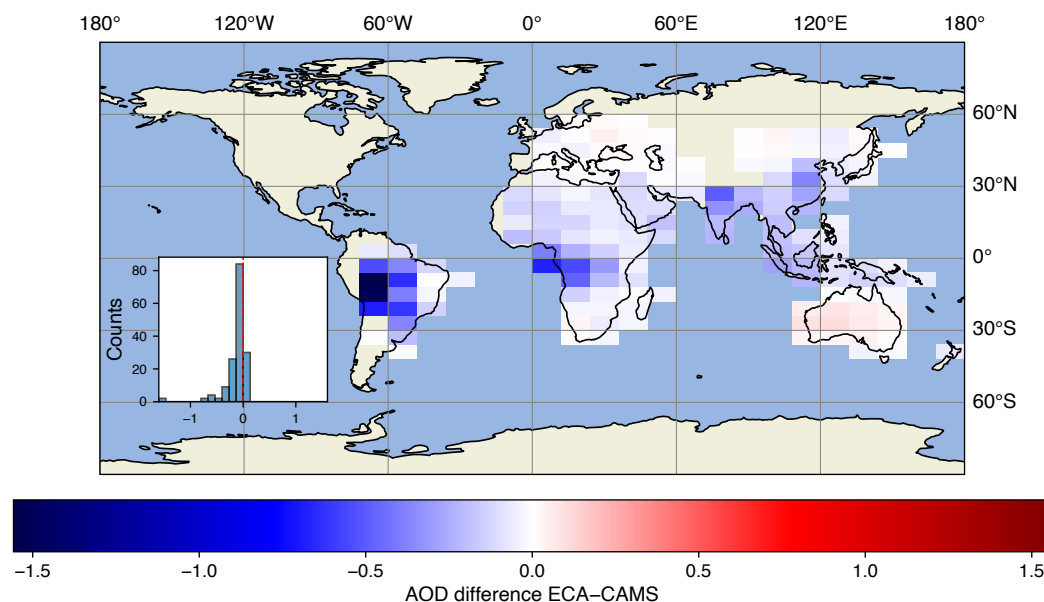


Figure 16. Global spatial distribution of AOD differences ECA–CAMS. Values are averaged on a $6^\circ \times 12^\circ$ latitude/longitude grid, excluding cells with fewer than 50 comparison points. Insets illustrate the count-based distribution of the differences for each category.

To conclude the AOD validation of EarthCARE, AERONET observations were used as a reference to cross-check the values provided by EarthCARE's two processors CAPTIVATE and composite, alongside CAMS values (Fig. 17). Both CAMS and EarthCARE composite exhibit similar performance levels when compared to AERONET, with RMSE values around 0.2 and near-zero biases. In contrast, EarthCARE CAPTIVATE displays a significantly higher RMSE (0.349) and a substantial negative bias ($MBE = -0.182$), suggesting that the CAPTIVATE processor produces less realistic results under these conditions. Especially at high AOD levels, the discrepancy is substantial, with CAPTIVATE failing to retrieve values above 0.8. While both CAMS and the composite product also underestimate AERONET observations at these higher levels, they remain significantly more accurate than CAPTIVATE. Consequently, EarthCARE achieves better AOD agreement with ground-based observations by using the composite processor rather than CAPTIVATE for baseline BA.

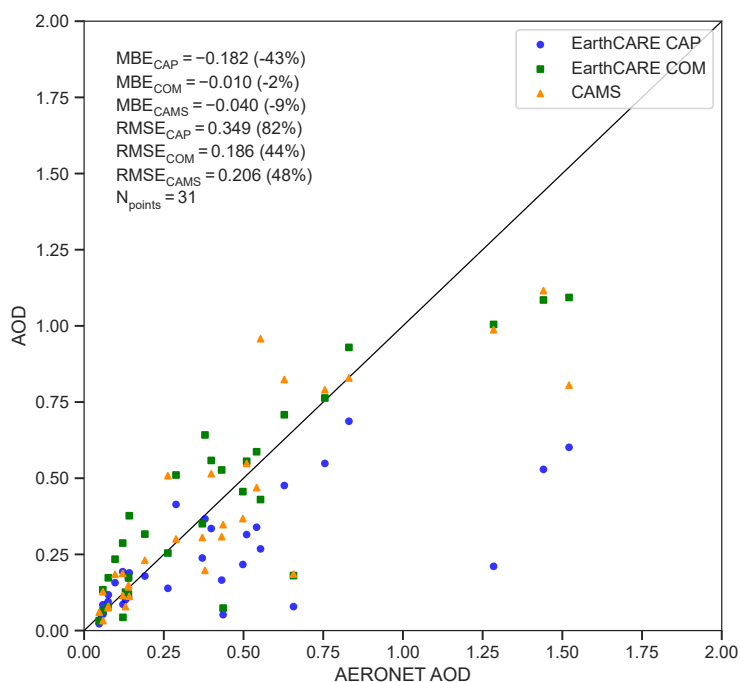


Figure 17. Validation of AOD retrievals produced by EarthCARE’s CAPTIVATE (CAP) and composite (COM) processors, alongside CAMS values, against ground-based AERONET observations.

3.4 Intercomparison against BBR differences at the TOA

To strengthen the assessment of EarthCARE’s RTMs and their inputs, flux discrepancies at the surface relative to BSRN/CAMS were intercompared against differences at the TOA with EarthCARE’s own radiative closure assessment instrument, the BBR (Fig 18). Compared to BBR measurements, the 1D RTM overestimates TOA flux (rMBE of 4.4 %), while the 3D RTM underestimates it (rMBE of −7.5 %). The 3D RTM exhibits greater deviation from the BBR observations, with an rRMSE of 18.0 % compared to 14.9 % for the 1D RTM. However, Salas Molar et al. (2026) found the opposite trend over a significantly larger sample size in the baseline BA. Consequently, our results reflect specific local conditions and should not be generalized as a broader trend. Under cloud-free conditions (ECA CMF = 1), the 3D surface flux estimates show high agreement with BSRN (ratios near 1), whereas the corresponding TOA flux ratios against BBR reflect a predominant underestimation by the 3D RTM. These discrepancies are likely attributable to uncertainties in surface albedo characterization and aerosol misclassification within the BA baseline. The 1D RTM does not display such discrepancies under cloud-free conditions. In general, the differences at TOA and at the surface do not exhibit a correlating trend with each other. The corresponding analysis with CAMS can be found in Appendix C (Fig. C8).

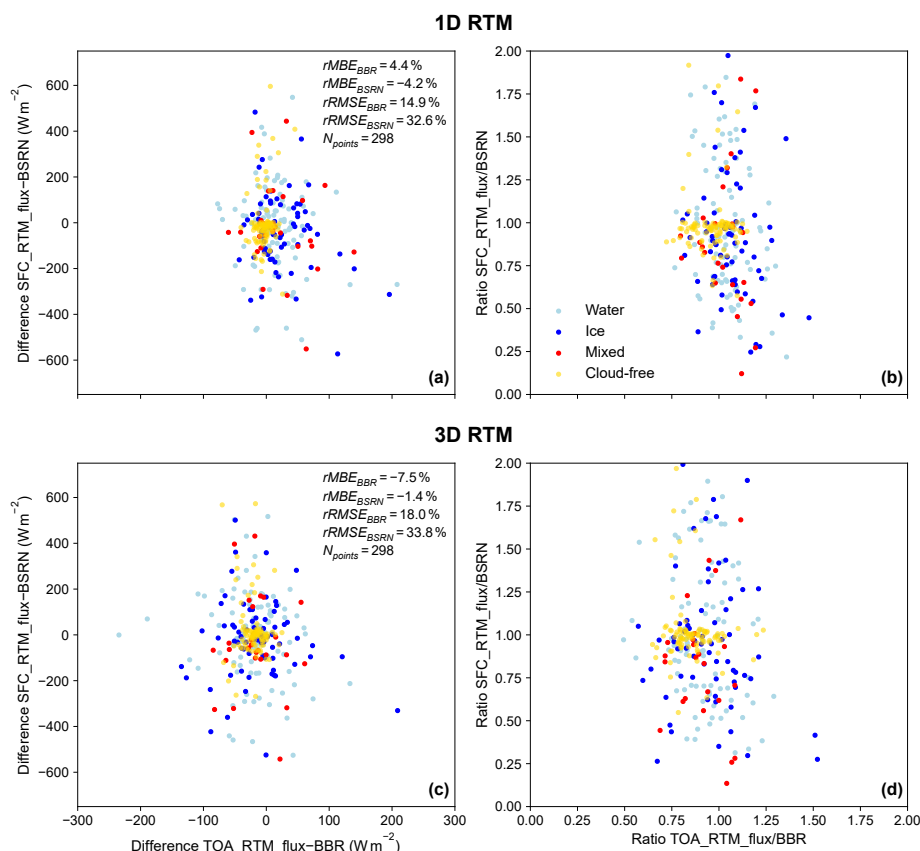


Figure 18. Intercomparison of EarthCARE 1D (top row) and 3D (bottom row) RTM flux differences relative to BSRN surface observations and BBR TOA measurements. Panel (a) and (c) depict the differences, while panels (b) and (d) present the corresponding ratios. Data is classified into cloud-free (yellow), water cloud (light blue), ice cloud (dark blue), and mixed cloud (red).

4 Conclusions

675 The EarthCARE satellite, launched in 2024, is the most complete cloud, aerosol, and precipitation observing satellite to date. Given the complexity of its systems and the reliance on synergistic retrieval algorithms, rigorous validation of the corresponding data products is essential. This study evaluated surface radiation estimates derived from the combined cloud and aerosol products of the ATLID, CPR, and MSI instruments. EarthCARE's SW and LW estimates were validated against ground-based measurements from BSRN stations, with SW estimates further intercompared with modelled values from CAMS. Initial assessments of SW along-track 1D estimates against BSRN revealed significant discrepancies, primarily driven by spatiotemporal

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variability in the radiation field under overcast or partly cloudy conditions. To reduce these effects, we evaluated spatial averages of 1×1 , 3×3 , and 5×5 EarthCARE pixels centered on the BSRN stations using EarthCARE's SCA algorithm. Results demonstrate that 3×3 and 5×5 pixel averages significantly improve agreement with ground-based measurements compared to single-pixel estimates. Furthermore, the analysis confirms that the SCA algorithm's performance diminishes with increasing distance from the satellite's ground track. While cloud-free conditions provide the most reliable comparison (exhibiting the lowest RMSE with 40.8 W m^{-2} for the 3×3 pixel average), they also exhibit a notable negative MBE (-17.9 W m^{-2}). Although elevated EarthCARE aerosol loads could theoretically explain this discrepancy, our analysis of ACM-RT input data from CAPTIVATE indicates that AOD is underestimated rather than overestimated. While other aerosol properties, such as the single scattering albedo, influence clear-sky irradiance, AOD is a primary driver. Thus, it is unlikely that aerosol retrieval biases are the source of this error. Alternatively, this bias may stem from the degradation of the SCA algorithm's performance with increasing distance from the satellite's ground track. Indeed, for distances below 25 km, the 7 resulting EarthCARE overpasses are in close agreement with BSRN observations (MBE = -4.5 W m^{-2} , RMSE = 12.0 W m^{-2}), while the 12 overpasses that are further than 25 km away from the ground station exhibit a significant negative bias (MBE = -25.8 W m^{-2}) and much larger discrepancies (RMSE = 50.7 W m^{-2}). This underscores the importance of reducing the spatial distance threshold in the validation. Comparison of the 1D and 3D EarthCARE RTMs demonstrated that the 3D RTM achieves an MBE closer to zero (-4.6 W m^{-2} , -0.9%) than the 1D RTM (-20.2 W m^{-2} , -4.0%), even when evaluated over the same assessment domain via the SCA algorithm (-19.5 W m^{-2} , -3.9%). However, this near-zero global bias masks significant discrepancies in the individual irradiance components: the 3D RTM consistently underestimates direct irradiance (MBE = -51.4 W m^{-2}) while overestimating the diffuse component (MBE = 47.1 W m^{-2}). This discrepancy might be attributed to differing definitions of direct and diffuse irradiance between EarthCARE and BSRN. While BSRN measures direct irradiance using a pyrheliometer with a 5° field of view, EarthCARE's ACM-RT processor defines the direct component strictly as Monte Carlo photons that have not undergone any scattering events. This could introduce differences particularly regarding the circumsolar contribution, as near-forward scattered photons are registered as direct by the ground instrument but classified as diffuse by the RTM. In addition to SW radiation, LW radiation was also evaluated. LW irradiance of EarthCARE is in good agreement with BSRN, achieving a near-zero MBE of -4.1 W m^{-2} (-1.2%) and a reduced RMSE of 34.9 W m^{-2} (10.0%).

To compare EarthCARE with CAMS, the quality of the different collocation methodologies was first determined. The 3D RTM exhibits the lowest bias (-7.6 W m^{-2} , -1.4%), which suggests that the actual bias may be even closer to zero when accounting for CAMS' documented overestimation of all-sky GHI (8.2 W m^{-2} , Lefèvre, 2024). However, discrepancies in the direct and diffuse components remain significant, with MBEs of -46.5 W m^{-2} (-13.6%) and 38.9 W m^{-2} (18.6%), respectively. Despite a substantially larger sample size than the other methodologies, the 1D RTM across-track extension (SCA algorithm) yields the lowest RMSE (88.4 W m^{-2} , 17.0%). This RMSE is notably lower than in the BSRN comparison, likely due to the improved collocation and more consistent methodology between the datasets. Comparing different averaging scales confirmed that the surface GHI bias between EarthCARE 1D RTM and CAMS is not a stochastic artifact from the collocation process, but reflect systematic differences between the two products. This was further illustrated by classifying the data



into different cloudiness regimes. The classified median GHI difference is only positive if CAMS detects overcast conditions ($CMF < 0.2$), representing a small number of cases (4 %). Approximately 65 % of the all-sky GHI bias occurs due to differences in cloud estimation, while the remaining 35 % can be attributed to discrepancies in the clear-sky irradiance evaluation. While most regions in the CAMS domain exhibit negative all-sky GHI biases, localized positive biases are observed in parts of South America, Northern Africa and Western Asia. In contrast, EarthCARE surface GHI is significantly lower than CAMS across Oceania, Central Africa, and Europe. The positive bias in Oceania can be primarily attributed to the documented over-estimation inherent in the CAMS Himawari 8 retrievals rather than to an EarthCARE deficiency. By including BSRN stations in the EarthCARE–CAMS comparison, we found that EarthCARE yields slightly lower GHI bias than CAMS. However, the increased RMSE suggests that the model is more sensitive to random errors or localized discrepancies than CAMS. For the direct and diffuse components, EarthCARE’s 1D RTM achieves closer alignment with BSRN and CAMS benchmarks than the 3D RTM.

To investigate the origins of the clear-sky irradiance discrepancies, the AOD inputs from EarthCARE and CAMS were compared. Results from the EarthCARE CAPTIVATE processor indicate a systematic underestimation of AOD relative to CAMS, with a global MBE of -0.108 (-35 %). This trend is further evidenced by the spatial distribution, which reveals negative biases across all major regions except Australia. While certain spatial patterns align with those found in the clear-sky irradiance maps, the AOD comparison shows a more neutral bias than the clear-sky irradiance comparison would suggest. Therefore, differences in AOD retrievals cannot fully explain the clear-sky irradiance bias. While EarthCARE CAPTIVATE exhibits a pronounced negative MBE, EarthCARE composite displays no significant bias relative to CAMS. However, the high RMSE (0.279 , 90 %) indicates substantial variability, suggesting that the comparison precision is not yet optimal. Validation against AERONET observations demonstrates that both the composite processor and CAMS estimates align more closely with high-precision ground-based measurements than CAPTIVATE, yielding significantly lower MBE and RMSE values. This suggests a systematic underestimation of AOD by the CAPTIVATE processor. In contrast to the ACM-RT baseline BA, the subsequent baseline BC takes this underperformance of the CAPTIVATE processor into account and utilizes aerosol properties derived from single-instrument products for radiative transfer simulations, rather than the synergistic CAPTIVATE product. Consequently, the clear-sky irradiance discrepancies could potentially be resolved with the baseline BC. Although a comparison with BSRN/CAMS could be used to confirm this improvement, the current analysis remains constrained by the limited data availability following the baseline’s implementation in November 2025. To finalize the analysis, we intercompared ACM-RT flux discrepancies at the surface relative to BSRN and differences at the TOA with BBR measurements. No statistically significant correlation was identified between the surface and TOA discrepancies, potentially due to the limited dataset size.

The evaluation demonstrates that the different EarthCARE solar irradiance products have distinct strengths and are therefore suited to different applications. The standard 1D ACM-RT product provides the most direct and internally consistent estimate along the nadir track, making it particularly useful for process studies and radiative closure analyses where consistency with the native cloud and aerosol retrievals is essential. The SCA-based across-track extension improves the spatial representativeness



of the 1D product and reduces random variability through averaging, making it the most appropriate product for comparison with ground-based observations. In contrast, the 3D ACM-RT product offers the most physically realistic representation of radiative transfer by accounting for horizontal photon transport and shows the lowest all-sky GHI bias, which makes it particularly valuable for studies of cloud-radiative effects and heterogeneous cloud fields. Overall, the results suggest that the choice of EarthCARE irradiance product should depend on the scientific objective, with each product offering specific advantages for different atmospheric, solar energy and other applications.

Expanding the scope and statistical robustness of this analysis depends heavily on the availability of the BSRN/CAMS datasets. While 43 BSRN stations are currently active, only 27 have released data since September 2024. Therefore, an increase in reporting consistency would significantly improve the validation of EarthCARE. A comprehensive list of active BSRN stations that have not yet released GHI data since September 2024 is provided in Appendix D (Tab. D1), including information about the EarthCARE overpasses which could potentially be validated as data becomes available. CAMS releases their solar radiation dataset in yearly batches. The 2025 dataset, which is expected by July 2026, would effectively triple the available comparison points. This would allow for a more comprehensive evaluation of long-term trends over all seasons.



765 Appendix A: List of ground stations used in analysis

Table A1. Overview of the 28 ground stations used in the analysis. Number of overpasses describes the amount of EarthCARE overpasses that are less than 50 km away from the ground station. For stations that exceed an absolute latitude of 67.5° , this threshold is reduced to 25 km.

Station	Latitude ($^\circ$ N)	Longitude ($^\circ$ E)	Elevation (m)	Number of overpasses	Mean distance (km)	Closest overpass (km)
Abashiri (ABS)	44.01	144.28	38	13	16.5	4.6
Budapest-Lorinc (BUD)	47.43	19.18	139	24	31.5	18.5
Cabauw (CAB)	51.97	4.93	0	26	30.4	11.1
Cener (CNR)	42.82	-1.60	471	24	36.4	7.1
Cocos Island (COC)	-12.19	96.84	6	14	37.7	7.8
Desert Rock (DRA)	36.63	-116.02	1007	13	21.0	12.8
Florianopolis (FLO)	-27.60	-48.52	11	16	22.8	4.2
Gobabeb (GOB)	-23.56	15.04	407	20	42.0	13.1
Granite Island (GIM)	46.72	-87.41	195	31	34.4	10.3
Ishigakijima (ISH)	24.34	124.16	6	17	32.4	7.2
Izaña (IZA)	28.31	-16.50	2373	20	39.5	29.0
Lampedusa (LMP)	35.52	12.63	50	13	7.3	1.1
Langley Research Center (LRC)	37.10	-76.39	7	23	36.9	26.0
Magurele (INO)	44.34	26.01	110	14	10.0	5.3
Minamitorishima (MNM)	24.29	153.98	7	18	40.9	33.3
Ny-Ålesund (NYA)	78.92	11.93	11	93	13.2	1.1
Palaiseau (PAL)	48.71	2.21	156	31	30.8	12.0
Paramaribo (PAR)	5.81	-55.21	4	12	43.5	36.3
Payerne (PAY)	46.81	6.94	491	25	34.3	8.7
Reunion Island (RUN)	-20.90	55.48	116	16	38.1	23.3
Selegua (SEL)	15.78	-91.99	602	16	35.1	28.8
Sonnblick (SON)	47.05	12.96	3109	11	10.4	6.1
Syowa (SYO)	-69.01	39.58	18	26	3.5	0.0
Tamanrasset (TAM)	22.79	5.53	1385	20	44.3	33.3
Tateno (TAT)	36.06	140.13	25	15	28.3	14.5
Thessaloniki (THS)	40.63	22.96	61	11	17.3	7.0
Toravere (TOR)	58.25	26.46	70	29	26.2	12.4
All stations				591	27.2	0.0



Appendix B: List of AERONET stations used in analysis

Table B1. Overview of the 19 AERONET stations used in the analysis. Number of overpasses describes the amount of EarthCARE overpasses that are less than 50 km away from the AERONET station.

Station	Latitude (°N)	Longitude (°E)	Elevation (m)	Number of overpasses	Mean distance (km)	Closest overpass (km)
ATTO Campina (ATC)	−2.18	−59.02	30	4	8.6	1.8
Bambey-ISRA (BAM)	14.71	−16.48	30	4	16.4	5.5
Ilorin (ILO)	8.48	4.67	400	4	26.2	15.3
Izaña (IZA)	28.31	−16.50	2401	5	41.2	32.9
KAUST Campus (KAC)	22.30	39.10	11	3	13.2	3.3
Kupang (KUP)	−10.14	123.67	30	4	9.6	3.7
KORUS UNIST Ulsan (KUU)	35.57	129.19	106	3	15.8	0.7
Leipzig (LPZ)	51.35	12.44	125	8	30.3	12.5
Lulin (LUL)	23.47	120.87	2868	5	8.5	4.3
ICIPE Mbita (MBI)	−0.43	34.21	1152	4	12.8	1.2
AU NSW Merriwa	−32.13	150.46	412	3	22.5	16.4
Mongu Inn (MOI)	−15.27	23.13	1040	6	36.3	31.9
Montevideo FING (MON)	−34.92	−56.17	71	4	23.7	6.0
Nong Khai (NOK)	17.88	102.72	175	2	32.6	27.9
Palencia (PAL)	41.99	−4.52	750	6	27.8	18.0
Palma de Mallorca (PDM)	39.55	2.63	10	4	12.3	3.2
Palangkaraya (PKY)	−2.23	113.95	27	2	21.1	14.5
Sofia IEBAS (SOF)	42.65	23.39	631	3	33.4	22.9
Sao Paulo (SPO)	−23.56	−46.73	786	2	32.6	23.2
All stations				76	22.9	0.7



Appendix C: Supplemental validation plots

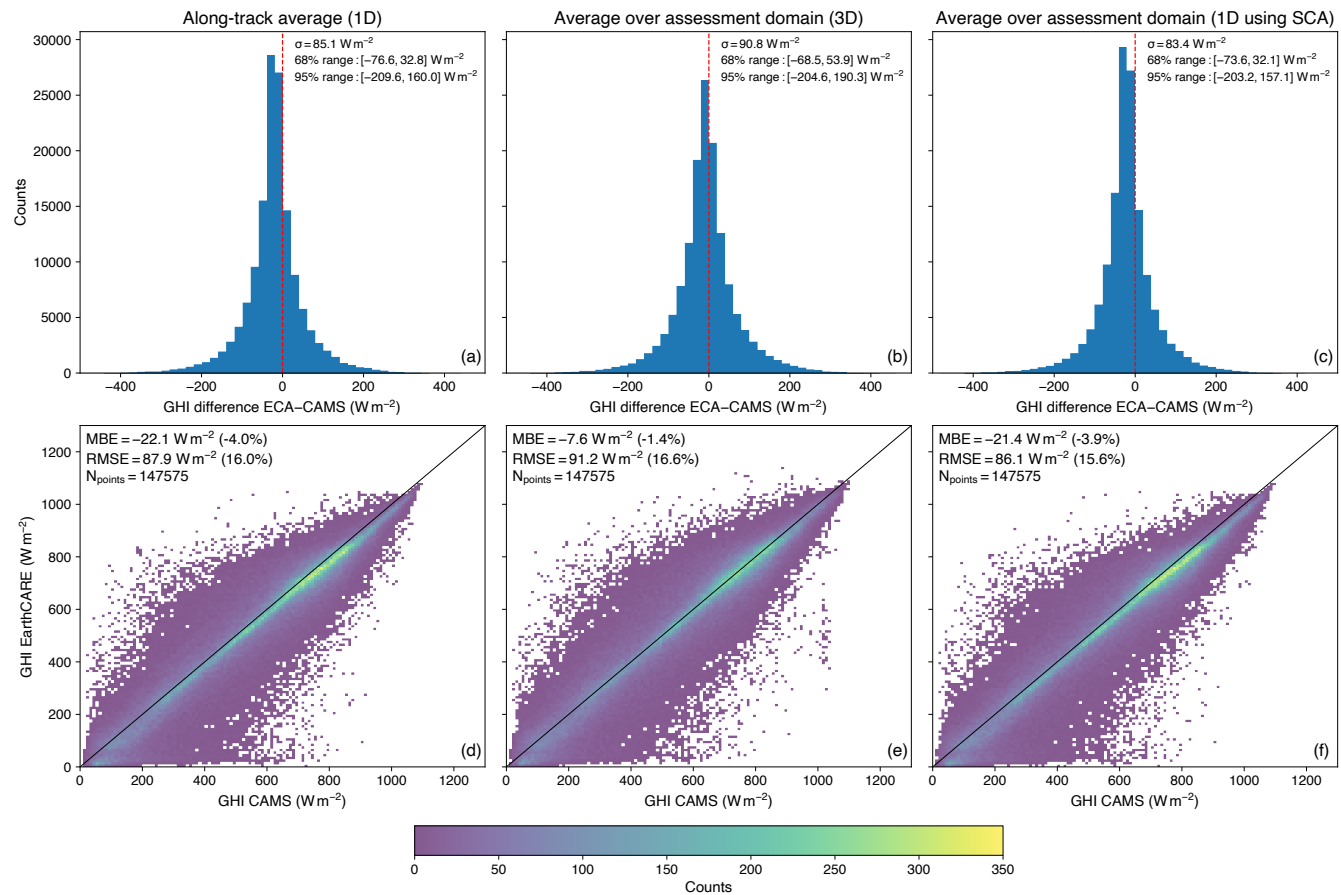


Figure C1. Intercomparison of EarthCARE surface GHI against CAMS radiation services. The columns represent different EarthCARE methodologies over a 5×21 pixel assessment domain: (left) Along-track average using the 1D RTM, (center) average over the assessment domain using the 3D RTM and (right) average over the assessment domain using the 1D RTM based on the SCA algorithm. Panels (a), (b), and (c) depict one-dimensional histograms of the GHI differences, while panels (d), (e), and (f) illustrate the corresponding two-dimensional scatter density plots.

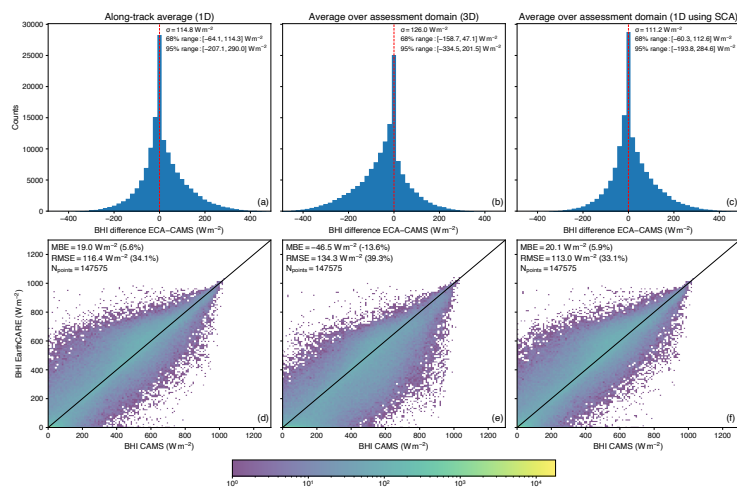


Figure C2. Intercomparison of EarthCARE surface BHI against CAMS radiation services. The columns represent different EarthCARE methodologies over a 5×21 pixel assessment domain: (left) Along-track average using the 1D RTM, (center) average over the assessment domain using the 3D RTM and (right) average over the assessment domain using the 1D RTM based on the SCA algorithm. Panels (a), (b), and (c) depict one-dimensional histograms of the GHI differences, while panels (d), (e), and (f) illustrate the corresponding two-dimensional scatter density plots. The scatter density plots are depicted with a logarithmic count scale.

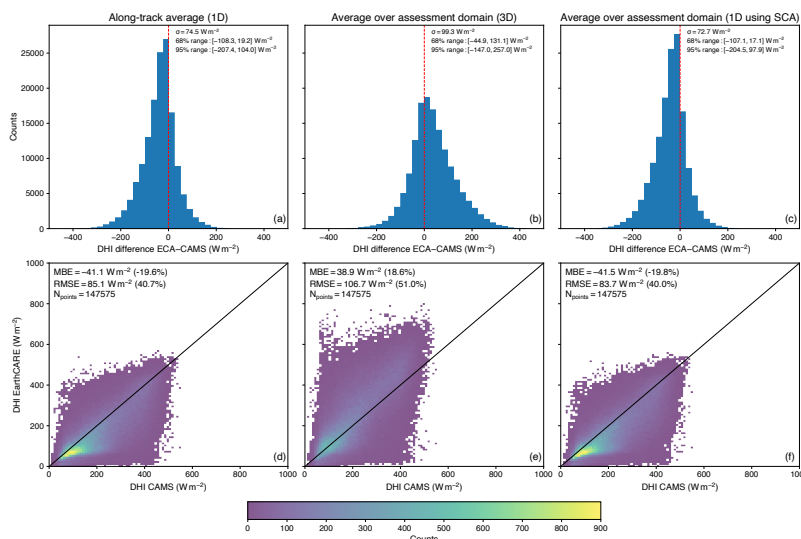


Figure C3. Intercomparison of EarthCARE surface DHI against CAMS radiation services. The columns represent different EarthCARE methodologies over a 5×21 pixel assessment domain: (left) Along-track average using the 1D RTM, (center) average over the assessment domain using the 3D RTM and (right) average over the assessment domain using the 1D RTM based on the SCA algorithm. Panels (a), (b), and (c) depict one-dimensional histograms of the GHI differences, while panels (d), (e), and (f) illustrate the corresponding two-dimensional scatter density plots. The scatter density plots are depicted with a logarithmic count scale.

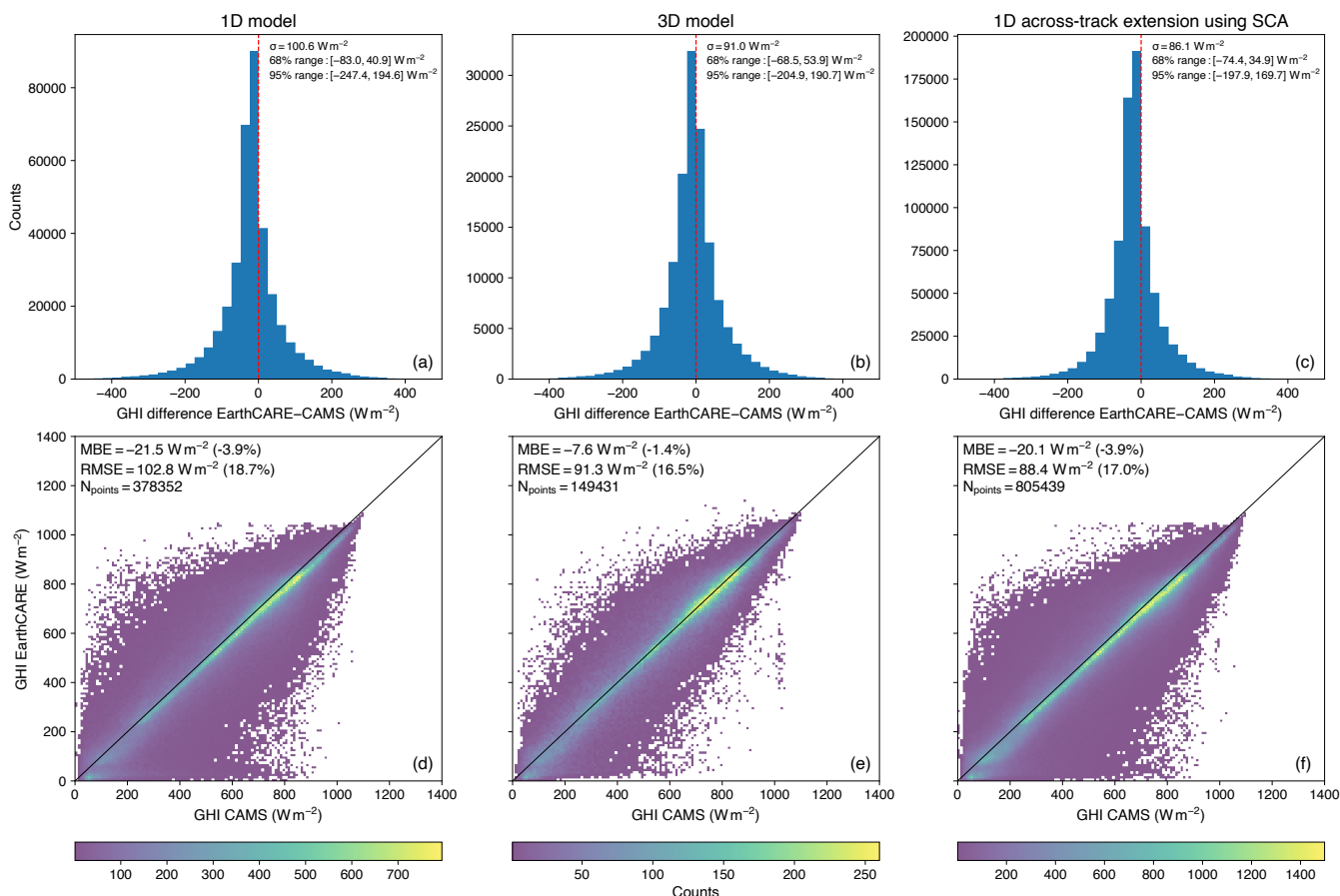


Figure C4. Intercomparison of EarthCARE surface GHI against CAMS radiation services, with the columns representing different collocation methodologies: (left) EarthCARE 1D along-track average over each CAMS cell, (center) CAMS collocation with EarthCARE 5×21 3D assessment domain using a weighted-average approach, (right) 1D across-track extension using the SCA algorithm. Panels (a), (b), and (c) depict one-dimensional histograms of the GHI differences, while panels (d), (e), and (f) illustrate the corresponding two-dimensional scatter density plots.

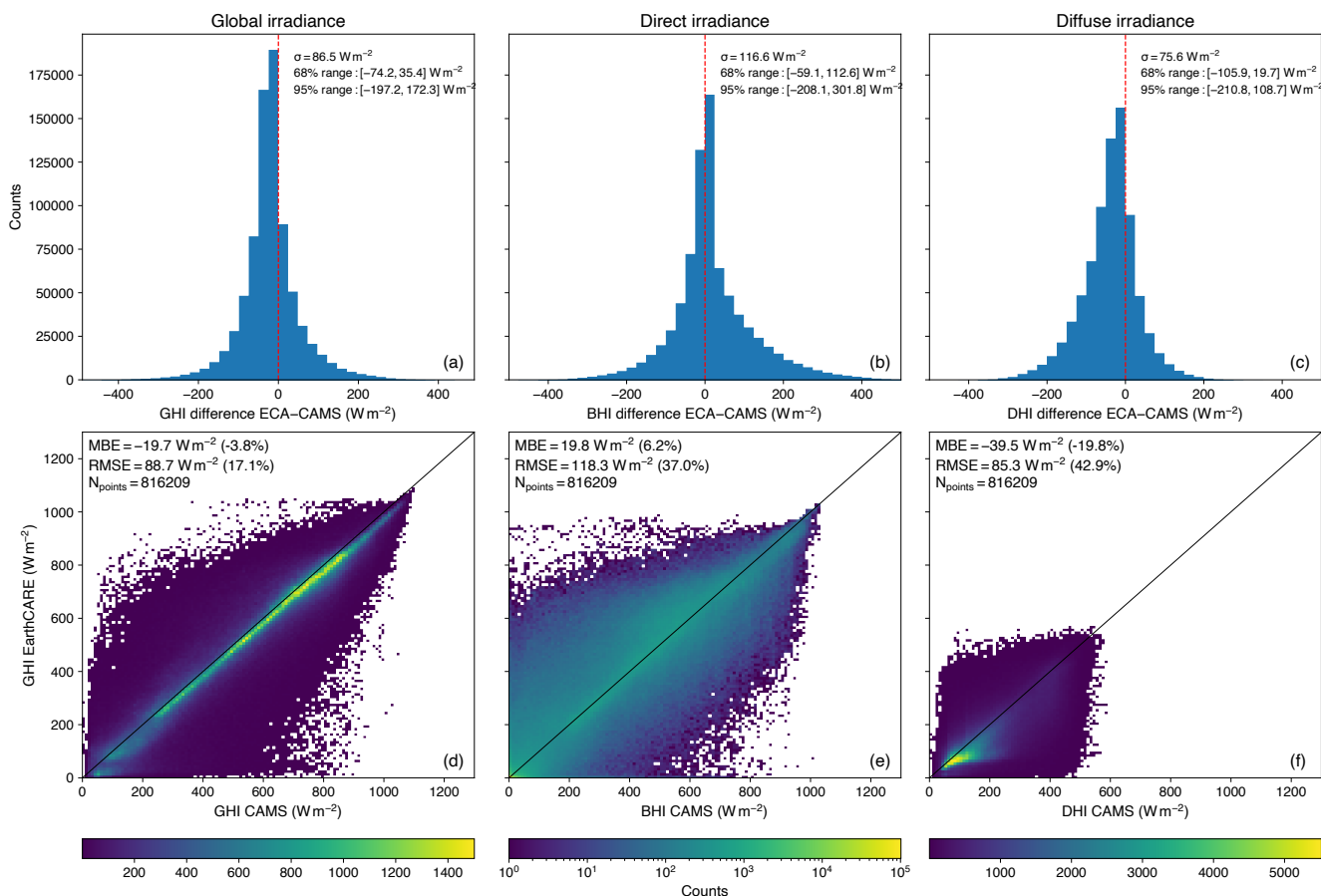


Figure C5. Intercomparison of EarthCARE 1D surface irradiance using the SCA algorithm against CAMS radiation services. The three columns represent global, direct, and diffuse irradiance, respectively. Panels (a), (b), and (c) depict one-dimensional histograms of the differences, while panels (d), (e), and (f) illustrate the corresponding two-dimensional scatter density plots. The color bar in panel (e) utilizes a logarithmic count scale.

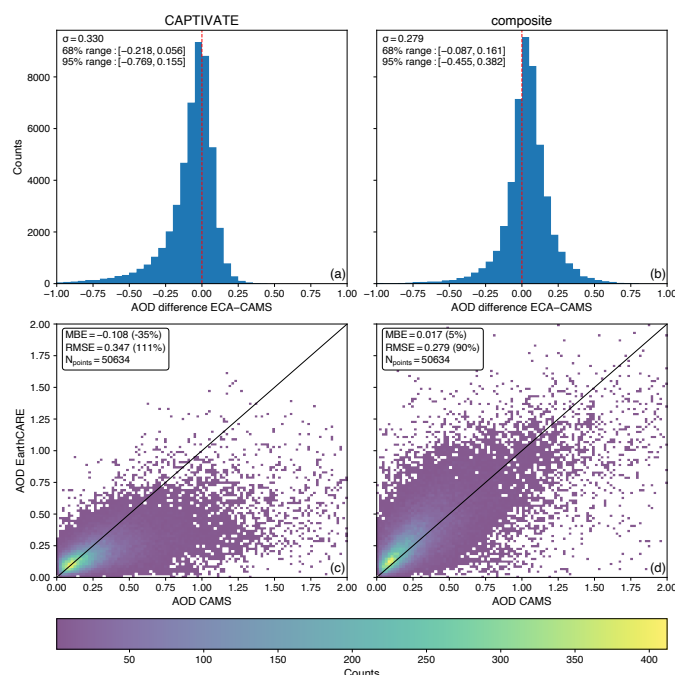


Figure C6. Intercomparison of EarthCARE AOD against CAMS atmospheric monitoring services. The columns represent the two different EarthCARE retrieval algorithms: CAPTIVATE (left) and composite (right). Panels (a) and (b) depict one-dimensional histograms of the AOD differences, while panels (d) and (e) illustrate the corresponding two-dimensional scatter density plots.

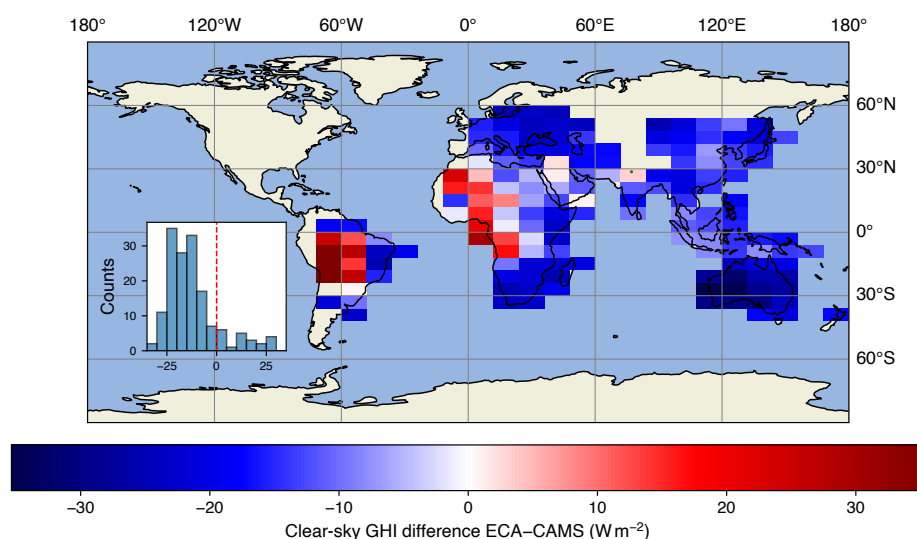


Figure C7. Global spatial distribution of clear-sky irradiance differences ECA-CAMS, subsampled to match the EarthCARE AOD data coverage. Values are averaged on a $6^\circ \times 12^\circ$ latitude/longitude grid, excluding cells with fewer than 50 comparison points. Insets illustrate the count-based distribution of the differences for each category.

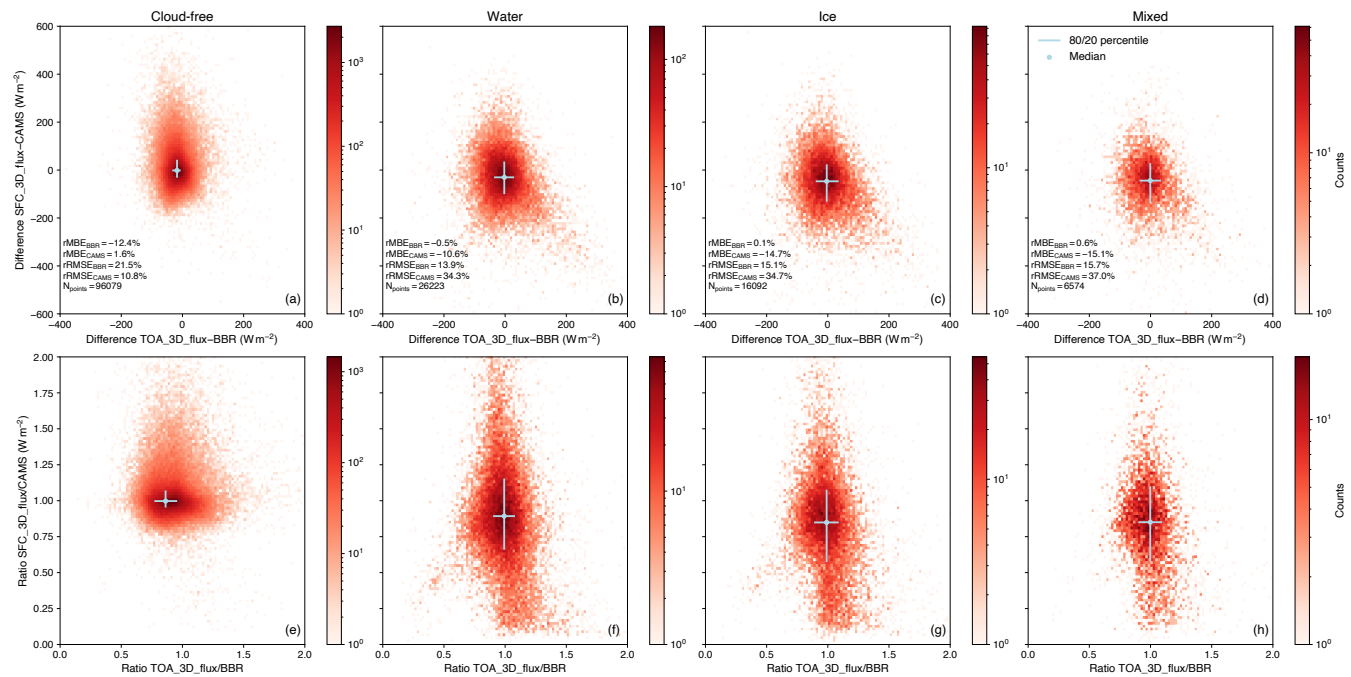


Figure C8. Intercomparison of EarthCARE 3D RTM flux differences relative to CAMS surface (SFC) observations and BBR TOA measurements. Data points are classified into distinct cloud phases (cloud-free, water, ice, and mixed). Panels (a), (b), (c), and (d) depict the differences, while panels (e), (f), (g), and (h) present the corresponding ratios.



Appendix D: Active BSRN stations

Table D1. Overview of all 16 BSRN stations that are active at the time of writing but haven't released data since September 2024. To account for EarthCARE's near-polar orbit, the distance limit was reduced from 50 km to 25 km for stations exceeding 67.5° absolute latitude, and further restricted to 5 km for those beyond 80° latitude.

Station	Latitude (°N)	Longitude (°E)	Elevation (m)	Number of overpasses	Mean distance (km)	Closest overpass (km)
Barrow	71.32	−156.61	8	31	4.7	0.2
Bermuda	32.30	−64.77	8	16	24.7	17.6
Billings	36.61	−97.52	317	17	23.0	12.6
Bondville	40.07	−88.37	213	23	36.1	6.8
Concordia Station	−75.10	123.38	3233	52	12.6	2.3
Fort Peck	48.32	−105.10	634	16	14.7	3.8
Georg von Neumayer	−70.65	−8.25	42	51	15.9	3.7
Goodwin Creek	34.25	−89.87	88	19	36.2	7.7
Huancayo	−12.05	−75.32	3314	11	32.0	1.0
Lanyu Island	22.04	121.56	324	17	9.1	0.6
Lindenberg	52.21	14.12	125	15	6.4	1.6
Rock Springs	40.72	−77.93	376	12	25.7	18.0
Sioux Falls	43.73	−96.62	473	26	34.8	16.8
South Pole	−89.98	−24.80	2800	—	—	—
Southern Great Plains	36.60	−97.49	318	17	20.6	9.9
Yushan	23.49	120.96	3858	16	7.2	0.5
All stations				339	19.1	0.2

Data availability. AERONET data are publicly available from the NASA AERONET website (<https://aeronet.gsfc.nasa.gov/>). CAMS grid-
ded solar radiation data can be accessed via the Copernicus Atmosphere Data Store (<https://ads.atmosphere.copernicus.eu>). BSRN data are
available through the PANGAEA Data Publisher (<https://dataportals.pangaea.de/bsrn/>). Data from the Thessaloniki station can be retrieved
through the World Radiation Data Centre (WRDC) archive (http://wrdc.mgo.rssi.ru/wrdc_en.htm). For more information, please contact
Alkiviadis Bais (abais@auth.gr). EarthCARE data are accessible via the ESA EO Gateway (<https://earth.esa.int/eogateway/missions/earthcare/data>).

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