



Evaluation of EarthCARE's Scene Construction Algorithm Using Airborne Observations

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Abstract. This study evaluates the performance of EarthCARE's scene construction algorithm (SCA) using airborne observations collected by the National Research Council Canada's Convair-580 research aircraft during the EarthCARE Commissioning Calibration/Validation Campaign in Ottawa (ECALOT). EarthCARE's three-dimensional (3D) SCA employs
15 a radiance-matching technique and nadir retrievals to construct 3D atmosphere-surface conditions around the nadir cross-section. While the SCA can be applied across the ~150 km swath of EarthCARE's Multispectral Imager (MSI), its operational application is limited to a ~30 km-wide region centered on the nadir track., which encompasses the 5 km across-track by 21 km along-track assessment domains and their associated buffer regions. The SCA facilitates lateral transport of photons in Monte Carlo radiative transfer simulations, and so its results influence simulated radiative quantities that are used, in part, to
20 perform radiative closure analyses. Two complementary evaluation strategies are applied. First, the Convair-580 underflew EarthCARE on a path angled at 20° to the satellite's track. Off-nadir measurements of cloud microphysical variables made in situ by the Convair-580 are used to assess SCA predictions for shallow cumulus and stratocumulus clouds. Second, for nimbostratus clouds, the Convair-580's side-viewing W-band radar reflectivities are compared to horizontal planes of reflectivities based on SCA allocations of nadir reflectivities from both Convair-580 and EarthCARE's Cloud Profiling Radar.
25 Evaluation against in situ observations showed little variation in mean bias error (MBE) and root mean square error (RMSE) for both liquid water content and effective radius at distances of up to ~12 km from the nadir track, indicating consistent SCA performance within this range. Comparison with side-viewing W-band radar reflectivity also yielded low MBE and RMSE, with correlation coefficients of 0.88 and 0.80 for Flights 6 and 5, respectively. The newer version of the SCA, Baseline BC, generally outperformed the earlier Baseline BA, particularly for the more complex cloud scene observed during Flight 5 on
30 January 27, 2024.



1. Introduction

The EarthCARE satellite mission is operated jointly by the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA). It combines active and passive remote sensing instruments to observe clouds, aerosols, and radiation with a view to improving understanding of their interactions and roles in Earth's climate system (Illingworth et al., 2015; Wehr et al., 2023; Eisinger et al., 2024). The active sensors, Cloud Profiling Radar (CPR) and Atmospheric Lidar (ATLID), and the passive Multispectral Imager (MSI) retrieve, both individually and synergistically, vertically-resolved cloud and aerosol properties for each ~1 km-wide column along the satellite's nadir cross-section (Mroz et al., 2023; Donovan et al., 2024; Mason et al., 2023; Hünnerbein et al., 2024; Docter et al., 2024).

To evaluate the quality and physical consistency of these retrievals, EarthCARE employs a radiative closure assessment framework (Illingworth et al., 2015; Barker et al., 2025). This approach performs shortwave and longwave radiative transfer (RT) simulations for predefined assessment domains (5 km across-track by 21 km along-track) using retrieved cloud and aerosol properties together with auxiliary information pertaining to atmospheric and surface conditions (Cole et al., 2023). Simulated top-of-atmosphere (TOA) upwelling radiative fluxes are then compared to inferences based on observations made by the onboard Broadband Radiometer (BBR) (Velázquez Blázquez et al., 2024). This radiative consistency test provides insight into the overall performance of the EarthCARE mission (Illingworth et al., 2015; Wehr et al., 2023; Barker et al., 2025).

Both one-dimensional (1D) and three-dimensional (3D) RT simulations are performed operationally. The independent column approximation (ICA) uses 1D RT results applied to each ~1 km column within a 5×21 km assessment domain. The 3D Monte Carlo (MC) RT model, however, requires a buffer zone around the assessment domain to handle lateral transfer of photon across assessment domain boundaries. Hence, both RT models require construction of a 3D atmospheric scene that surrounds the satellite's nadir track. This is achieved by EarthCARE's Scene Construction Algorithm (SCA) that is based on an MSI radiance-matching technique to populate off-nadir columns with, ideally nearby, profiles of information inferred along nadir (Barker et al. 2011, 2012, 2014; Qu et al., 2023). However, because MSI radiances are governed much by both cloud total optical depth and cloud-top temperature, there is always the potential for structural errors in constructed 3D scenes to propagate into RT simulations and diminish both the accuracy of simulated radiative fluxes and reliability of the radiative closure assessment.

Thus far, assessments of the SCA have relied primarily on synthetic 3D cloud fields generated by high-resolution numerical weather prediction (NWP) models (Barker et al., 2014, 2021; Qu et al., 2023; Donovan et al. 2023). These kinds of experiments have the advantage of knowing the 3D atmospheric conditions that the SCA is aiming for. But model-generated cloud fields and radiances are never perfect and always lack the full complexity of the real world. The purpose of the current study is to perform an evaluation of the SCA using real observations as opposed to synthetic ones. This is done using observations made during the EarthCARE Commissioning Calibration/Validation Campaign in Ottawa (ECALOT) (Qu et al., 2026). The tactical objective of ECALOT was to underfly EarthCARE with the National Research Council Canada (NRC) Convair-580 research



aircraft. Specially designed flight patterns were implemented to sample off-nadir SCA-generated cumulus (Cu) and stratocumulus (Sc) cloud properties using in situ probes. The side-viewing W-band radar onboard the Convair-580 was also used to provide horizontal planar cross-sectional views of cloud structure that intersect SCA results for nimbostratus (Ns) clouds. Further comparisons between EarthCARE’s ice cloud retrievals and values derived from the Convair-580’s side-viewing radar system provide additional tests on the quality of SCA fields.

The paper is structured as follows. Section 2 provides an overview of EarthCARE’s SCA and its ACMB-3D processor. Section 3 describes ECALOT observations. Sections 4 and 5 present evaluations based on in situ cloud measurements and side-viewing radar observations, respectively. Last, conclusions and perspectives for future studies are summarized in Section 6.

2. EarthCARE’s scene construction algorithm

The SCA has been implemented operationally in the ACMB-3D processor within the EarthCARE data processing chain (Qu et al., 2023; Eisinger et al., 2024). This section provides an overview of the algorithm and its implementation in ACMB-3D. Details of its development and testing can be found in Barker et al. (2011; 2012; 2014) and Sun et al. (2016).

Each orbit of EarthCARE yields eight ~4500 km long *frames* of data. Horizontal position within a *frame* is defined on the Joint Standard Grid (JSG), which consists of $N_{\text{JSG}}(\approx 4500)$ pixels along-track and $M_{\text{JSG}}(=150)$ pixels across-track at approximately 1 km horizontal resolution. For a given off-nadir pixel (i, j) with $i \in [1, N_{\text{JSG}}]$ and $j \in [-35, 115] \setminus \{0\}$ (hereafter *recipient pixel*), radiance matching is performed to identify the pixel on the nadir track ($j = 0$) that matches it best. The search window contains $2M + 1$ potential candidates between $[i - M, i + M]$, with M being a configurable parameter. In addition to radiance similarity, several additional criteria must be satisfied. For example, differences in $\cos(\text{SZA})$ and SAA between the candidate and recipient pixels must be less than 0.005 and 5° , respectively, to avoid selecting pixels with similar top-of-atmosphere (TOA) radiances but different illumination conditions. The along-track distance from (i, j) is also considered with closer pixels given higher priority. Once the best-matching pixel is identified at $(m^*, 0)$, referred to hereinafter as the *donor pixel*, its profiles of retrieved properties are replicated at the recipient pixel (i, j) . Figure 1 shows a schematic of this procedure. Repeating this for all off-nadir pixels yields a complete 3D atmospheric scene as required by the RT models.

As implemented in the ACMB-3D processor, radiance matching uses four MSI channels at 0.67, 2.21, 8.80, and 12.0 μm that are assigned equal weights. To become a potential recipient, differences in $\cos(\text{SZA})$ and SAA must be less than 0.005 and 5° , respectively. The 1% smallest radiance differences are then identified and the pixel closest to recipient pixel at (i, j) is selected as the donor.

Beginning with Baseline BC, three modifications were introduced into the ACMB-3D processor. Here, “Baseline” refers to a specific version of the processor software and the configuration of the data processing system used operationally to generate data products (European Space Agency, n.d.). First, 0.67 μm radiances are set to zero when $\text{SZA} > 90^\circ$ thus guarding against



visible channel noise at nighttime. Second, maximum search length M was increased from 200 km to 400 km, and third, checks on SZA and SAA differences are dropped when radiances at (i, j) fall outside the range of all candidate nadir-track pixels by more than 20%. These changes improve construction quality when off-nadir regions are sampled poorly along nadir. In this study, ACMB-3D processor software version 11.3 (Baseline BA) and 11.4 (Baseline BC) were evaluated.

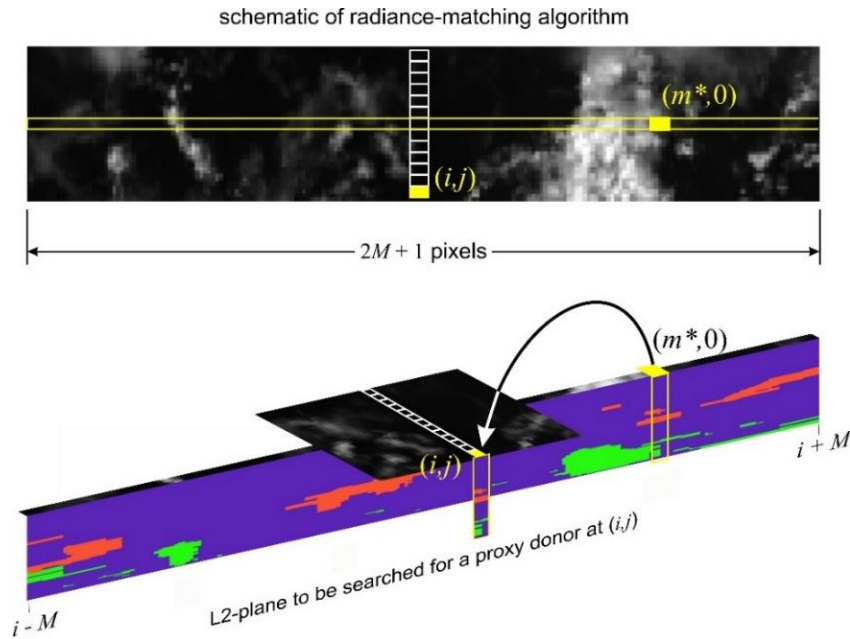


Figure 1: Top panel shows a swath of passive imagery with nadir indicated by the yellow lines. According to the SCA, radiances for the off-nadir pixel at (i, j) best match nadir radiances at $(m^*, 0)$. Lower panel is a schematic illustrating the attribution of cloud and aerosol inferences pertaining to the donor column located at $(m^*, 0)$ to the recipient column at (i, j) (from Barker et al. 2011).

3. ECALOT campaign data

ECALOT is an airborne and surface-based campaign supporting the calibration and assessment of EarthCARE's Level 1 and Level 2 products (Qu et al., 2026). The campaign was conducted between October 2024 and March 2025 in the vicinity of Ottawa and Montreal, Canada. Airborne observations were carried out on NRC Convair-580 research aircraft, which has been used extensively in atmospheric research over the past several decades (e.g., Lawson et al., 1993; Cober et al., 2001; Barker et al., 2008; McFarquhar et al., 2011; Qu et al., 2018; Liggio et al., 2019; Wolde et al., 2019; Nguyen et al., 2022; Minder et al., 2023; Kollias et al., 2025). The aircraft was equipped with remote sensing instruments including the NRC Airborne W-band (NAW), a nadir/zenith/side-viewing 94 GHz cloud radar system and zenith/nadir-looking 355 nm Airborne Elastic Cloud Lidar, together with a suite of in situ cloud and aerosol sampling probes. Surface-based observations were made near Ottawa Macdonald-Cartier International Airport (YOW) and at two Climate Sentinel stations (McGill University and Université du

Qu bec   Monr al, n.d.) located in downtown Montreal and at Gault natural reserve, approximately 33 km east of downtown Montreal. Figure 2 shows the locations of the airborne observations and surface sites, together with the corresponding EarthCARE descending orbital tracks.

Of particular relevance to this study are cloud observations from the Convair-580's in situ probes and the NAW cloud radar. In situ samplers were used to evaluate SCA performance for liquid cloud conditions, while the remote-sensing observations from the NAW side-viewing radar were used primarily for evaluating ice and mixed-phase clouds. Table 1 summarizes variables used to assess the SCA. For additional information on data processing and quality control see Qu et al. (2026).

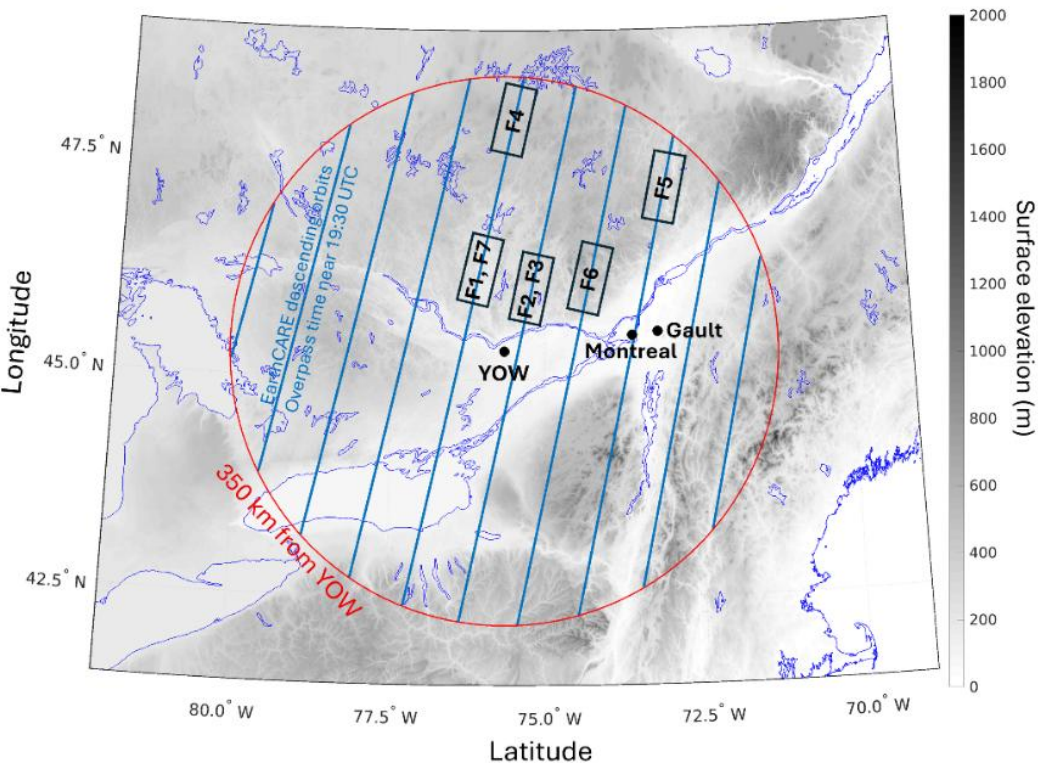


Figure 2: Blue lines indicate EarthCARE descending overpasses while rectangles show locations of ECALEOT airborne sampling regions. Flight identifiers F1 (Flight1), F2, etc. correspond to individual research flights. Locations of the surface observation sites are also shown.



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Table 1: Measured variables, and instrument information, used in this study.

Geophysical variables	Convair-580 Instruments	Relevant EarthCARE product	Observation requirements for SCA evaluation
In situ observation & geophysical retrieval			
Ice water content Ice effective radius	Composite estimation based on SPEC 2D-S and High-Volume Precipitation Spectrometer-ver.3 (HVPS-3)	A-ICE (Donovan et al., 2024) C-CLD (Mroz et al., 2023) M-COP (Hünerbein et al., 2024) ACM-COM (Cole et al., 2023) ACM-CAP (Mason et al., 2023)	Cloud properties were sampled in the off-nadir region within approximately 15 km of the satellite ground track and within ±15 min of the satellite overpass time, with sampling designed to represent a range of distances from the track.
Liquid water content Liquid effective radius	DMT Cloud Droplet Probe (CDP-2)	C-CLD M-COP ACM-COM ACM-CAP	
Bulk Ice water content Bulk liquid water content	Nevzorov probe	ACM-COM and ACM-CAP	
Remote sensing observation			
Radar reflectivity	NRC Airborne W-band (NAW) radar	C-NOM (Eisinger et al., 2024) C-FMR (Kollias et al., 2023)	NAW has zenith-, nadir-, and side-viewing beams. The latter provide horizontal cross-sections on the starboard side of the aircraft, which are well suited for evaluating the SCA at distances of up to 10 km from the nadir track.

During 2 Flights (10 October 2024) and 4 (20 November 2024), conducted under Cu/Sc cloud conditions, the Convair-580 underflight tracks were oriented at an angle of approximately 20° relative to EarthCARE’s ground-track, with satellite and aircraft tracks intersecting near the center of the underflight segment. This flight geometry enables collocated in situ sampling at nadir while also sampling off-nadir regions at increasing distances from the nadir track shortly before and after overpass. Porpoising maneuvers were also performed during several segments of both flights to sample vertical variations in cloud properties along the flight track. See Figure 3 for a schematic of flight tracks.

During 3 Flights (4 November 2024), 5 (22 November 2024), 6 (27 January 2025), and 7 (25 March 2025), conducted under Ns conditions, the Convair-580 underflight tracks were aligned with EarthCARE’s ground-track. The Convair-580 starboard-side-viewing W-band radar provides measurements of horizontal cross-sections extending out ~ 10 km from the aircraft. This configuration provides continuous sampling of off-nadir cloud structure at flight altitude. Vertical cross-sections observed by the zenith- and nadir-looking radars can be used to generate the 3D scene and that can then be compared to side-viewing cross-sections. EarthCARE’s CPR nadir cross section can also be used in a similar way.



Given that EarthCARE's RT simulations (Cole et al., 2023) require 3D atmospheric conditions that extend out to ~15 km from the nadir-track, with most important contributions occurring within 10 km, sampling by the side-viewing W-band radar will be captured in most cases. Beyond 15 km, however, SCA indices are still generated by the ACMB-3D processor but they are not used for RT calculations, though they might be useful for other applications.

While EarthCARE's instruments operated fully during most ECALOT flights, its CPR was off for Flight 1 (1 October 2024), and there were several large gaps in MSI products for Flight 2 (10 October 2024). As such, evaluation was not conducted for Flight 1, while for Flight 2 GOES-East (or GOES-16) radiances, interpolated to the JSG resolution (~1 km) using a nearest-neighbour method, took the place of the MSI and were employed by the SCA.

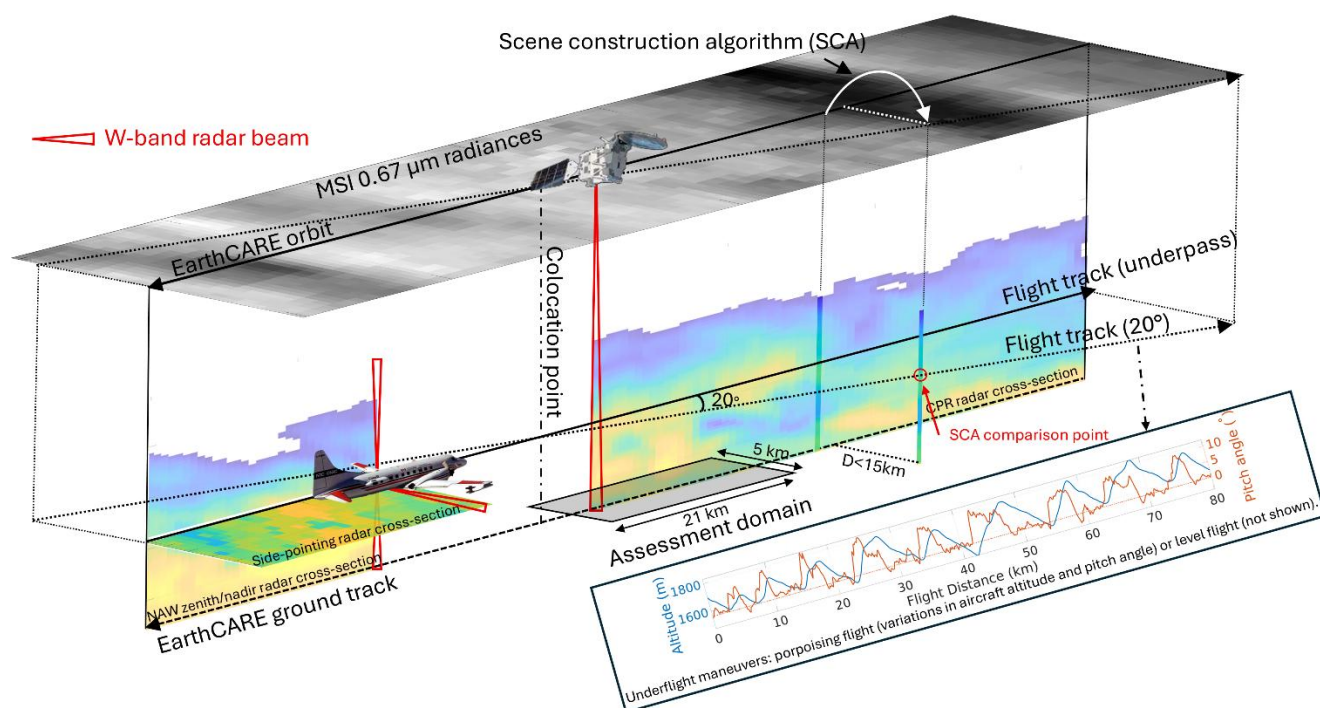


Figure 3: Schematic illustrating the aircraft sampling strategies used during ECALOT to assess EarthCARE's SCA. Two underflight configurations were employed: one aligned with the EarthCARE ground track and the other crossing it at a 20° angle off-set. Both are referred to as underflight segments, in contrast to the sampling tracks conducted before and after the satellite overpass that did not include a collocation point with EarthCARE.



4. Results I: Evaluation of the SCA for liquid clouds

4.1. Evaluation with high-resolution numerical weather prediction (NWP) model simulation

155 To demonstrate the effectiveness of the campaign design for SCA validation using in situ observations for liquid cloud cases, simulations from a high-resolution numerical weather prediction (NWP) model were used. An advantage of using NWP-simulated clouds is that the cloud properties and 3D cloud structure of the model atmosphere are fully known, thereby eliminating uncertainties associated with retrieval errors. In addition, the temporal and spatial mismatches arising from the large difference in speed between the Convair-580 and EarthCARE can be eliminated by deriving both the sampled and
160 constructed cloud properties from the same model time step. The sampled cloud properties are obtained directly from the NWP fields through spatial matching along the aircraft track. In contrast, the constructed properties are generated by the SCA using NWP nadir columns and TOA spectral radiances simulated with the MSI Tool (Madenach et al., 2022). This approach allows the SCA performance to be assessed independently of retrieval errors and temporal and spatial sampling mismatches.

To simulate the realism of the cloud structure and properties, Environment and Climate Change Canada's Global
165 Environmental Multi-scale Model (GEM, Côté et al., 1998; Girard et al., 2014; McTaggart-Cowan et al., 2019) with a horizontal grid spacing of 250 m and 84 vertical hybrid layers was used (Leroy et al., 2014, 2018; Bélair et al., 2018; Qu et al., 2018, 2023). This high-resolution simulation was downscaled from the simulations at 1.0 km and 2.5 km horizontal grid-spacings (Milbrandt et al., 2016; Cholette et al., 2024).

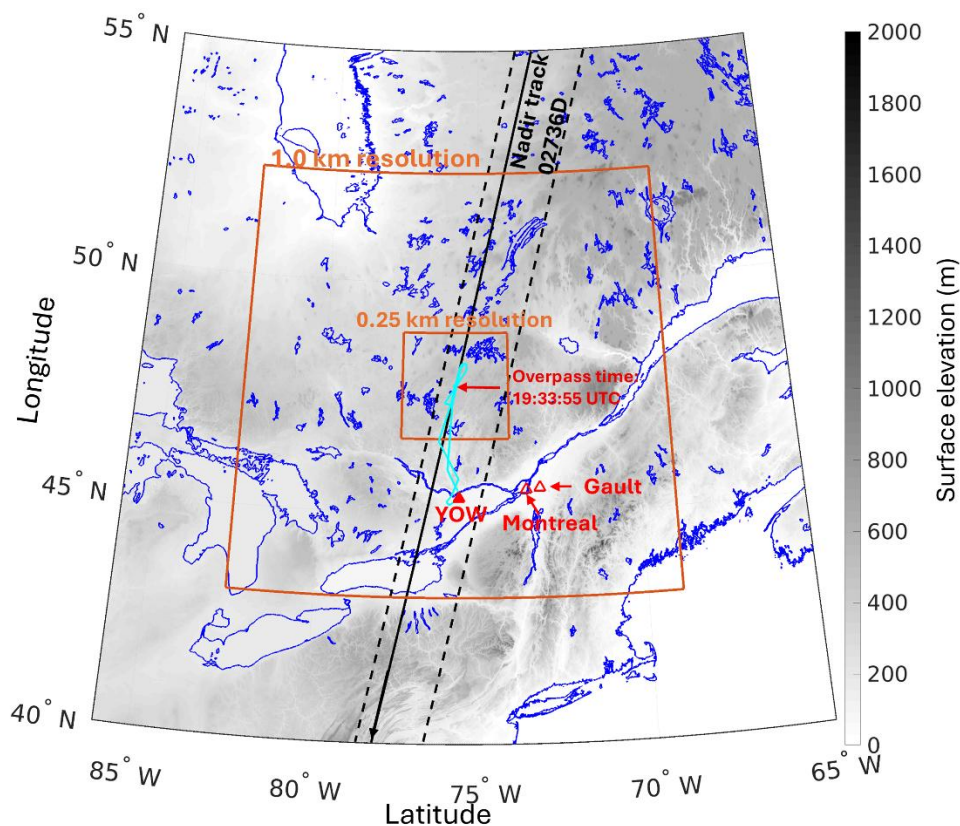


Figure 4: map showing the simulation domains for 1.0 and 0.25 km horizontal grid-spacing using GEM (orange squares), EarthCARE MSI swath (dashed black lines) and nadir track (solid black line) for a section of the frame 02736D, Convair-580 flight track during ECALOT Flight 4 (cyan line), and surface sites (red triangles; filled: Ottawa; open: Montreal and Gault).

The simulation was initialized at 00:00 UTC on 20 November 2024, centred on the region north of Ottawa in southern Quebec, and was run for 24 h. Low-level liquid Cu clouds were present around the EarthCARE overpass time (~19:33 UTC), with cloud tops near 1 km altitude. The 1 km and 250 m simulation domains are shown by the orange rectangles in Figure 4, with the innermost domain centred on the satellite-aircraft collocation point (indicated by the red arrow). Model output at 19:30 UTC, closest to the EarthCARE overpass time, was saved and used for the analysis. The GEM-simulated cloud and atmospheric state properties were interpolated onto EarthCARE's Joint Standard Grid (JSG) for Frame 02736D (ECALOT Flight 4), which has a horizontal resolution of 1 km and a vertical resolution of 100 m below 20 km altitude.

The TOA radiances at 0.67 μm (Figure 5a) and 10.08 μm (Figure 5d) were simulated using the MSI Tool (Madenach et al., 2022) for the innermost simulation domain. As shown in Figure 4, this domain has a horizontal grid spacing of 250 m and covers an area of approximately $250 \times 250 \text{ km}^2$. SCA version 11.4, the same version used in the operational Baseline BC, successfully constructs the general cloud pattern for Frame 02736D (Figure 5b, e). The construction errors are generally below $10 \text{ W m}^{-2} \text{ sr}^{-1}$ for the 0.67 μm channel and $0.1 \text{ W m}^{-2} \text{ sr}^{-1}$ for the 10.08 μm channel (Figure 5c, f).



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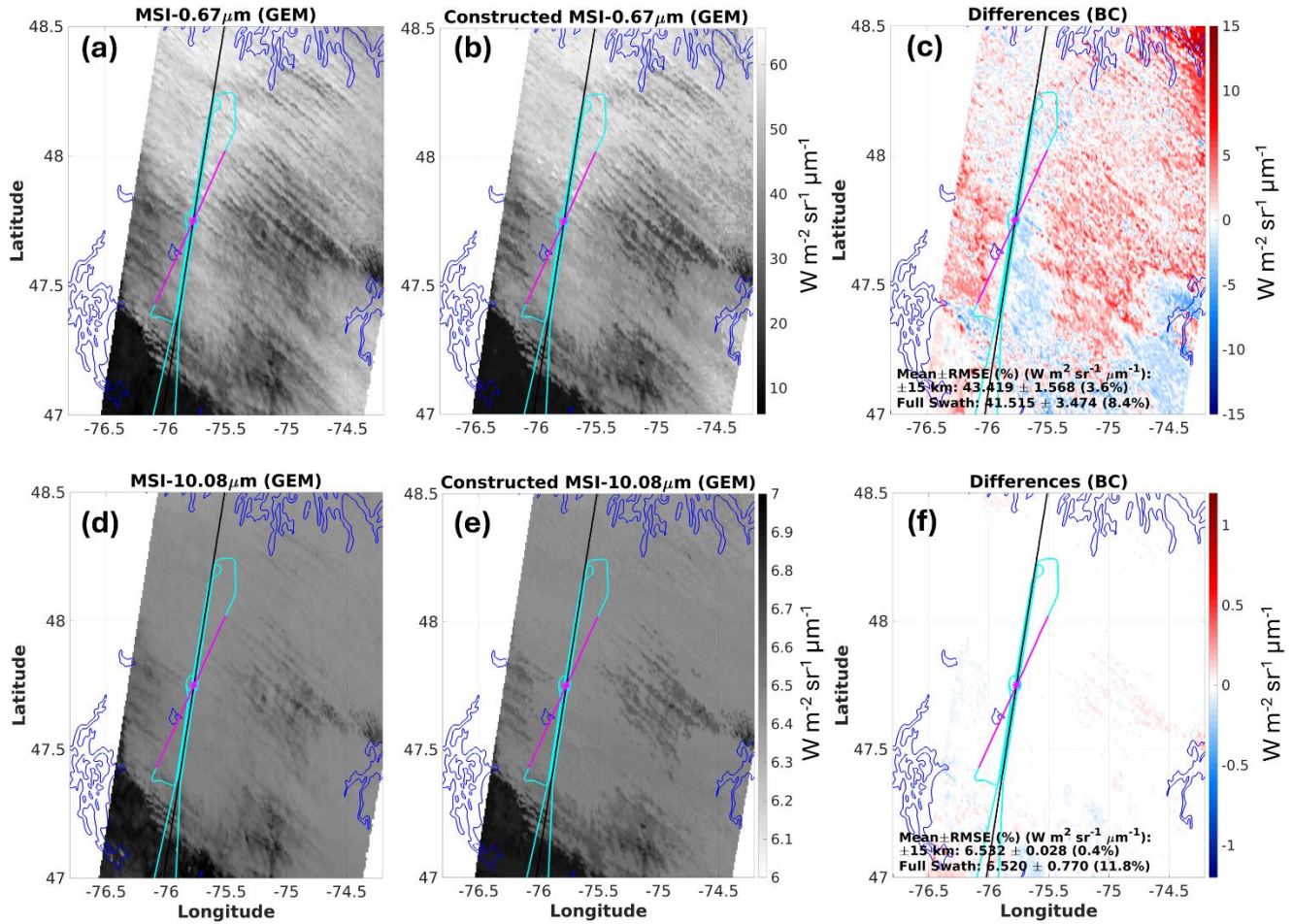


Figure 5: ECALOT Flight 4 on 20 November 2024, with the EarthCARE track for Frame 02736D indicated by black lines. Panels (a) and (d) show MSI radiances at 0.67 μm and 10.08 μm , respectively, simulated using the MSI Tool with GEM-simulated clouds at 0.25 km horizontal grid spacing. Panels (b) and (e) show the corresponding radiances constructed by the SCA, while panels (c) and (f) show the differences between the constructed and simulated MSI radiances. Cyan lines indicate the aircraft flight track, while magenta lines indicate the underflight segments used for SCA assessment. The magenta asterisk marks the satellite-aircraft collocation point.

Although the high-resolution GEM simulation provides more realistic cloud properties and structures than the lower-resolution simulations (Bélair et al., 2018; Leroyer et al., 2022), one limitation is that the domain extends only ~ 250 km along the satellite track. This limits the pool of available *donor pixels* along the nadir track and may negatively affect the construction quality. The impact of this limitation may become more pronounced with increasing distance from the satellite nadir track (> 15 km), as suggested by the larger construction errors in Figure 5c and f.

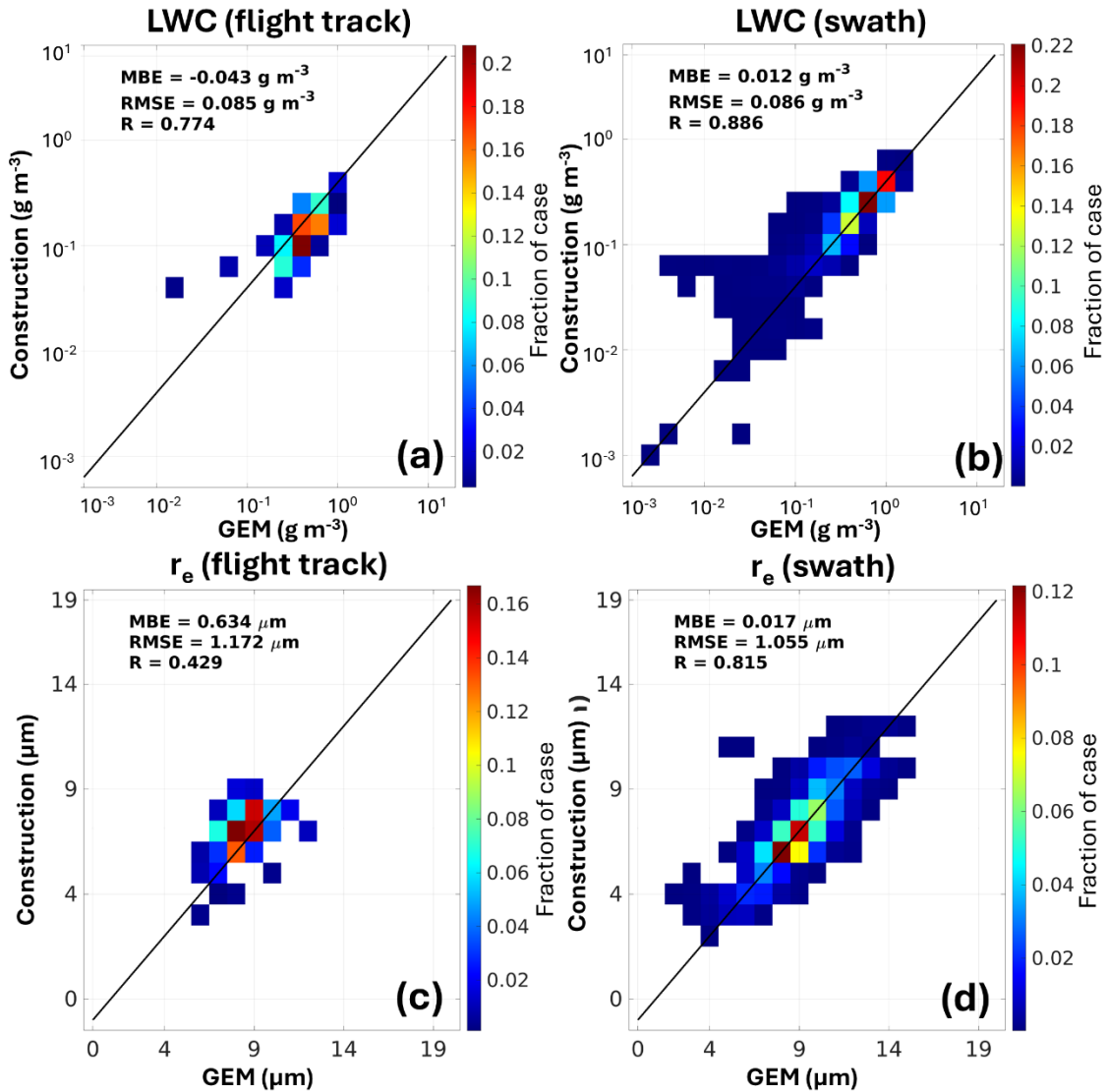


Figure 6: Scatter plots of GEM simulated LWC (x-axis) and constructed LWC (y-axis). Panel (a) shows the comparison on Convair-580's flight track during the underflight segment; panel (b) shows the results using all the available LWC at the flight level within 15 km of distance to the satellite nadir track. Panels (c) and (d) are the same as (a) and (b), respectively, but for r_e .

For the comparison between NWP-simulated and constructed cloud properties, two sampling approaches are considered: (1) aircraft-track sampling, in which validation points are selected using nearest-neighbour matching along the Convair-580 underflight track within a distance of ~ 15 km to the satellite nadir track (magenta lines in Figure 5), and (2) swath sampling, in which all available points at the aircraft flight altitude within a 30 km-wide swath centered on the satellite nadir track (15 km on each side) are used, with the nadir pixels excluded from the comparison.



For the aircraft-track sampling approach, the simulated and constructed liquid water content (LWC) values show good agreement, with a mean bias error (MBE) of -0.043 g m^{-3} , a root-mean-square error (RMSE) of 0.085 g m^{-3} , and a correlation coefficient (R) of 0.744. The mean simulated LWC on the flight track is 0.273 g m^{-3} . The 2D histogram in Figure 6a shows that the distribution is closely aligned with the 1:1 line. The swath sampling approach includes values from a 30 km wide 2D cross-section, rather than a single flight track, resulting in a broader range of LWC values in Figure 6b. Nevertheless, the overall performance is comparable, with an MBE of 0.012 g m^{-3} , an RMSE of 0.086 g m^{-3} , a R of 0.886, and a mean simulated LWC of 0.365 g m^{-3} .

For liquid effective radius (r_e), MBEs of 0.634 and $0.017 \mu\text{m}$ are found for the aircraft-track and swath sampling approaches, respectively, with corresponding RMSEs of 1.172 and $1.055 \mu\text{m}$, and R of 0.429 and 0.815. The mean values of r_e for the aircraft-track and swath sampling approaches are 8.43 and $8.93 \mu\text{m}$, respectively (Figure 6c-d).

The distance from the nadir track can potentially have a strong impact on scene construction quality, as demonstrated in previous studies (Barker et al., 2011, 2012, 2014; Qu et al., 2023). Figure 7 shows the MBE, mean, and RMSE as functions of distance from the satellite nadir track, up to 15 km, for both the aircraft-track and swath sampling approaches. For both LWC and r_e , the MBEs remain small and show no clear increase with distance from the nadir track (Figure 7a, c). For swath sampling, the LWC RMSE increases slightly from approximately 0.07 g m^{-3} near nadir to 0.09 g m^{-3} at a distance of 15 km (Figure 7b). Aircraft-track sampling exhibits greater variability w.r.t the distance to nadir due to the smaller number of samples but likewise shows no systematic increase in LWC RMSE with distance. A similar behaviour is observed for r_e (Figure 7c, d). Overall, these results indicate that the SCA performance for this Sc case remains stable within 15 km of the nadir track. Therefore, despite its smaller sample size, aircraft-track sampling provides a representative assessment of the overall SCA performance, supporting the effectiveness of the underflight sampling strategy for SCA validation.

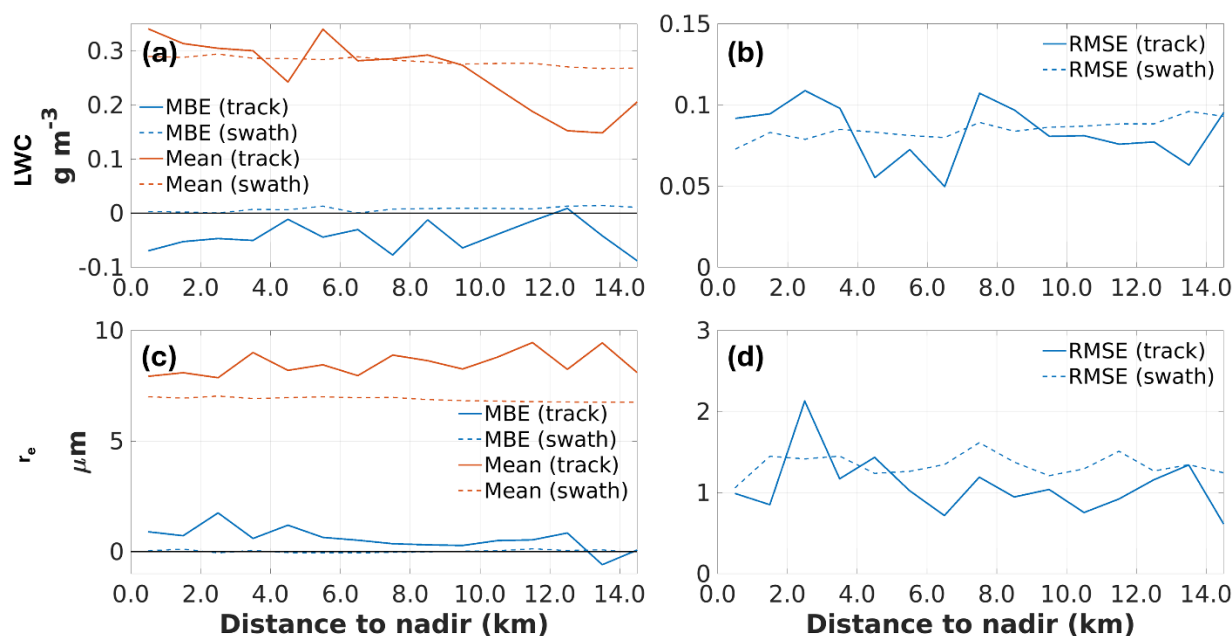


Figure 7: (a) GEM-simulated mean LWC (red lines) and SCA bias (blue lines) as functions of distance from the nadir track for Flight 4. (b) Corresponding RMSE. Solid lines represent aircraft-track sampling along the Convair-580 underflight segment, while dashed lines represent swath sampling at the aircraft flight altitude within 12 km on either side of the satellite nadir track. Panels (c) and (d) are the same as (a) and (b), respectively, but for r_e .

4.2. Evaluation of the construction quality of TOA radiances

We first assess the construction quality of the TOA radiances across the entire MSI swath (~150 km) for flights sampling liquid clouds (Sc/Cu). Figure 8 (a) and (d) shows MSI images, for the 0.67 μm and 10.08 μm channels, that correspond to ECALOT Flight 4 on 20 November 2024. While a two-layer stratocumulus cloud system was observed in the southwest at altitudes of ~1 km and 3 km (red cycle in Figure 8a), to the north there was just one layer at ~1 km. The underflight segment sampled along EarthCARE's ground-track between 47.4° N and 48.1° N. The SCA's constructed TOA radiances, using the version of Baseline BC, are shown in (b) and (e) of Figure 8. Differences between constructed and observed MSI radiances are shown in (c) and (f). For the full, 150 km-wide, MSI swath, RMSE, calculated on the JSG grid, is 1.360 $\text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (4.0% of the mean) for the 0.67 μm channel and 0.124 $\text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (2.0% of the mean) for the 10.08 μm channel. Construction quality improves slightly when limiting the analyses to within 15 km of the satellite ground track, which is most relevant for radiative closure assessment, and when evaluated at the assessment-domain scale (i.e., 5×21 arrays of pixels), RMSE is reduces further to 0.190 $\text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (0.60% of the mean) for the 0.67 μm channel and 0.028 $\text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (0.44% of the mean) for the 10.08 μm channel. In contrast, MBEs are small at all scales, even across the full MSI swath where they are 0.167 $\text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (-0.49%) and -0.0036 $\text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (-0.056%) for the 0.67 μm and 10.08 μm channels, respectively.

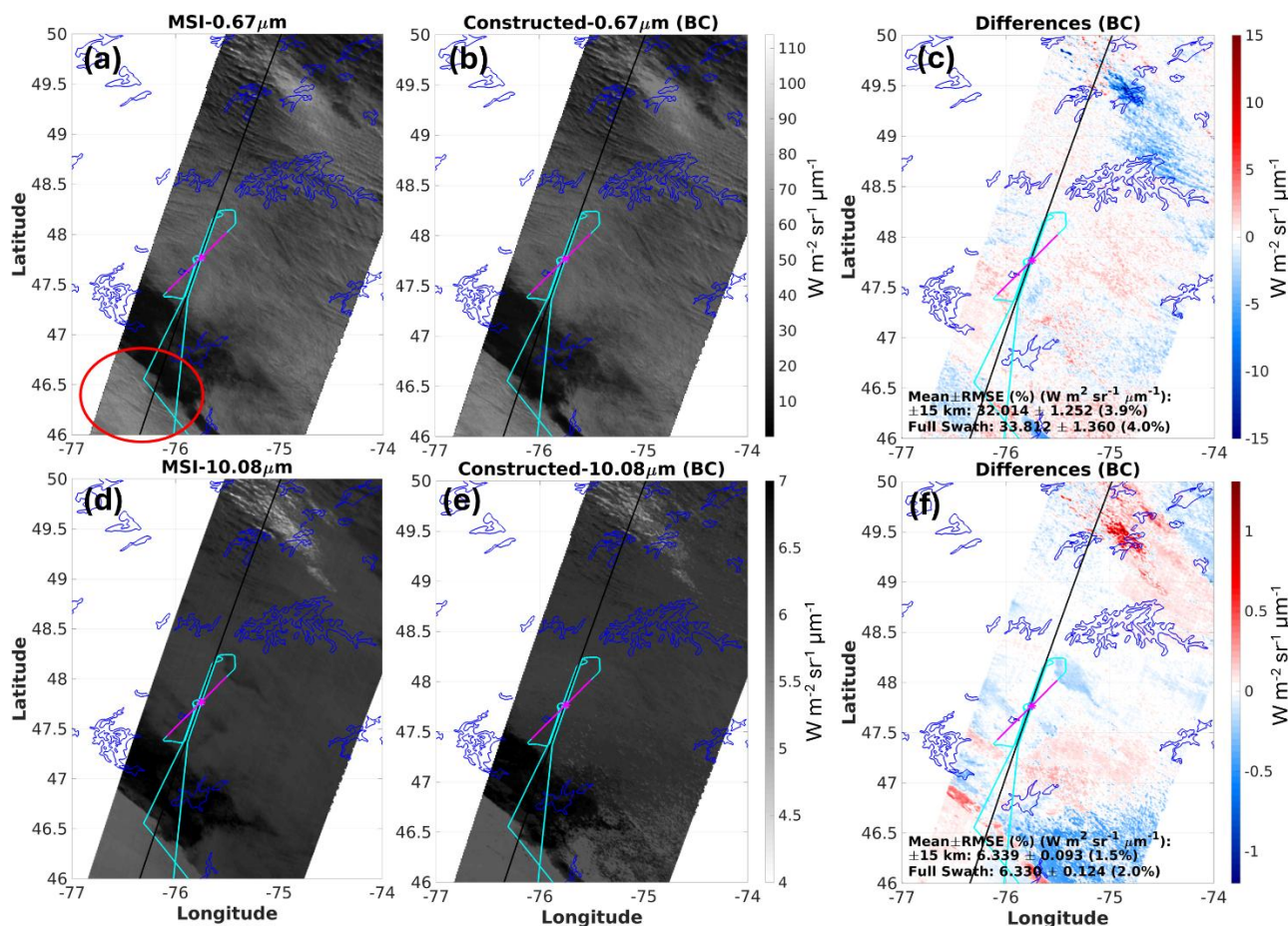


Figure 8: ECALOT Flight 4 on November 20, 2024 with EarthCARE's track, for Frame 02736D, indicated by black lines. (a) and (d) show MSI radiances at 0.67 μm and 10.08 μm , respectively, while (b) and (e) show corresponding radiances constructed by the SCA. (c) and (f) are differences between SCA and MSI radiances. Cyan lines indicate aircraft path while magenta lines mark aircraft position for SCA assessment. Magenta asterisk is the satellite-aircraft collocation point.

Figure 9 shows aircraft and satellite tracks for ECALOT Flight 2, on 10 October 2024, which encountered a shallow boundary-layer cumulus/stratocumulus deck, exhibiting organized wave-like (*undulatus*) structure, between altitudes 1.3 km and 1.8 km. To mitigate gaps in MSI observations during this frame, GOES-16 radiances measured at 19:26-19:28 UTC, which was close to EarthCARE's overpass at 19:29:50 UTC, were interpolated via nearest-neighbour for spectral channels close to the MSI's (i.e., GOES channels 0.64, 2.24, 8.4, and 12.3 μm), and used by the SCA.

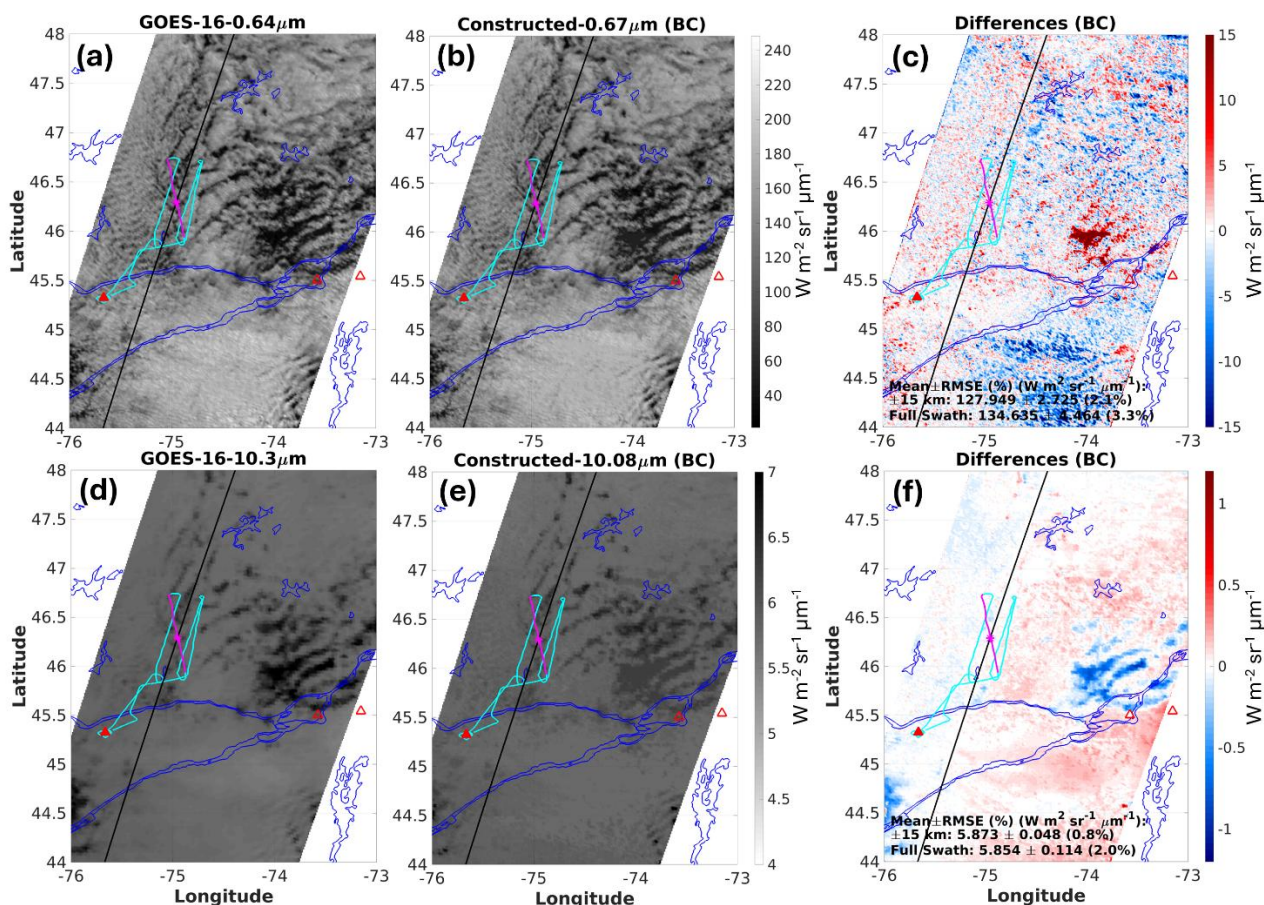


Figure 9: As in Figure 8 but for ECALOT Flight 2 on October 10, 2024 and EarthCARE Frame 02098D. Note that GOES-16 radiances, interpolated to EarthCARE's grid, are used as proxies for this Frame's missing MSI measurements. Red triangles: YOW site near Ottawa (filled), Montreal and Gault stations (open).

260 For the full 150 km-wide MSI swath, RMSE, calculated on the JSG grid, is $4.464 \text{ W m}^{-2} \text{ sr}^{-1} \mu\text{m}^{-1}$ (3.3% of the mean) for the $0.67 \mu\text{m}$ channel and $0.114 \text{ W m}^{-2} \text{ sr}^{-1} \mu\text{m}^{-1}$ (2.0% of the mean) for the $10.08 \mu\text{m}$ channel. Restricting analysis to within 15 km of EarthCARE's nadir-track reduces RMSE to $2.725 \text{ W m}^{-2} \text{ sr}^{-1} \mu\text{m}^{-1}$ (2.1%) and $0.048 \text{ W m}^{-2} \text{ sr}^{-1} \mu\text{m}^{-1}$ (0.8%) for the two channels, respectively.

265 At the assessment-domain scale, RMSE values become almost negligible at $0.407 \text{ W m}^{-2} \text{ sr}^{-1} \mu\text{m}^{-1}$ (0.32%) for the visible channel and $0.007 \text{ W m}^{-2} \text{ sr}^{-1} \mu\text{m}^{-1}$ (0.12%) for the thermal channel. In contrast, MBEs are small at all scales, maximizing across the full MSI swath at $-0.482 \text{ W m}^{-2} \text{ sr}^{-1} \mu\text{m}^{-1}$ (-0.36%) and $0.014 \text{ W m}^{-2} \text{ sr}^{-1} \mu\text{m}^{-1}$ (0.23%) for the $0.67 \mu\text{m}$ and $10.08 \mu\text{m}$ channels, respectively.



Overall, the Baseline BC of the ACMB-3D product constructs well the TOA radiances for the cumulus/stratocumulus conditions, especially for the region within a distance of 15 km from the satellite nadir track. In this section, comparison results are presented for the 0.67 and 10.08 μm channels (0.64 and 10.3 μm for GOES-16). Similar conclusions are obtained for the other channels. Although the impact of scene construction on TOA radiances is generally small, as indicated by the low RMSE values listed in Figure 8 and Figure 9, it remains unclear as to whether the same can be said for vertical and horizontal structures of cloud microphysical properties. To address this, in situ cloud observations collected along the underflight segments are used to evaluate SCA results.

4.3. Evaluation with in situ data and EarthCARE retrievals

Having demonstrated with the high-resolution NWP simulation in the section 4.1 that the ECALOT underflight sampling strategy provides a representative assessment of SCA performance, we now use actual in situ observations collected during the underflight segments of ECALOT Flights 2 and 4 to evaluate the SCA for Sc and Cu clouds. Unlike the controlled NWP experiment, the full 3D cloud fields and their properties are unknown under real atmospheric conditions. The in situ measurements can serve as reference observations, but are available only along the aircraft flight track. Furthermore, uncertainties in the EarthCARE retrievals of liquid cloud properties directly affect the SCA evaluation and may complicate the attribution of errors to the scene construction itself.

Two EarthCARE operational cloud retrieval products are available: the composite (ACM-COM, Cole et al., 2023) and synergy (ACM-CAP, Mason et al., 2023) products. Currently, the retrieval of liquid cloud properties remains challenging for the Baseline BA, the most recent baseline reprocessed to cover the commissioning phase from June to December 2024. Preliminary evaluation of the ACM-CAP product indicates that Baseline BA may underestimate LWC and liquid effective radius and may not adequately represent the expected adiabatic or sub-adiabatic vertical profile.

The ACM-COM product, in contrast, combines single-instrument retrievals to provide a complete representation of the observed cloud field. However, each contributing retrieval has limitations for liquid clouds. The CPR may not detect optically thin or weakly reflecting liquid clouds in the C-CLD product (Mroz et al., 2023) because of its sensitivity limit, while the ATLID A-ICE product (Donovan et al., 2024) retrieves ice cloud properties but does not provide liquid cloud properties. The MSI M-COP product (Hünerbein et al., 2024) provides vertically integrated cloud water path or cloud top effective radius, but does not resolve their vertical structures.

In this study, we therefore independently apply an ATLID-extinction-based method to retrieve LWC following Eq. 1 (Hu et al., 2007, 2021; Donovan et al., 2015):

$$LWC = \frac{2\rho r_e \alpha}{3} \quad (1)$$

in which ρ is density of water, α is the calibrated ATLID lidar extinction coefficient. The liquid effective radius near cloud top is obtained from the M-COP product. An empirical correction is then applied to adjust vertical profiles of LWC and effective



radius to improve their agreement with the in situ observations. Specifically, the LWC profiles derived from ATLID extinction in the A-EBD product (Donovan et al., 2024) are adjusted to better represent an adiabatic or sub-adiabatic vertical structure, with cloud-base height identified using the C-TC target classification product (Irbah et al., 2023). Such an adiabatic-like increase in LWC with height is clearly evident from the in situ observations for Flight 4 (see Figure 11d). The effective radius profile below cloud top is adjusted assuming that effective radius increases approximately as the one-third power of height above cloud base (Eq. 2), based on the relationship between effective radius, LWC, and droplet number concentration (Martin et al., 1994; Brenguier et al., 2000):

$$r_e \propto \left(\frac{z - z_{cloud\ base}}{z_{cloud\ top} - z_{cloud\ base}} \right)^{1/3} \quad (2)$$

in which z is the in-cloud altitude, and $z_{cloud\ top}$, $z_{cloud\ base}$ representing the cloud top and cloud base height. The minimum value of r_e is set to 4 μm at the cloud base (Hirsch et al., 2014).

The adjustments described above aim to minimize discrepancies between the retrieved cloud properties and the in situ observations, thereby reducing retrieval-related uncertainties and allowing the subsequent evaluation to better isolate errors associated with the SCA. Further evaluation will be conducted when improved synergy and composite products for liquid cloud retrievals become available.

For both Flight 4 and Flight 2, the SCA were applied to generate off-nadir LWC and r_e based on the EarthCARE retrievals using the method described in the subsection 4.2. Due to the $\sim 20^\circ$ angle of the underflight segment relative to the satellite ground track, the analysis includes both near-nadir satellite-aircraft collocations (magenta asterisks in Figure 8 and Figure 9) and off-nadir observations sampled shortly before and after the overpass time. Figure 10 shows constructed cloud-property cross-sections along the underflight segments for Flight 4 and Flight 2. As the aircraft moves away from the satellite-aircraft collocation point, temporal mismatches increase due to the Convair-580's lower airspeed relative to EarthCARE's. These temporal differences further translate into spatial mismatches through cloud evolution and advection. To mitigate these effects in the following analyses, in situ data are averaged over 3 km segments, corresponding to approximately 30 s of aircraft sampling, and EarthCARE retrievals are averaged over 3×3 pixel regions ($\sim 3 \times 3 \text{ km}^2$).

The circles with red borders, also highlighted by the red arrows, in Figure 10 indicate locations approximately 12 km from the nadir track. From the satellite-aircraft collocation point to these locations, the Convair-580 requires approximately 6 minutes. During this time, cloud advection can reach on the order of $\sim 3 \text{ km}$, further reducing the validity of direct comparisons, even when averaging over 3 km (in situ) and $\sim 3 \times 3 \text{ km}$ (satellite) domains.

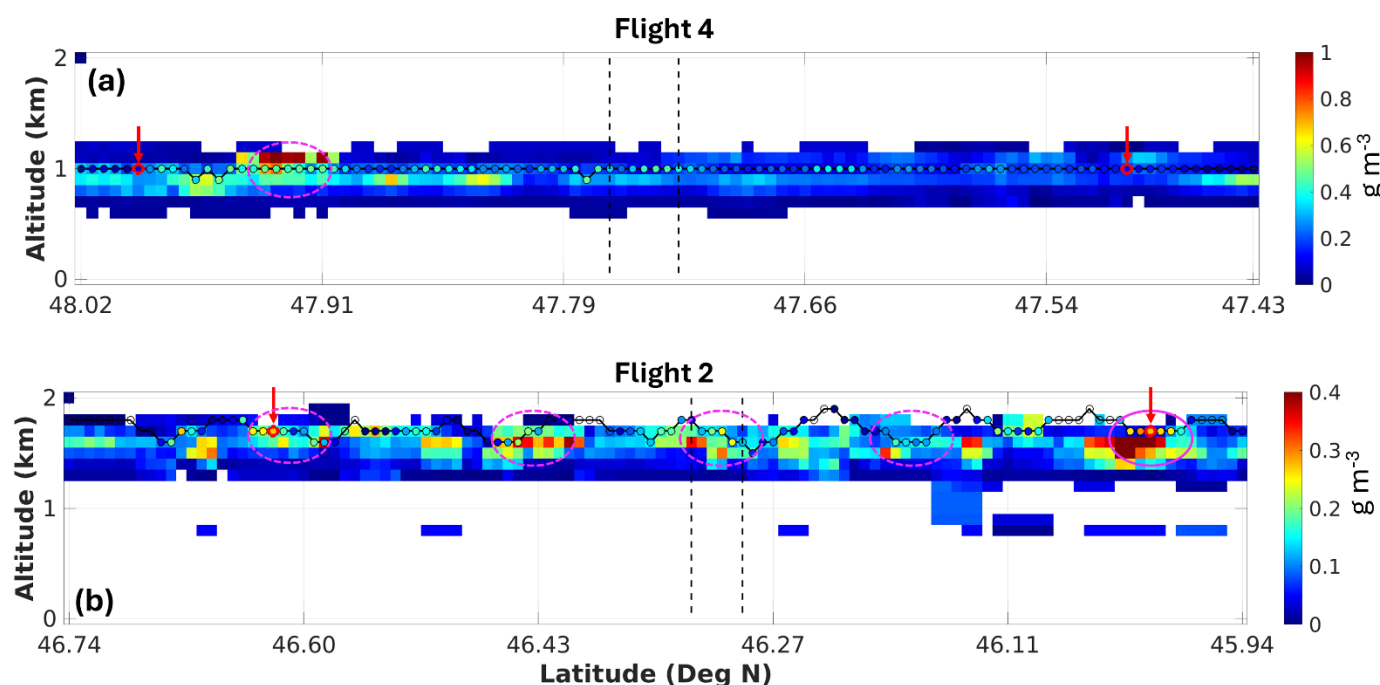


Figure 10: Cross-sections of cloud water contents from ACM-CAP along nadir track segments (magenta lines in Figure 8 and Figure 9) for Flights 4 (a) and 2 (b). Coloured circles represent in situ measurements. Circles with red borders (also pointed by the red arrows) indicate that measurements were made more than 12 km away from the nadir track. The two dashed vertical lines indicate the region within 1 km of distance to the nadir track.

For Flight 4, although the cloud layer appears relatively uniform in Figure 8 based on TOA radiances, substantial horizontal variability in LWC is evident in the in situ measurements (coloured circles in Figure 10a). The constructed fields also capture pronounced variability. In particular, enhanced LWC near 47.91° N is consistently observed by the in situ probes and reproduced in the construction (dashed magenta cycle in Figure 10a).

For Flight 2, enhanced LWC is observed in situ near 46.60°N, 46.43° N, 46.32° N, 46.17° N and 46.03° N (magenta cycles in Figure 10b). The construction captures the enhancement near 46.60°N, 46.403° N, 46.32°N and 46.17° N (dashed magenta cycles in Figure 10b), but underestimates LWC at 46.03° N, although layers with comparable values are present slightly below the flight altitude (solid magenta cycle in Figure 10b).

To provide a broader assessment of the SCA performance, we also include a non-underflight segment for each flight. Although these segments are less reliable for direct SCA validation, they provide complementary information on the vertical structure of the cloud layers. They also allow comparison between the retrieved and in situ cloud properties beyond the altitudes and regions sampled during the underflight segments. Because of the substantially larger temporal mismatches with the EarthCARE observations, however, these comparisons should be interpreted with caution.

For ECALOT Flight 4, the retrieved cloud properties agree reasonably well with the in situ observations along the underflight segment, where the aircraft maintained level flight at ~1000 m altitude. The LWC has a bias of $-0.015 g m^{-3}$ and an RMSE of



0.136 g m⁻³, while r_e has an MBE of -1.079 μm and an RMSE of 2.931 μm (Figure 11a-c). The 2D histograms show that the retrieved and observed LWC and r_e values are generally distributed around the 1:1 line, although the values are concentrated within a relatively narrow range and with a systematic negative bias for r_e (Figure 12a, b).

After the EarthCARE underpass, the Convair-580 proceeded to porpoising through an upper stratocumulus layer located approximately at 3200 m altitude. The porpoising manoeuvre provides measurements of the vertical cloud structure, which exhibits an approximately adiabatic profile (Figure 11a, d, e). The retrieved properties also show reasonable agreement with the in situ observations for this upper cloud layer, with an MBE and RMSE of 0.127 and 0.270 g m⁻³, respectively, for LWC, and -1.868 and 2.771 μm , respectively, for r_e . It should be noted that the upper-layer porpoising flight was conducted approximately 1.5 h after the satellite overpass (20:55-21:10 UTC compared with 19:33 UTC) thus, introducing additional uncertainty due to cloud evolution and advection. Nevertheless, the retrieved vertical profiles reproduce the observed approximately adiabatic structure of the cloud layer.

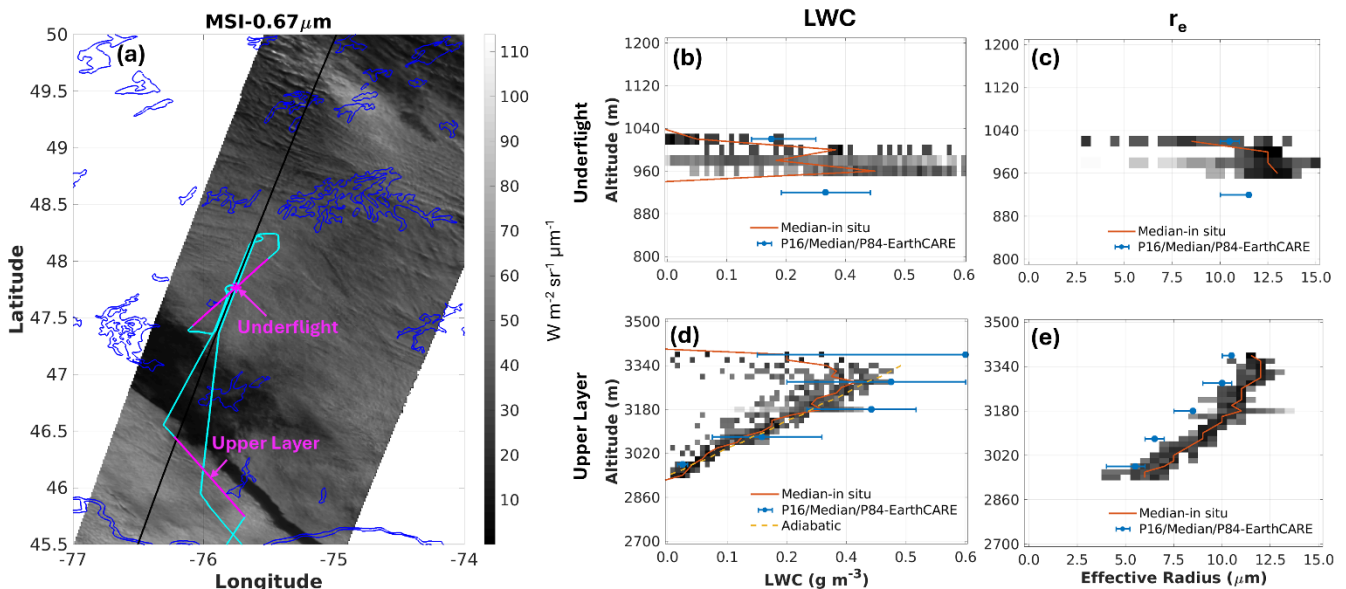


Figure 11: comparison of in situ observed cloud properties with EarthCARE retrievals for ECALOT Flight 4. (a) MSI TOA radiance at 0.67 μm , with cyan lines indicating the aircraft flight track and magenta lines highlighting the two flight segments used for the cloud-property comparisons. Panels (b) and (c) show comparisons of LWC and liquid effective radius, respectively, for the underflight segment at ~ 1 km altitude, while panels (d) and (e) show the corresponding comparisons for the upper cloud layer at ~ 3 km altitude.

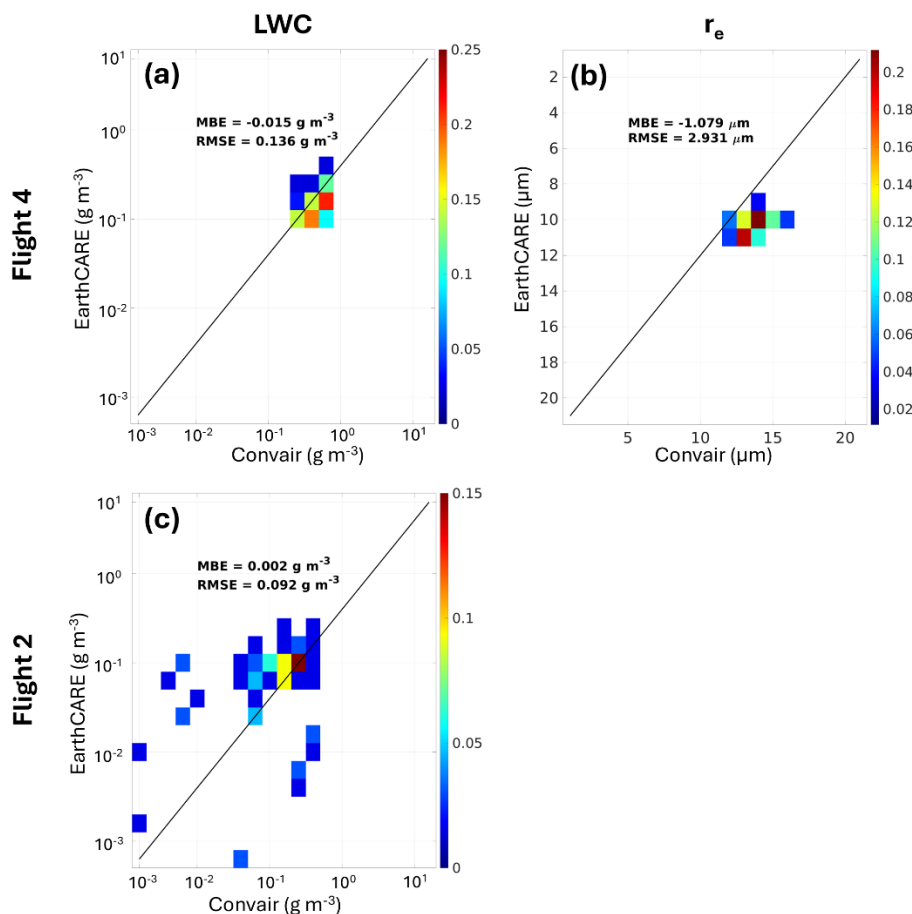


Figure 12: Scatter plots of EarthCARE retrievals against Convair-580 in situ observations for the underflight segments of Flights 4 and 2.

365 For Flight 2, the absence of MSI observations necessitated the use of GOES-16 radiances, which likely degrades the construction quality due to their coarser spatial resolution at the thermal infrared channels ($>2 \text{ km}$) and parallax effects in the region between 46° N and 47° N .

Overall, the retrieved LWC agrees well with the in situ observations along the underflight segment, during which the Convair-580 performed porpoising manoeuvres within the upper 200 m of the cloud layer, with an MBE of 0.002 g m^{-3} and an RMSE of 0.092 g m^{-3} (Figure 12c, Figure 13b). Good agreement is also found for the subsequent full-profiling segment, during which the Convair-580 porpoised through the entire cloud layer, with an MBE of 0.007 g m^{-3} and an RMSE of 0.115 g m^{-3} (Figure 13c). Due to the absence of reliable MSI observations, liquid effective radius is not included in the comparison.

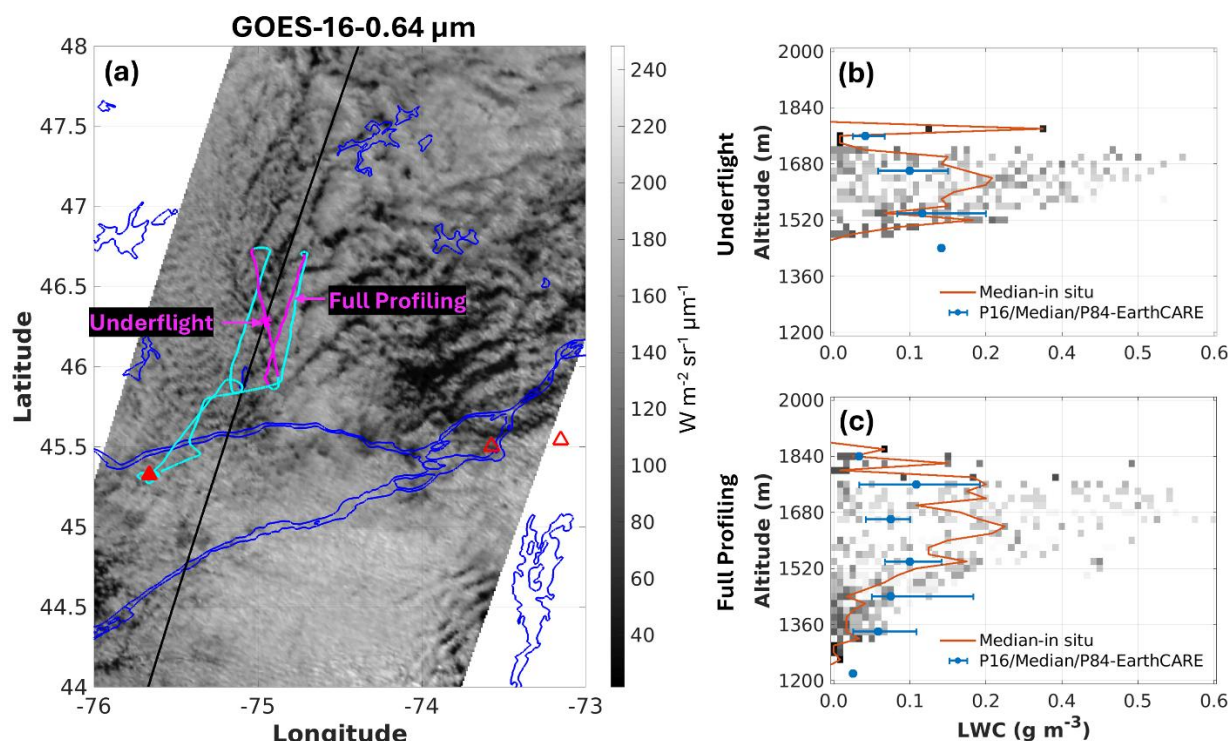


Figure 13: similar to Figure 11, but for ECALOT Flight 2. Due to gaps in the MSI observations during this frame, GOES-16 radiances were mapped onto the MSI swath and used for the SCA. Liquid effective radius is not shown because the missing MSI observations prevent a reliable retrieval. (a) GOES-16 TOA radiance at 0.64 μm . (b) LWC comparison for the underflight segment, during which the Convair-580 conducted porpoising flight within the upper ~ 200 m of the cloud layer. (c) LWC comparison for the subsequent full-profiling segment, during which the Convair-580 porpoised through the entire cloud layer.

Because the previous studies (Barker et al., 2011, 2012, 2014; Qu et al., 2023) have shown that the construction quality degrades with increasing distance from nadir. A key question is therefore what constitutes a suitable distance for reliable construction. To assess this for these particular cases of flights 2 and 4, the mean, MBE, and RMSE as functions of distance to the nadir track are shown in Figure 14 and Figure 15.

For the LWC of Flight 4, the absolute MBE and the RMSE are generally below 0.2 g m^{-3} for distances up to approximately 12 km (solid lines in Figure 14a, b). Beyond this distance, both MBE and RMSE increase further, suggesting that the degradation is primarily due to increasing temporal and spatial mismatches rather than SCA performance, as the GEM-based assessment showed no comparable increase in errors beyond 12 km (Figure 7). One exception occurs in the region very close to the nadir track (<1 km), where a negative MBE and elevated RMSE are observed. This behaviour is primarily attributed to retrieval uncertainties rather than scene construction errors, as the influence of the construction algorithm is minimal near nadir. In this region, uncertainties in the vertical structure of liquid clouds are the dominant source of error.



390 For r_e during Flight 4, both the MBE and RMSE remain low within 12 km of the nadir track, with the absolute MBE below 3 μm and the RMSE below 4 μm (Figure 14c, d). Beyond 12 km, the errors increase gradually, reaching approximately 7 μm for both MBE and RMSE, indicating a degradation in performance.

Similar behaviour for LWC is observed for Flight 2 (Figure 15). The MBE and RMSE remain small and relatively stable for distances up to approximately 10-11 km, beyond which both metrics increase substantially. This increase is likely driven by
 395 growing temporal and spatial mismatches associated with the large difference in airspeed between the Convair-580 and EarthCARE.

Because GOES-16 radiances were used for the scene construction for Flight 2, additional uncertainties may be introduced compared with the use of MSI observations. To assess whether the use of GOES-16 radiances affects the conclusions, we conducted a similar analysis for Flight 4 by replacing the MSI observations with GOES-16 radiances. The results are shown
 400 by the dashed lines in Figure 14. The use of GOES-16 radiances introduces noticeable differences in both MBE and RMSE, particularly for LWC. Nevertheless, the overall conclusion remains unchanged: SCA-related errors remain relatively small within 12 km of the satellite nadir track.

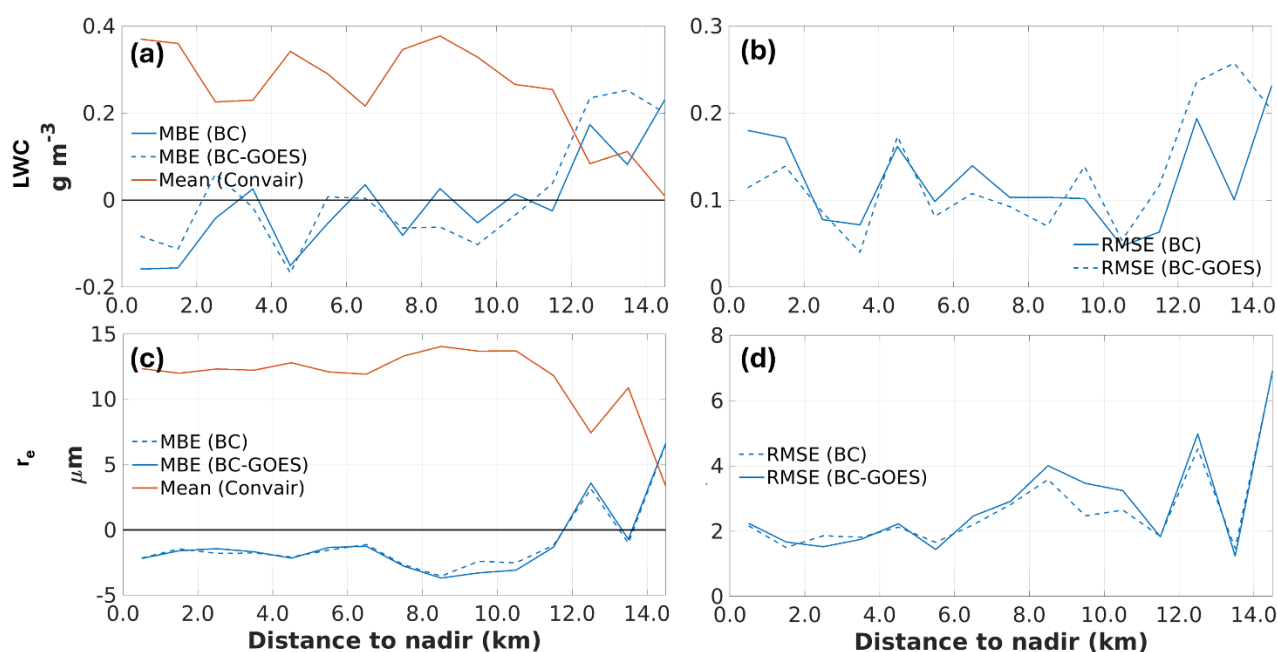


Figure 14: (a) Observed mean value (red line) and SCA bias (blue line) for LWC as functions of distance from nadir track for Flight 4. (b) Corresponding RMSE for (a). (c) and (d) are as (a) and (b) except for r_e . The data used are along the underflight track highlighted by the magenta lines in Figure 8.
 405

These results demonstrate that the scene construction algorithm performs robustly for these cases at distances up to approximately 12 km from the satellite nadir track. This finding supports the requirements for radiative closure assessment,



which is typically confined to within 10 km of the nadir track. Beyond 11–12 km, comparisons with in situ observations might
 410 become increasingly limited by inherent temporal and spatial mismatches, similar to the Flight 4 case.

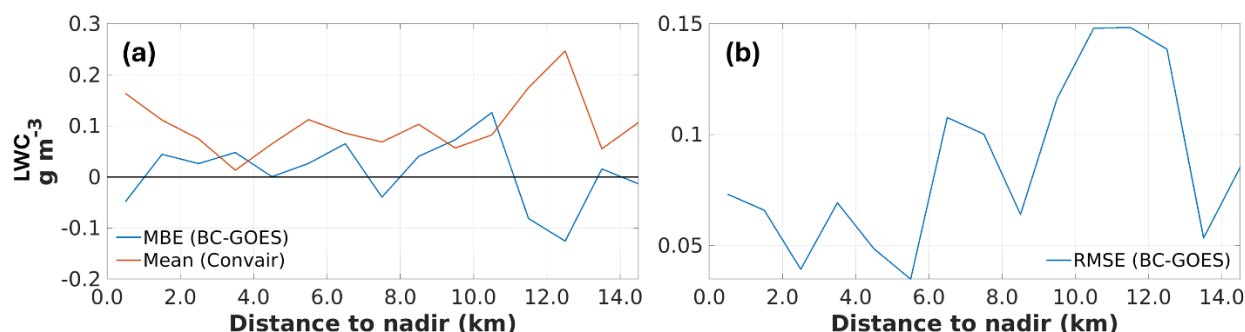


Figure 15: similar to Figure 14a, b but for the underflight segment of Flight 2.

The improvement from Baseline BA to BC is not clearly evident based on the in situ results (not shown). One reason is that, for Flight 4, the stratocumulus cloud layers are relatively homogeneous in terms of TOA radiances (Figure 8). EarthCARE
 415 samples representative *donor pixels* along the nadir track at proximity to the recipient pixels. Under these conditions, expanding the search distance up to 400 km does not impact on the construction quality, as the most suitable donor pixels are already located nearby.

For Flight 2, the fractured stratocumulus cloud field (Figure 9) allows nadir observations to sample a range of conditions, including both cloudy and clear-sky regions, thereby providing a sufficiently diverse pool of *donor pixels* for scene
 420 construction. As a result, suitable donor pixels are again available within the nearby region, and the performance of Baseline BC remains very similar to that of Baseline BA.

5. Results II: Evaluation of the SCA for ice and mixed-phase clouds using side-viewing radar observations

5.1. ECALOT Flight 6 on 27 January 2025

This section examines the construction quality for cases involving ice and mixed-phase clouds. During ECALOT Flight 6 on
 425 27 January 2025, a nimbostratus cloud system was observed (Figure 16a, Figure 17a), with cloud top reaching up to 8 km altitude (Figure 18a). The aircraft underflight segment was conducted at an altitude of 4.5 km, approximately 3.5 km below cloud top as indicated by the black line in Figure 18a. At this level, the aircraft sampled ice cloud conditions with an ambient temperature of approximately -23°C (figure not shown).

Unlike the previous cases (Flights 4 and 2), the extensive overcast conditions limit the ability of nadir observations to sample
 430 a diverse range of cloud states, which in turn affects the scene construction in off-nadir regions. This behavior is evident for Frame 03794D during Flight 6, where the construction quality from Baseline BA is degraded over the eastern portion of the



MSI swath (44.2°-45.3° N) for both the 0.67 μm (Figure 16d) and 10.08 μm channels (Figure 17d), particularly under thin cirrus or clear-sky conditions. By extending the search distance in Baseline BC, up to 400 km, more suitable *donor pixels* can be identified, resulting in a substantial improvement in construction accuracy for this case (Figure 16e and Figure 17e).

435 The constructed TOA radiances from the Baseline BC show good agreement with the MSI observations. The constructed radiances for the 0.67 μm and 10.08 μm channels (Figure 16c and Figure 17c) reproduce the overall cloud horizontal structure well. The differences between the constructed and original MSI radiances are presented in Figure 16e and Figure 17e. Over the full swath, the RMSE values are 2.88 $\text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (3.1%) and 0.122 $\text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (4.0%) for the 0.67 μm and 10.08 μm channels, respectively. For the region within 15 km of the nadir track, the RMSE decreases to 2.399 $\text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (2.5%)
 440 and 0.075 $\text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (2.5%), respectively. The MBE remains low over the full swath, with values of 0.0844 $\text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (0.091%) and -0.0243 $\text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (-0.804%) for the two channels.

At the assessment-domain level, the RMSE values from the Baseline BC are 0.306 $\text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (0.32%) and 0.0127 $\text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (0.43%), which are substantially lower than those at the JSG pixel level. This indicates that the scene construction introduces only a minor impact on the radiative closure assessment.

445 The construction quality for the TOA radiance is similar for the Baseline BA within a distance of 15 km from the nadir track with RMSE values of 2.306 $\text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (2.4%) and 0.075 $\text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (2.5%) for the 0.67 μm and 10.08 μm channels, while the quality is significantly lower for the full swath with RMSE values of 7.977 $\text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (8.6 %) and 0.301 $\text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (10.0%). The MBE for the full swath is also larger with values of 1.608 $\text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (1.735%) and -0.0601 $\text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (-1.989%) for the two channels.

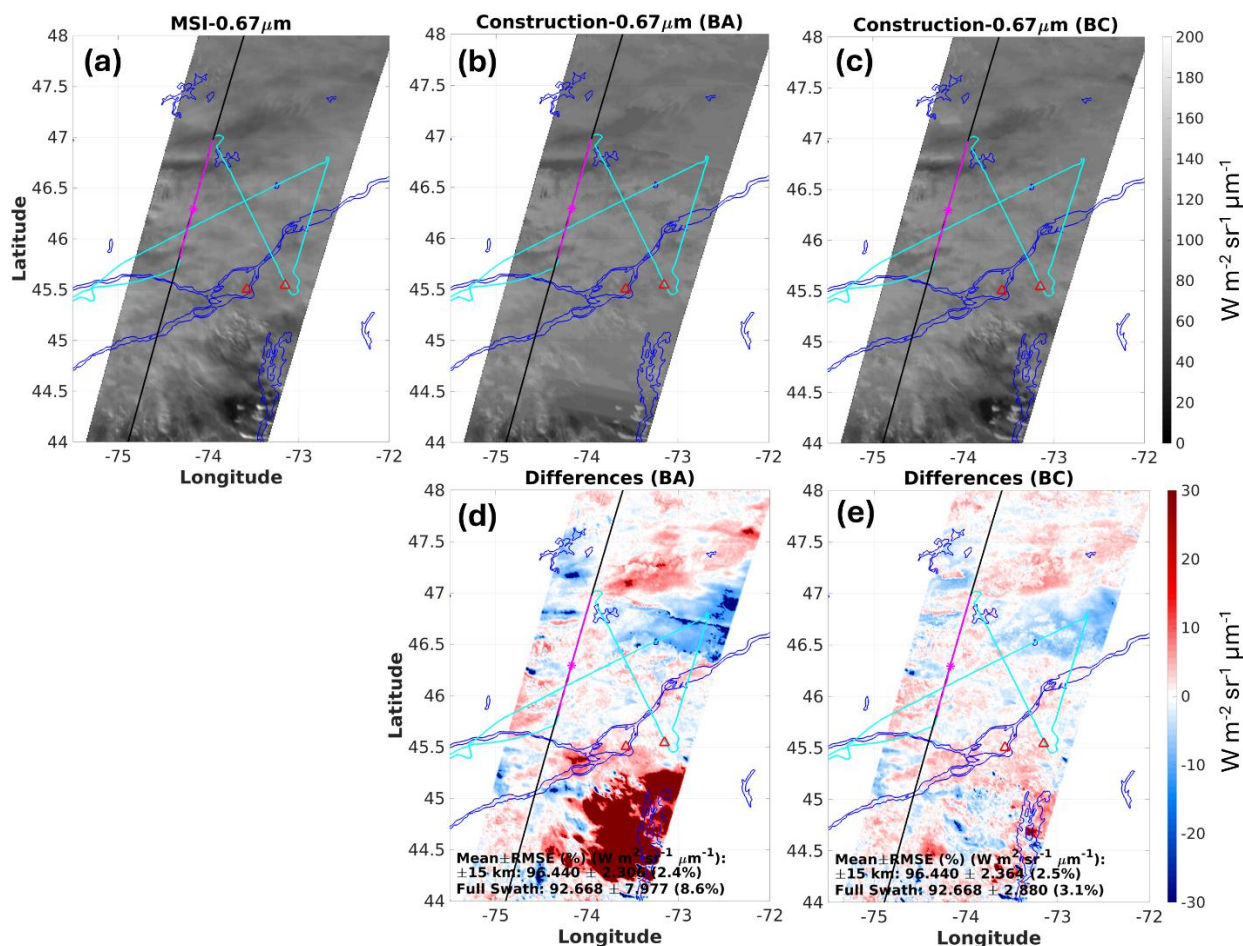


Figure 16: ECALOT Flight 6 on January 27, 2025 for the EarthCARE Frame 03794D. (a) MSI radiances at 0.67 μm . (b) and (c) are constructed SCA radiances for Baselines BA and BC, respectively. (d) and (e) Differences between SCA and MSI radiances for Baselines BA and BC, respectively. Black line indicates EarthCARE's track, cyan line show aircraft path, while magenta line highlights the segment used for SCA assessment. Magenta asterisk marks satellite-aircraft collocation point, and open red triangles indicates location of the Montreal and Gault surface sites.

During Flight 6, the starboard side-viewing NAW radar sampled the off-nadir cloud structure up to approximately 10 km from the satellite nadir track (Figure 18b). During the underflight segment, the Convair-580 continuously adjusted its roll and heading angles to maintain close alignment with the satellite nadir track. These variations affect the apparent sampling geometry of the radar, such that the observed reflectivity in Figure 18b does not lie on a single geometric plane but spans variable altitudes, from -1.4 to 2.7 km at a horizontal distance of 10 km from the nadir track. These effects are accounted for in the comparison with the constructed fields. Near the satellite-aircraft collocation point, the NAW radar was intentionally turned off to avoid interference with EarthCARE's W-band radar, resulting in the data gap between 46.16° N and 46.18° N in Figure 18a.

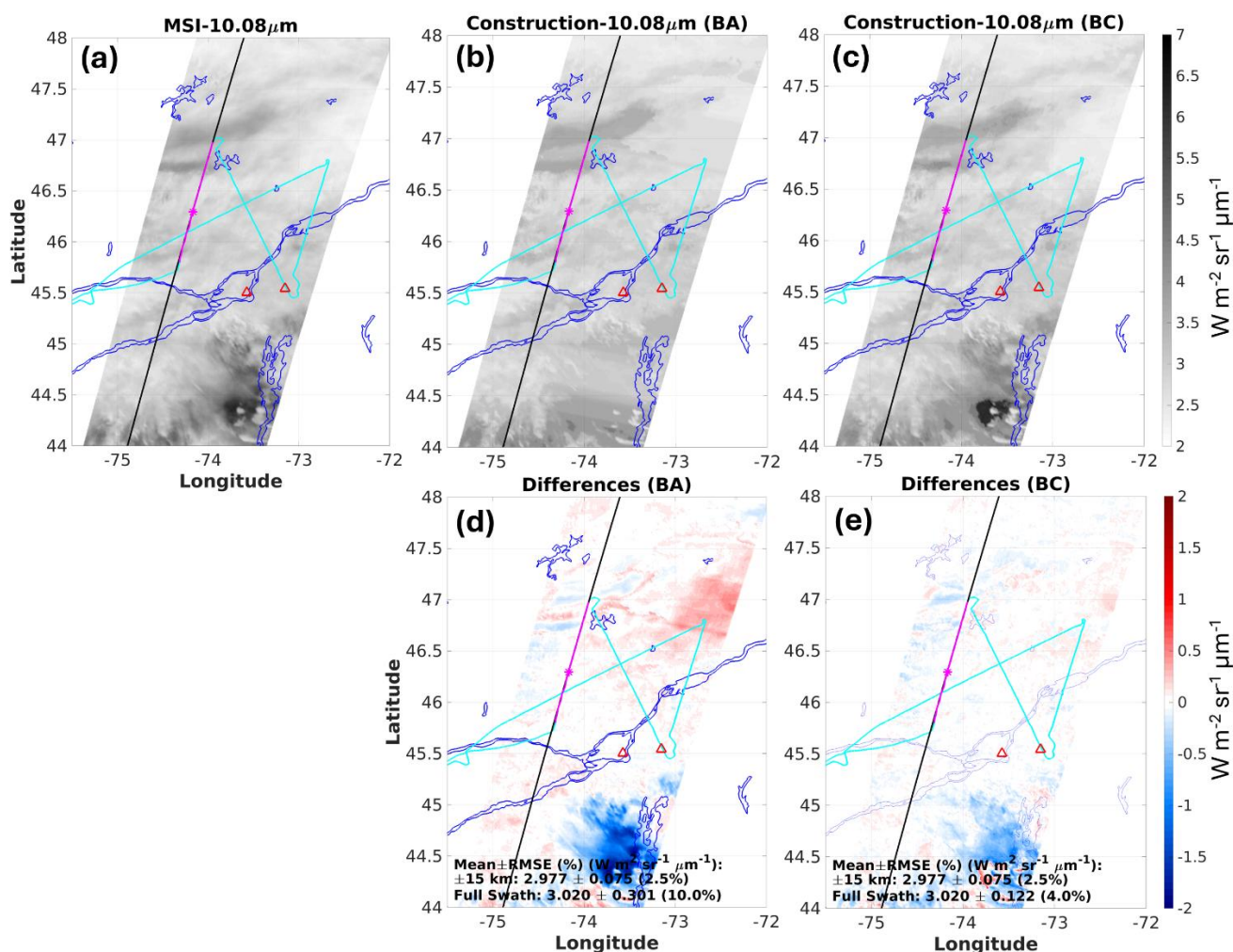


Figure 17: As in Figure 16 except these are for the 10.08 μm channel.

To reconstruct side-viewing radar reflectivity using NAW zenith- and nadir-looking profiles as *donor profiles* and EarthCARE ACMB-3D construction indices, the NAW profiles were first interpolated onto the JSG grid at approximately 1 km horizontal and 100 m vertical resolution (Figure 18a). The near-range radar blind zone was filled by linear interpolation between the nearest valid reflectivity values above and below the aircraft. The reconstructed side-viewing reflectivity fields are shown in Figure 18c and d for Baselines BA and BC, respectively.

In addition to the segment near the collocation point where NAW was switched off, blank pixels in Figure 18b-d result from four exclusion criteria: (1) construction indices referencing donor profiles acquired while NAW was switched off; (2) construction indices referencing locations outside the available NAW zenith/nadir transect (45.8-47.0° N); (3) a signal-to-noise ratio below 0 dB in the NAW side-viewing observations; or (4) reflectivity below -20 dBZ in the observations or either

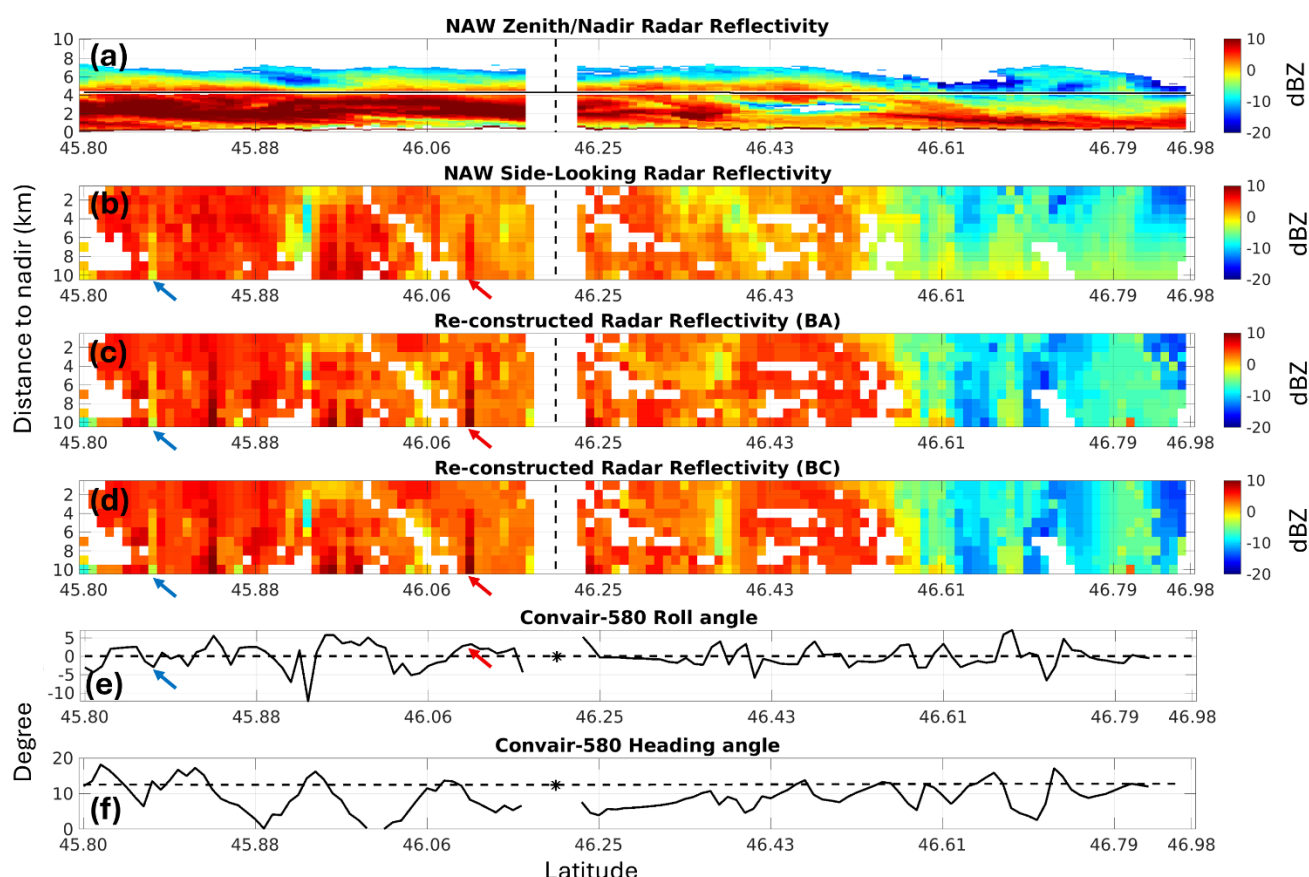


reconstruction. If a pixel met any applicable exclusion criterion in the NAW side-viewing observations or either baseline reconstruction, the corresponding pixel was excluded from all three fields to ensure consistent comparisons.

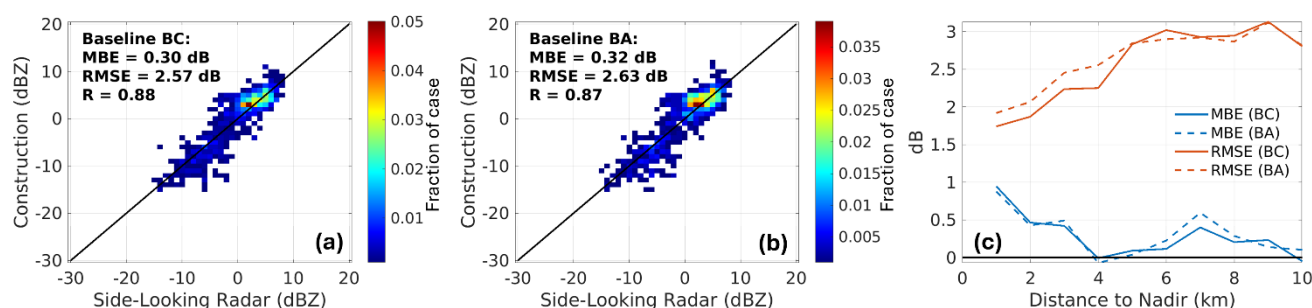
480 A visual comparison between the observed and constructed side-viewing radar reflectivity shows consistent spatial patterns, with higher reflectivity in the southern portion of the scene and lower reflectivity toward the northern end (Figure 18b, c and d). Linear (“line-shaped”) features present in both fields are associated with abrupt changes in aircraft roll angle (Figure 18e), which redirect the radar beam toward lower altitudes (indicated by red arrows) or higher altitudes (blue arrows).

For Baseline BC, the 2D histogram in Figure 19a shows a correlation coefficient between the construction and NAW of 0.88, an MBE of 0.3 dB, and an RMSE of 2.57 dB. The variation of MBE and RMSE as a function of distance from the satellite nadir track is presented in Figure 19c (solid lines). The biases remain below 1 dB at all distances, while the RMSE increases
485 gradually from 1.75 dB within 1 km of the nadir track to approximately 3.1 dB at a distance of 9 km. This gradual increase is consistent with previous studies (Barker et al., 2011, 2012, 2014; Qu et al., 2023) and remains moderate.

For Baseline BA, the correlation coefficient between the construction and NAW is 0.87, with an MBE of 0.32 dB and an RMSE of 2.63 dB, indicating slightly poorer performance compared to Baseline BC (Figure 19a and b). The variation of MBE and RMSE as a function of distance from the satellite nadir track for Baseline BA is also shown in Figure 19c (dashed lines).
490 The MBE is higher than that of Baseline BC within 5 km of the nadir track, while the RMSE is generally higher between 5 and 9 km. These results suggest that Baseline BC performs slightly better in this case, although the differences are minor. This is consistent with the minor differences between the two Baselines for the construction of TOA radiances within 15 km distance to the nadir track, presented previously.



495 Figure 18: Radar reflectivity and aircraft attitude during ECALOT Flight 6. (a) NAW zenith- and nadir-beam reflectivity as a function of
 time and altitude; the solid line indicates aircraft altitude. (b) NAW side-viewing-beam reflectivity as a function of time and distance from
 the aircraft. (c, d) As in (b), but for SCA reflectivity derived from EarthCARE CPR Baselines BA and BC, respectively, and collocated with
 the NAW side-viewing beam. Dashed lines in (a-d) mark the location of vertical alignment between the aircraft and EarthCARE. (e) Convair-
 500 580 roll angle averaged over approximately 1 km flight segments, matching the JSG horizontal resolution; positive angles indicate right
 wing down and left wing up. (f) As in (e), but for heading, measured clockwise from north (0°); the dashed line indicates the heading aligned
 with EarthCARE's ground track. Asterisk signs in (e, f) mark the location of vertical alignment between the aircraft and EarthCARE. Arrows
 mark aircraft roll manoeuvres.



505 Figure 19: (a) 2D histogram of NAW side-viewing radar reflectivities against SCA values, derived from EarthCARE’s CPR reflectivities, for Flight 6 using Baseline BC. (b) As in (a) but this is for Baseline BA. (c) MBE and RMSE for data shown in (a) and (b) as functions of distance to nadir track.

The construction results shown in Figure 18 and Figure 19 are based on NAW zenith- and nadir-pointing radar profiles used as the *donor profiles*. The advantage of this approach is that the different NAW beams are internally well calibrated, thereby minimizing inter-beam offsets. However, the construction indices are derived from EarthCARE’s ACMB-3D product, which
 510 relies on MSI radiances acquired during the satellite overpass. As a result, the construction quality degrades with increasing distance from the satellite-aircraft collocation point due to temporal mismatch, as well as cloud evolution and advection.

An alternative approach is to use CPR-observed radar profiles as *donor profiles* to construct the side-viewing radar reflectivity and compare it with NAW side-viewing radar observations. This approach has two main limitations: (1) a reflectivity offset is
 515 present in the C-NOM product from the most recent Baseline DA; and (2) temporal mismatches between CPR and NAW observations can reach up to 12.5 minutes near the edges of the underflight segment during Flight 6. As expected, this approach yields poorer performance for Baseline BC, with an MBE of -1.92 dB, an RMSE of 3.84 dB, and a correlation coefficient of 0.75, and shows only weak dependence on distance from the nadir track.

5.2. ECALOT Flight 5 on 22 November 2024

520 During ECALOT Flight 5 on 22 November 2024, a low-pressure system was observed over eastern Canada. The region north of Montreal was predominantly cloudy, with thin cirrus above 5 km and thicker ice and mixed-phase clouds below (Figure 20a, Figure 21a and Figure 22a). MSI observations at visible and thermal wavelengths show strong spatial variability in TOA radiances (Figure 20a, Figure 21a), indicating a complex multilayer cloud system with fragmented cloud cover. Such conditions present a particularly challenging test for the SCA.

525 Due to the high spatial variability of clouds in this case, the impact of the updates to the scene construction algorithm from Baseline BA to BC appears more pronounced than in Flight 6. The Baseline BC reproduces the 0.67 μm MSI radiances reasonably well (Figure 20c), while the Baseline BA didn’t construct well enough the lower radiance regions in the central section (Figure 20b). The Baseline BA produced many localized errors exceed 30 $\text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ for the 0.67 μm channel (Figure 20d) while the Baseline BC’s errors are generally smaller (Figure 20e). These larger errors in Baseline BA are primarily



530 associated with the high spatial variability of TOA radiances. In some regions, particularly farther from the nadir track, suitable *donor pixels* cannot be identified along the nadir track within a given searching distance (<200 km for Baseline BA due to the maximal search distance and solar geometry restriction), while when increasing the searching distance to 400 km in Baseline BC, better *donor pixels* could be found. Similarly for the $10.08\ \mu\text{m}$ channel, the construction quality is also improved significantly (Figure 21d, e).

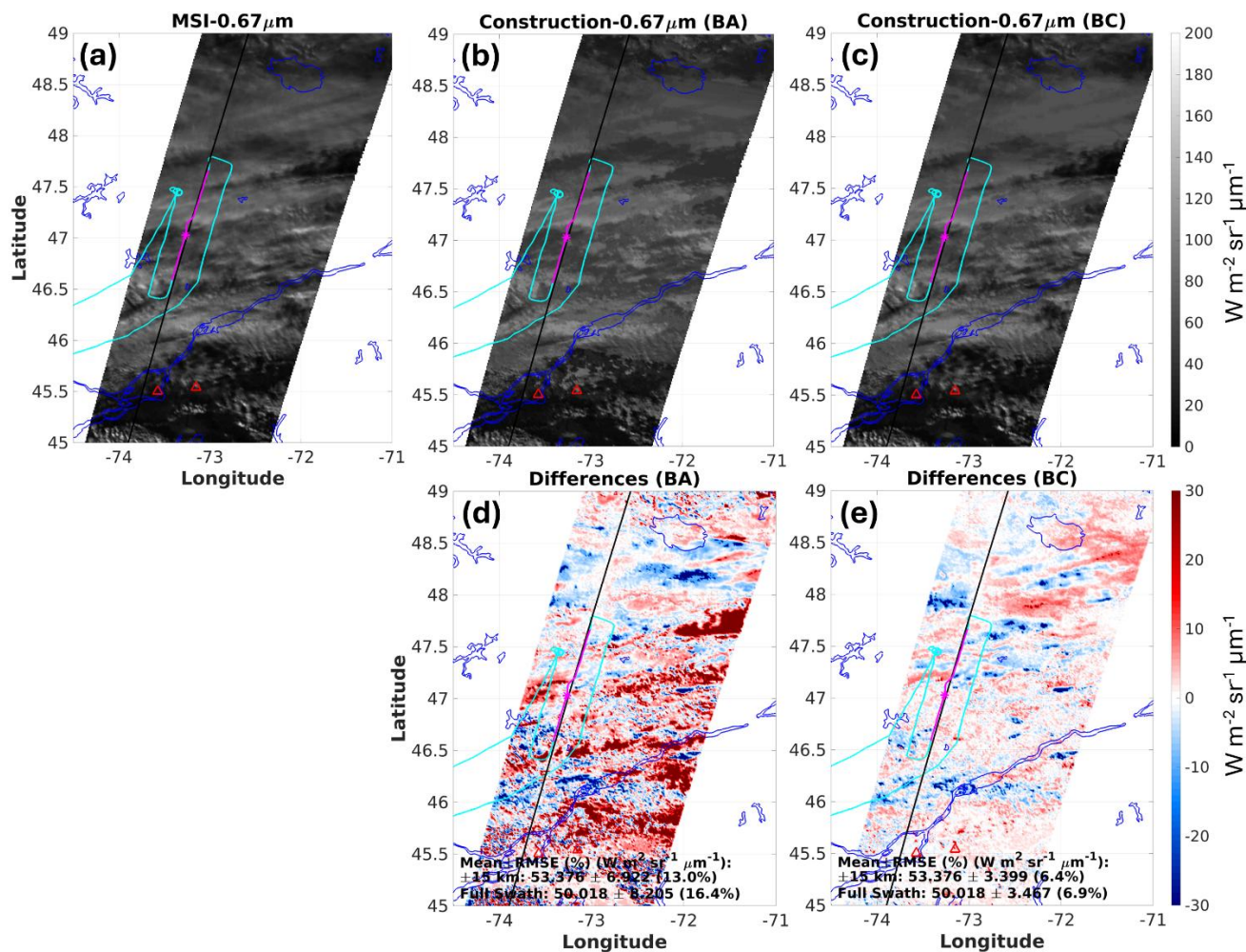


Figure 20: As in Figure 17 but for ECALOT Flight 5 on November 22, 2024 and EarthCARE Frame 02767D.

A comparison between Baseline BA and Baseline BC shows consistent behavior across spatial scales. For the full swath, Baseline BC exhibits lower RMSE values ($3.467\ \text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$, 6.9% and $0.273\ \text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$, 5.8% for the $0.67\ \mu\text{m}$ and $10.08\ \mu\text{m}$ channels, respectively) compared to Baseline BA ($8.205\ \text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$, 16.4% and $0.411\ \text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$, 8.7%).
540 When restricting the analysis to within 15 km of the nadir track, the RMSE decreases for most cases, with values of $6.922\ \text{W}$



$\text{m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (13.0%) and $0.256 \text{ W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (5.2%) for Baseline BA, and $3.399 \text{ W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (6.4%) and $0.173 \text{ W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (3.5%) for Baseline BC.

The MBE for the full swath remains generally low for both configurations, with values of $1.4167 \text{ W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (2.83%) and $0.0916 \text{ W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (1.93%) for Baseline BA, and $0.148 \text{ W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (0.295%) and $0.0974 \text{ W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (2.05%) for Baseline BC. At the assessment-domain level, the RMSE is further reduced to $0.966 \text{ W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (1.783%) and $0.046 \text{ W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (0.925%) for Baseline BA, and $0.443 \text{ W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (0.82%) and $0.0365 \text{ W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$ (0.74%) for Baseline BC.

Overall, Baseline BC shows improved performance relative to Baseline BA at both the full-swath and near-nadir scales. In both cases, however, the impact on radiative closure at the assessment-domain level remains minimal, even under these challenging conditions.

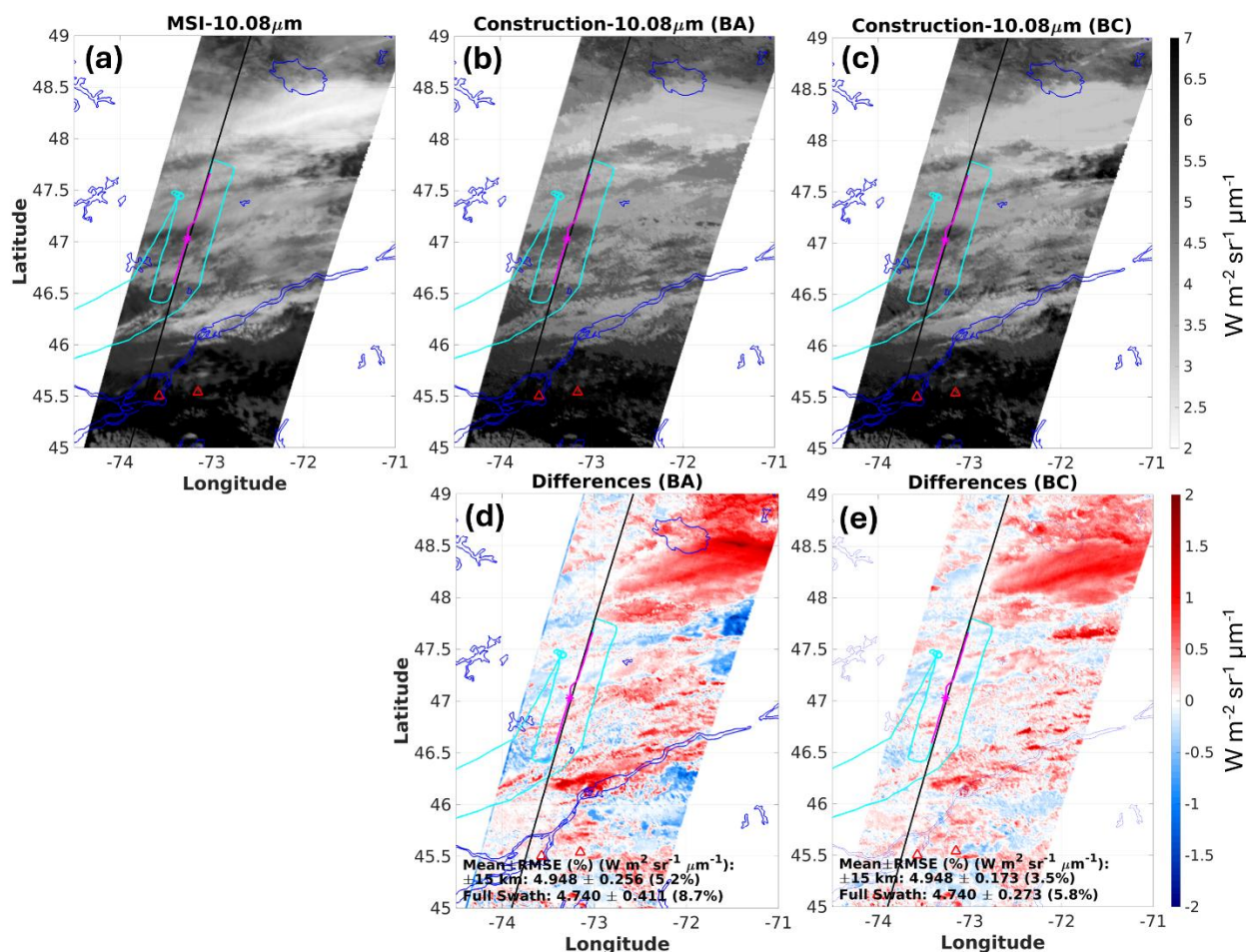


Figure 21: As in Figure 17Figure 20 but for ECALOT Flight 5 on November 22, 2024 and EarthCARE Frame 02767D.

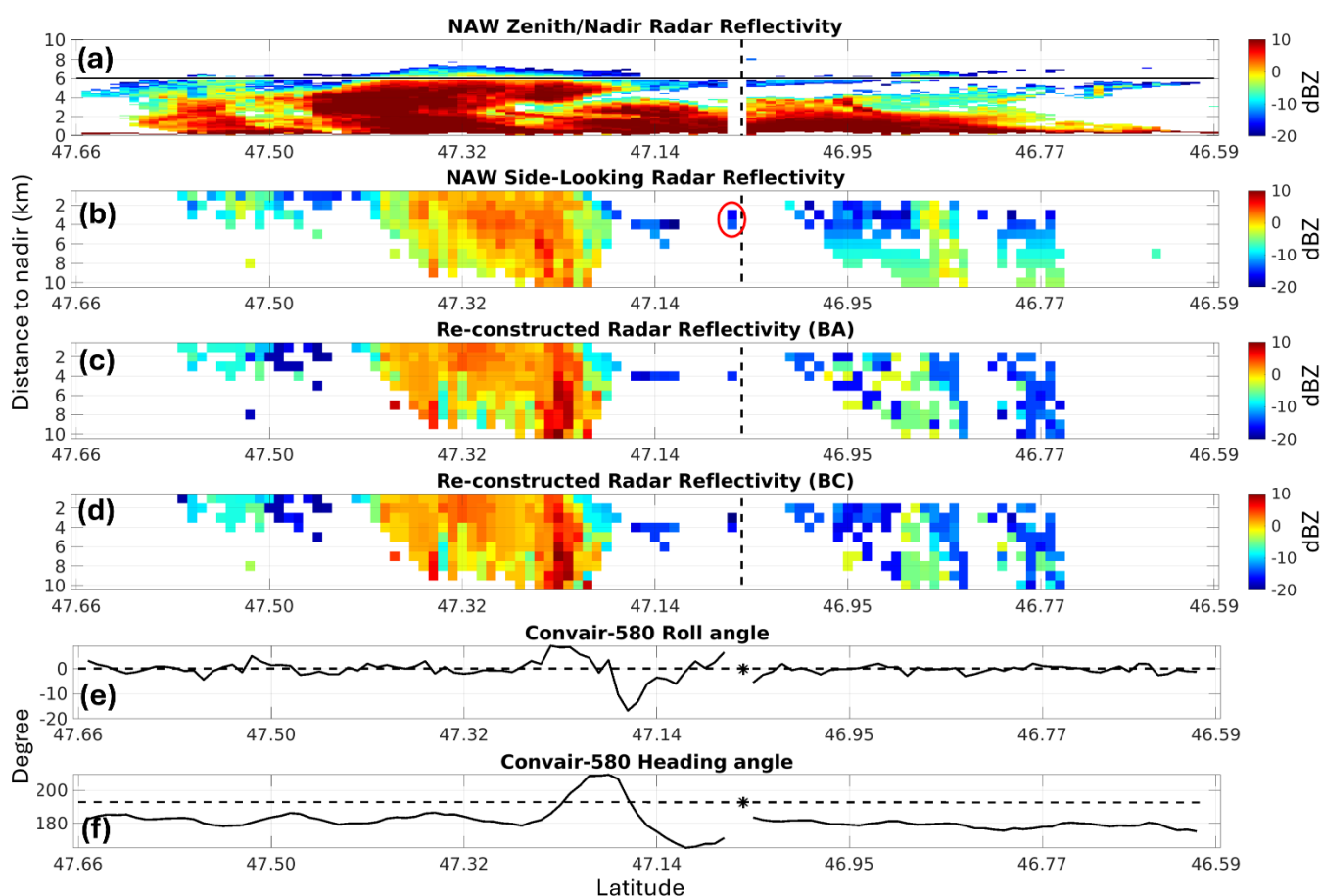


Figure 22: As in Figure 18 but for ECALOT Flight 5 on November 22, 2024 and EarthCARE Frame 02767D.

Figure 22 shows the NAW zenith- and nadir-looking radar reflectivity, together with the observed side-viewing reflectivity and the corresponding reconstructions for both baselines. Although the interpolated zenith/nadir cross-section contains no data within the segment where NAW was switched off (Figure 22a), reflectivity values are present in the corresponding region of the side-viewing cross-section (red circle in Figure 22b). These observations were acquired just before radar shutdown, following an abrupt change in the Convair-580's heading (Figure 22f). The resulting -21.76° difference between the aircraft heading (solid line) and EarthCARE's ground-track direction (dashed line) gave the side-viewing beam a forward component relative to the satellite track, allowing it to sample clouds in the region corresponding to the subsequent radar-off segment. Comparison of Figure 22b-d indicates that the scene construction algorithm reproduces the cloud structures observed by the NAW side-viewing radar.



The construction using Baseline BA yields a correlation coefficient of 0.76, an MBE of -0.69 dB, and an RMSE of 5.41 dB (Figure 23b), whereas Baseline BC shows improved performance with a correlation coefficient of 0.80, an MBE of -0.47 dB, and an RMSE of 4.71 dB (Figure 23a). The MBE remains low for the Baseline BC, with values generally within -1 dB for most distances within 10 km from the nadir track, while the MBE is slightly higher for Baseline BA but within -2 dB for all distances (Figure 23c). Similarly, the RMSE for Baseline BC is generally below 6 dB across all distances, whereas Baseline BA exhibits higher RMSE values, often exceeding 6 dB (Figure 23c, red lines). Overall, Baseline BC outperforms Baseline BA.

For Baseline BC, when using CPR nadir radar reflectivity from the C-NOM product as the *donor*, the correlation coefficient decreases slightly to 0.76, while the MBE and RMSE degrade to -3.7 dB and 6.4 dB, respectively. This degradation is expected, given existing offset in radar reflectivity and temporal mismatches of up to 10 minutes near the beginning and end of the underflight segment.

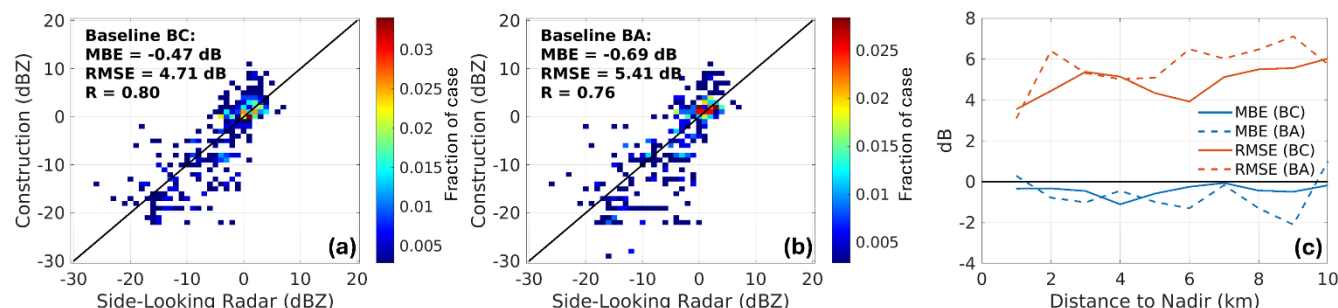


Figure 23: As in Figure 19 but for ECALOT Flight 5 on November 22, 2024 and EarthCARE Frame 02767D.

In summary, the SCA performs well under ice and mixed-phase cloud conditions. The improvements from Baseline BC relative to Baseline BA are most pronounced in complex cloud environments, while they are less evident for stratiform cloud systems in regions close to the nadir track (<10 km). Beyond 10 km from the nadir track, Baseline BC consistently outperforms Baseline BA in both cases. However, in this study, this improvement at larger off-nadir distances can only be assessed using TOA radiance construction, as these regions lie beyond the coverage of the side-viewing radar observations.

6. Conclusion and perspectives

The SCA is an important component for EarthCARE's radiative closure assessment. It constructs 3D atmospheric-surface scenes surrounding the 2D curtain of nadir retrievals thus enabling both 1D ICA and 3D MC radiative transfer simulations, especially the latter as they include horizontal transport of photons. The quality of constructed scenes directly influences the accuracy of radiative transfer calculations and, consequently, the reliability of the radiative closure assessment.



590 During the ECALOT campaign, two complementary flight strategies were implemented to verify the scene construction algorithm. For liquid cloud cases, underflight segments were designed to cut across the satellite's nadir-track at an acute angle of 20° yet be right below EarthCARE at its overpass. This enabled near-collocated satellite-aircraft observations at the segment's centre, while also sampling off-nadir regions shortly before and after overpass. For ice and mixed-phase cloud cases, the NRC Convair-580 flew straight along the satellite's nadir track with the NAW starboard-side-viewing radar providing
595 information on off-nadir region cloud structure. The combination of these two approaches enables novel evaluation of the SCA.

For liquid cloud cases observed during ECALOT Flights 4 and 2, the construction quality remains relatively stable from the nadir track to distances of approximately 12 km, beyond which the experimental assumptions become less valid due to increasing spatial and temporal mismatches. Moreover, in advance of the SCA, uncertainties in liquid cloud property retrievals
600 remain a dominant source of error (Qu et al., 2025). Both Baselines BA and BC show very similar performances indicating that changes introduced in Baseline BC have limited impact for cumulus/stratocumulus conditions near the nadir-track.

For ice and mixed-phase cloud cases during Flights 6 and 5, Baseline BC demonstrates good constructions of side-viewing radar reflectivity values, with correlation coefficients of 0.88 and 0.80, respectively. MBE remains less than 0.5 dB up to 10 km from nadir-track. On the other hand, RMSE generally increases with distance but remains less than 3 dB out to 10 km. For
605 TOA radiance construction, Baseline BA performs similarly to Baseline BC near nadir for the relatively homogeneous cloud case sampled during Flight 6, but exhibits substantially larger errors across the full MSI swath.

Overall, Baseline BC provides improved performance under more heterogeneous atmospheric conditions. Based on the constructed TOA radiances, the uncertainties introduced by the SCA at the assessment domain level are expected to remain small in the context of the overall radiative closure assessment.

610 Future work will incorporate additional variables and reassess LWC and r_e using updated retrieval products. For ice and mixed-phase clouds, verification studies will be extended to additional parameters, including cloud properties retrieved from the Convair-580 side-viewing dual-polarization radar system.

Beyond ECALOT's airborne measurements, surface radiation observations were also made at off-nadir locations. Since surface- and TOA-based radiative quantities have fundamentally different underlying distributions of photon pathlengths and
615 number of scattering events, surface observations provide independent and novel perspectives for evaluating the SCA (Liu et al., 2026). As such, surface radiation observations should help identify deficiencies in both retrieved and constructed cloud structures that are not apparent from TOA observations, such as presence and location of supercooled liquid layers near cloud base.



Code, data, or code and data availability

620 ECALOT data are available through the ESA Validation Data Centre (EVDC) data portal (<https://evdc.esa.int/search/>) (ESA, n.d.). Users must register and log in to access and download the datasets, which can be searched and filtered by location, data source type, scientific discipline, campaign, and other metadata. The portal also provides quick-look visualizations for data inspection. EarthCARE satellite products used in this study are available through the EarthCARE Multi-Mission Algorithm and Analysis Platform (MAAP) (<https://portal.maap.co.esa.int/earthcare/>) (ESA, 2025). The GEM code (version 5.3.0-a18) is
625 available from <https://github.com/ECCC-ASTD-MRD/gem/releases/tag/5.3.0-a18> (ECCC, 2026).

Author contributions

ZQ, HWB, CN, AK and JNSC contributed to the conceptualization and design of the study. CN, PB, AK, IH, KR, KB, MK, NB, LN, and MW contributed to airborne observations, instrument operation, and airborne data processing and data archiving. ZQ, HWB, CN, JNSC and MK performed the analysis and interpretation presented in this paper. ZQ led preparation of the
630 original manuscript draft. All authors contributed to the discussion of the results, manuscript review and editing, and approved the final version.

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