



An airborne all-sky radiative closure test of microwave radiometers

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Abstract. Microwave radiometers can observe the atmosphere through clouds and are widely used for all-sky atmospheric monitoring. New hyperspectral microwave sounders and cloud-sensitive W-band radiometers are expanding microwave observing capabilities, but their performance under cloudy conditions requires careful experimental evaluation before they can be fully used for all-sky retrievals. We present one of the first experimental all-sky radiative closure analyses of these advanced radiometers under liquid stratocumulus conditions, using the High Spectral Resolution Airborne Microwave Sounder (HiSRAMS) and the Radar Enhanced W-band Airborne Radiometer Detection System (REWARDS) aboard the National Research Council Canada (NRC) Convair-580 during a research flight in Canada. Observed brightness temperatures were compared with radiative transfer simulations constrained by colocated airborne radar, lidar, and in situ cloud microphysical measurements, together with modelled temperature and water vapour profiles. In situ microphysical measurements provided a reference cloud absorption profile, while radar and lidar observations constrained its instantaneous vertical location and extent. REWARDS observations were used to constrain the empirical cloud profile configuration, whereas HiSRAMS provided a more independent assessment across spectral regions sensitive to oxygen and water vapour. For both instruments, most observations were consistent with the simulations within the estimated radiative closure uncertainties, indicating broad agreement under all-sky conditions. The uncertainty analysis showed that the vertical distribution of cloud absorption was the principal limitation in cloud-sensitive channels, while water vapour variability contributed substantially at selected frequencies in the water vapour band. These complementary spectral sensitivities also suggest potential for joint retrievals of cloud and thermodynamic properties. Nevertheless, large residuals in some cloudy scenes reveal continuing limitations in representing rapidly varying cloud structure and microphysics. Overall, this study demonstrates the feasibility of all-sky radiative closure analysis for HiSRAMS and REWARDS under liquid stratocumulus conditions and highlights the importance of coordinated passive microwave, active cloud, and in situ microphysical observations for constraining cloud properties and diagnosing



35 closure uncertainties. This multi-instrument approach provides a valuable pathway for future all-sky radiative closure studies and, ultimately, for the development of more reliable all-sky retrievals.

1 Introduction

In the atmospheric microwave radiation spectrum, measured brightness temperatures (BTs) result from combined emissions by atmospheric gases (primarily oxygen and water vapour), liquid and ice cloud particles, aerosols, and the underlying surface
40 (e.g., Weng, 2017; Schanda, 1976). Different microwave frequency channels exhibit distinct sensitivities to these variables, enabling passive microwave radiometers to probe a range of atmospheric and surface conditions (e.g., Cadeddu et al., 2013; Du et al., 2014; Liu et al., 2005; Njoku et al., 1999; Walbröl et al., 2022). A distinct advantage of passive microwave observations is their ability to reach through most cloud layers, unlike visible and infrared wavelengths that are obstructed by clouds (e.g., Grody, 1993). This characteristic allows for near-continuous atmospheric monitoring under a wide range of
45 conditions.

The application of passive microwave radiometry to Earth observation can be traced back to early space missions in the 1960s and 1970s (Carver et al., 1985). For instance, the Nimbus E (Nimbus 5) Microwave Spectrometer (NEMS) aboard the National Aeronautics and Space Administration (NASA) Nimbus-5 satellite, although offering only 5 observational channels, demonstrated the feasibility of measuring microwave emissions from the Earth's atmosphere and surface to offer various
50 information of the Earth system (e.g., Grody, 1976; Staelin et al., 1973; Staelin et al., 1975; Waters et al., 1975), providing new avenues for climate and weather-related studies. Subsequent advancements in passive microwave remote sensing were realised through instruments like the Special Sensor Microwave/Imager (SSM/I) launched on the Defense Meteorological Satellite Program (DMSP) spacecraft (Hollinger et al., 1990) and the Advanced Technology Microwave Sounder (ATMS) aboard National Oceanic and Atmospheric Administration (NOAA)/NASA Suomi National Polar-orbiting Partnership (SNPP)
55 environmental satellite (Kim et al., 2014; Zou et al., 2018). By the early 21st century, these sensors had become essential components of global observing systems, informing weather forecasting, climate monitoring, and environmental assessments. For example, spaceborne microwave observations have become the most impactful for forecasts among all types of observations due to their abundance and unique cloud-penetrating capability, which provides excellent temporal and spatial coverage (Saunders, 2021).

60 Despite these achievements, most operational passive microwave radiometers still employ a relatively small number of channels, which may limit their ability to resolve overlapping atmospheric signals. With fewer than two dozen channels, such as 22 channels in ATMS, the complexities introduced by varying temperature profiles, water vapour gradients, liquid and ice clouds, aerosols, precipitation, and heterogeneous surface conditions can degrade the fidelity of retrieved geophysical variables. This shortcoming raises a key question: can increasing the number of microwave channels, particularly those
65 sensitive to clouds, temperature, and water vapour, improve all-sky retrievals of atmospheric properties? Although studies have shown promising performance gains in temperature and water vapour profiling when employing hundreds of microwave



channels under clear-sky conditions (Aires et al., 2015; Mahfouf et al., 2015), it remains unclear whether using thousands of channels, comparable to current infrared hyperspectrometers, would similarly enhance retrievals under all-sky conditions.

Recent technological advances have enabled the design and construction of hyperspectral microwave radiometers. Instruments such as the High Spectral Resolution Airborne Microwave Sounder (HiSRAMS, Auriacombe et al., 2022; Bliankinshtein et al., 2023a) employ fast Fourier transform (FFT) spectrometer technology to achieve high temporal and spectral resolutions in both the oxygen (49.6–58.3 GHz) and water vapour (175.9–184.6 GHz) bands, with spectral resolution reaching up to 305 kHz. In both HiSRAMS radiometers, two FFT spectrometers, FFT0 and FFT1, are installed. Under the single-polarisation mode used in this work, they cover the lower and the upper parts of the total frequency range, respectively, with a small overlap at the boundary between the two. Initial studies indicate that HiSRAMS can retrieve atmospheric temperature and water vapour profiles under clear-sky conditions (Liu et al., 2024, 2025). Moreover, HiSRAMS covers a wide range of microwave channels sensitive to cloud absorption.

In addition, W-band radiometers (operating roughly between 75 and 110 GHz) have demonstrated sensitivity for cloud monitoring (Küchler et al., 2017). The Radar Enhanced W-band Airborne Radiometer Detection System (REWARDS), operating at 94.05 GHz with a bandwidth of approximately 20 MHz and a noise equivalent differential temperature (NEDT) of 0.3 K assuming constant receiver gain under a reference scene temperature of 313 K, offers heightened sensitivity to both liquid and ice hydrometeors, thereby providing valuable information for potential all-sky retrievals (Bliankinshtein et al., 2024; Nguyen et al., 2024).

Before all-sky retrieval capabilities that utilise additional cloud-sensitive microwave channels can be fully realised, rigorous radiative closure analyses of the radiometers are necessary. Radiative closure tests compare observed BTs (BT_{obs}) with those simulated by forward radiative transfer models (BT_{sim}). The BT bias at a specific frequency ν in the radiative closure analysis is defined as the difference between the observed and simulated BT, as expressed in Eq. 1. We do not explicitly distinguish whether the terms in Eq. 1 refer to monochromatic (single-frequency) or channel-averaged BTs, as the difference between the two is typically negligible in the microwave spectral range. This is due to the smooth and quasi-continuous nature of atmospheric absorption features in microwaves, which reduces rapid spectral variations within instrument channel bandwidths. The adopted bandwidth of HiSRAMS is 6.1 MHz, and that of REWARDS is 20 MHz.

$$BT_{bias}^{\nu} = BT_{obs}^{\nu} - BT_{sim}^{\nu} \quad \text{Eq. 1}$$

Conducting these tests across diverse environmental conditions validates both instrument performance and the assumptions underlying the radiative transfer models. While expanding the number of microwave channels can capture more detailed atmospheric variability, it also places higher demands on radiative transfer models, which must accurately represent nuanced signals. Radiative closure analyses help identify the key variables influencing these signals, guiding refinements in retrieval algorithms and data assimilation methods for all-sky conditions. The detailed methods for obtaining the two terms in Eq. 1 are presented in Sect. 2 and 3.

This study aims to perform all-sky radiative closure analyses under stratocumulus cloud conditions for the two aforementioned advanced passive microwave radiometers, HiSRAMS and REWARDS, and to determine which atmospheric variables are most



critical for achieving accurate all-sky radiative transfer simulations using the data collected from a research flight in Canada. The insights gained will guide the next steps in the deployment of these instruments, as well as the design of next-generation instruments, retrieval algorithms, and data assimilation strategies, ultimately enhancing our ability to monitor and understand the atmosphere across a broad spectrum of conditions.

2 Microwave radiative transfer forward model

Radiative closure analysis involves comparing simulated radiative quantities with corresponding observations obtained from radiometers. In this context, a radiative transfer forward model is essential for converting atmospheric profiles into simulated radiative quantities.

The microwave radiative transfer model used in this study was originally developed for HiSRAMS under clear-sky conditions (Bliankinshtein et al., 2019). It incorporates the Rosenkranz gas absorption parameterisation (Rosenkranz, 2017) and employs a plane-parallel radiative solver. In the microwave spectral range, the dominant absorbers are oxygen and water vapour, with additional contributions from ozone and nitrogen. All these absorbers are accounted for in the HiSRAMS radiative transfer forward model, which has been extensively validated under clear-sky conditions (Bliankinshtein et al., 2019; Bliankinshtein et al., 2022; Bliankinshtein et al., 2023b; Liu et al., 2024). As a result, the HiSRAMS forward model is also applicable to REWARDS.

Conducting an all-sky radiative closure analysis requires an all-sky microwave radiative transfer model. The model employed in this study builds upon our clear-sky version by incorporating cloud absorption at microwave frequencies. However, for simplicity, we currently exclude cloud scattering. This approximation is justified for liquid clouds with small droplet sizes, as the wavelengths under consideration (1.62 mm to 6.12 mm, corresponding to 49–185 GHz) are much larger than the typical radii of liquid cloud droplets (generally less than 50 μm). Under these conditions, scattering occurs in the Rayleigh regime, where the scattering cross-section is negligible compared to absorption. In contrast, for ice clouds, scattering can be significant, making this assumption invalid. Since the present study focuses primarily on liquid clouds, the exclusion of scattering is appropriate (Bohren et al., 2008; Burrows et al., 2011; Weng, 2017).

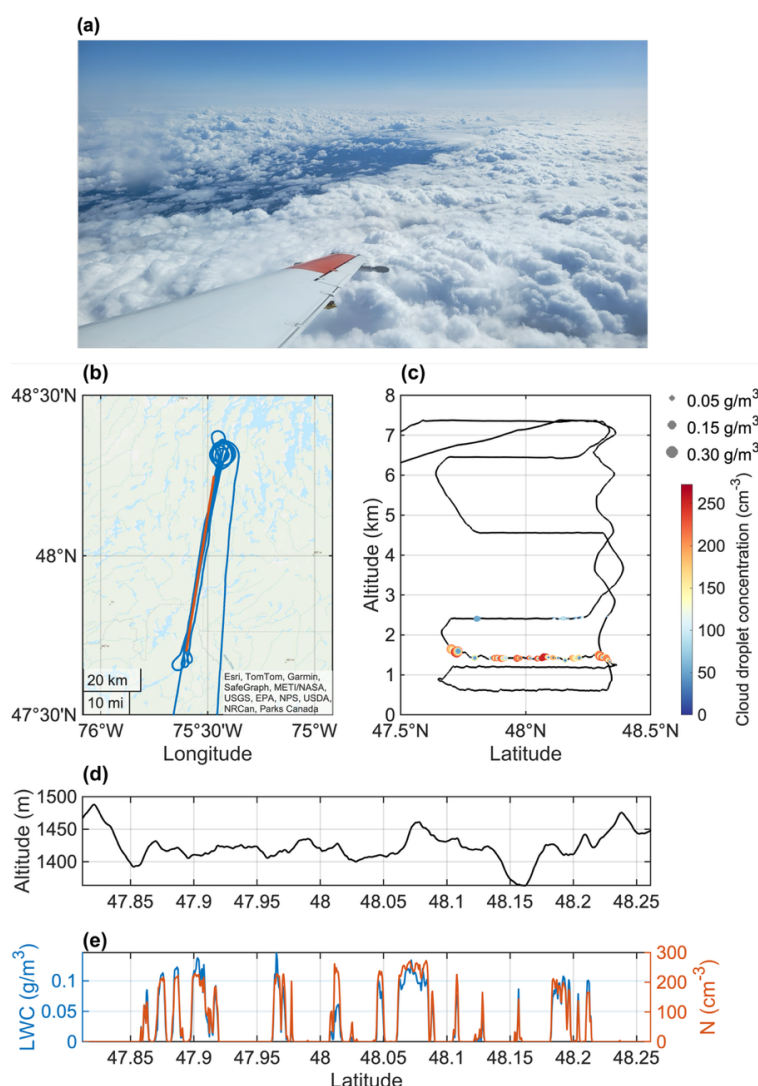
3 Field campaign description and data processing

This study focuses on a specific flight conducted on 12 May 2023, from 11:30:48 to 15:51:25 UTC in Canada. Various instruments, including HiSRAMS and REWARDS, were mounted on the National Research Council of Canada's (NRC) research aircraft, the Convair-580. The flight targeted sampling above, within, and below a thin stratocumulus cloud deck, as shown in Figure 1a. Figure 1 also presents the flight trajectory, during which seven straight-and-level flight legs were flown. Table 1 summarises the key observational and model data used in this study. Most measurements were collected at a temporal resolution of approximately one second. Onboard the Convair-580, in addition to HiSRAMS and REWARDS, the cloud



130 droplet probe, version 2 (CDP-2, Lance et al., 2010) and Fast CDP (FCDP) measure the forward scattered light intensity from individual droplets, which is then used to derive cloud particle size distributions (PSDs). The NRC Airborne W-band (NAW, Wolde et al., 2019; Wolde et al., 2005) radar and Airborne Elastic Cloud Lidar (AECL, Baibakov et al., 2016) provide cloud microphysical structure (see Sect. 3.2 for details), while arrays of sensors collect atmospheric and aircraft state parameters. Additionally, the two-dimensional stereo (2D-S) probe (Lawson et al., 2006) was used to capture images of cloud particles.

135 During the flight, multi-layer clouds were observed, consisting of two primary layers located above and below an altitude of 1.5 km, and extending horizontally over several hundred kilometres (Figure 1a). The lower layer was located at a height between 1.32 and 1.51 km, and the upper layer between 1.56 and 1.73 km (detection details provided in Sect. 3.1).



140 **Figure 1: Observations of the research flight in Canada on 12 May 2023. (a) Photo of the stratocumulus clouds taken from the Convair-580 aircraft. (b) Zoomed-in view of the flight path over the surface map. The red line indicates the location of the stacking flight legs. (c) The vertical flight trajectory as a function of latitude. The dots along the trajectory indicate observed cloud properties,**



with colour representing cloud droplet concentration and size corresponding to liquid cloud water content. (d) Altitude, and (e) liquid water content (LWC) and cloud droplet concentration (N) during the flight leg at approximately 1400 m altitude, where most of the cloud liquid was sampled.

145 All measurements summarised in Table 1 were linearly interpolated in time to match the HiSRAMS temporal intervals, except the cloud particle size distributions (PSD) from the CDP and the particle imagery from the 2D-S. This synchronisation enables radiative closure analyses to be conducted at a high temporal resolution (approximately 1 s).

Table 1: Observational data and model data used in this study.

Data		Temporal resolution	Spatial resolution	Notes
Radiometer data	BT spectra from HiSRAMS	0.58 or 0.97 s	Along the aircraft track, with a spatial resolution of ~ 100 m	Alternating nadir- and zenith-pointing BT observations for oxygen and water vapour bands
	BT from REWARDS	1 s after averaging		zenith-pointing W-band BT observations
In situ data	Atmospheric state and aircraft state data from in situ sensors			Aircraft states: altitude, latitude, longitude, roll, pitch, and heading Atmospheric states: pressure, temperature, and water vapour concentration
	PSDs from CDP and FCDP			In-cloud PSD observations
	Particle imagery from 2D-S probe			2D-S sample shadow images, used qualitatively to identify the presence of different types of cloud and drizzle-sized droplets
Remote sensing data	Cloud structure from NAW Radar reflectivity			Zenith-pointing remote sensing observations, used qualitatively to identify the presence of cloud particles and aerosols
	Cloud base and phase from AECL backscatter			
Model data	Vertical profiles from GEM simulations	30 min	2.5 km × 2.5 km	Vertical profiles of altitude, pressure, temperature, water vapour concentration, liquid water content, and ice water content

150 The workflow of the all-sky radiative closure analysis is illustrated in Figure 2. HiSRAMS and REWARDS provide observed BT at various microwave frequencies, representing the term BT_{obs}^v in Eq. 1. The corresponding simulated term, BT_{sim}^v , is obtained using the all-sky microwave radiative transfer forward model described in Sect. 2, incorporating cloud absorption



profiles. Ideally, an observed instantaneous vertical profile of cloud absorption at each time instance along the aircraft trajectory is required to ensure accurate BT simulations. However, due to the flight pattern and in particular altitude changes, in situ cloud microphysical observations from CDP yield only one reference cloud absorption coefficient profile for the entire flight, which does not capture the spatial and temporal variability of clouds along the aircraft trajectory. To address this limitation, we refine the reference cloud profile using instantaneous radar and lidar data collected onboard, reconstructing a more locally adapted cloud absorption coefficient profile at each time instance as input to the radiative transfer model. Additional inputs, such as instantaneous temperature and water vapour concentration profiles, are also included. Detailed procedures for processing these inputs are described in the following subsections.

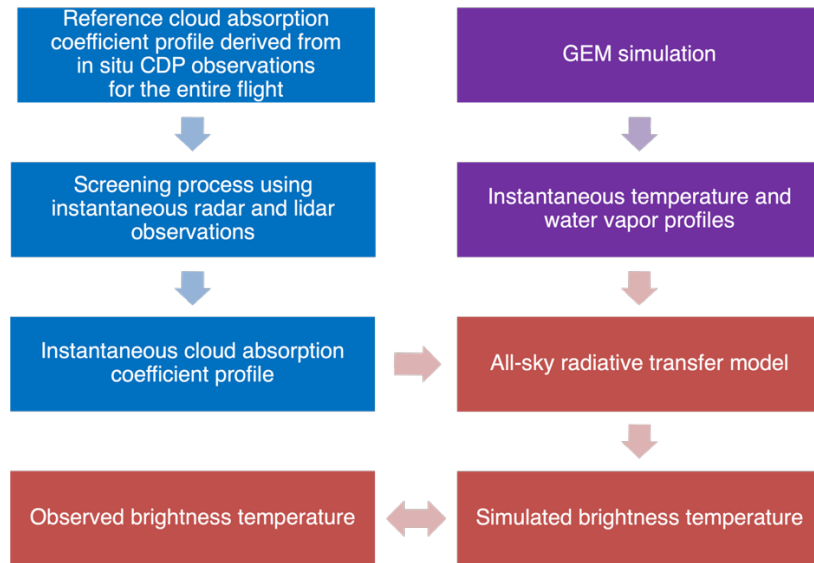


Figure 2: Workflow for the all-sky radiative closure analysis.

3.1 In situ cloud observations from the Cloud Droplet Probe

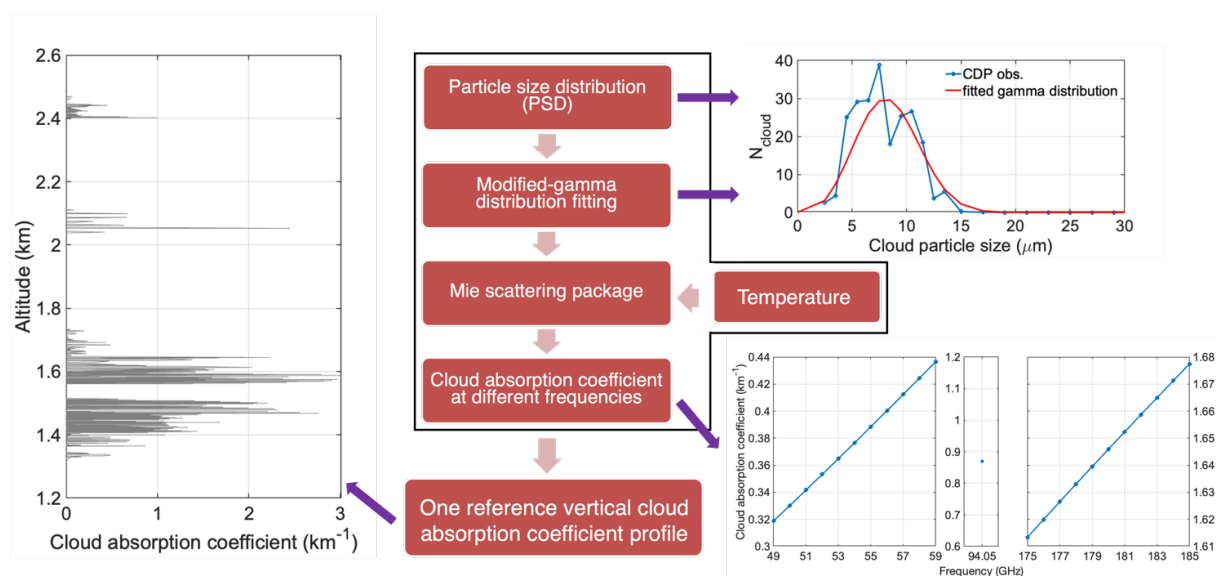
The CDP provides in situ measurements of cloud PSDs, which serve as the basis for deriving cloud absorption coefficients. The process for deriving the vertical profile of cloud absorption coefficients is presented in Figure 3. First, the observed PSDs are fitted with a modified gamma distribution:

$$N(r) = A r^{\alpha} e^{-Br^{\gamma}} \quad \text{Eq. 2}$$

where N and r represent the cloud particle number concentration and particle radius, and A , B , α , and γ are fitted parameters. A nonlinear least-squares solver (MATLAB's `lsqnonlin`) is employed to determine these parameters with the following constraints: $A > 0$ and $B > 0$. The fitted distribution, along with in situ cloud temperature, is then input into a linearised Mie scattering package developed by RT Solution (Fortran routines provided by Mick Christi and translated to MATLAB by Horizon Science and Technology) (Spurr et al., 2012) to compute the cloud absorption coefficient at selected microwave



frequencies. An example fit for an instantaneous PSD observation and the corresponding cloud absorption coefficient at different microwave frequencies are shown in Figure 3.



175 **Figure 3: Workflow for determining the reference vertical profile of cloud absorption coefficients, with example results shown for selected steps to illustrate key processes. The left side shows the cloud absorption coefficient at 94.05 GHz, while the lower-right section displays coefficients for multiple frequencies, derived from the fitted gamma distribution depicted in the upper-right section.**

Because the cloud absorption coefficient in the microwave range is spectrally continuous, a spectral resolution of 1 GHz is chosen within the HiSRAMS absorption range to construct a lookup table. In HiSRAMS cloudy-sky radiative transfer simulations, the cloud absorption coefficient is interpolated to match the high spectral resolution of HiSRAMS frequencies. These computations are repeated for each PSD observation, typically recorded every second.

Since PSD measurements are collected in situ, only one “stacked” vertical cloud absorption coefficient profile can be derived for a given flight by sorting the observations according to altitude. This composite profile, shown in Figure 3, has a nominal vertical resolution of approximately 0.5 m owing to the high temporal resolution of the CDP measurements. Multi-layer clouds were detected during the flight, with two primary layers located above and below 1.5 km. For the entire flight, this composite profile is used as the baseline cloud microphysical profile, while its vertical location and extent are refined at each time step using airborne radar and lidar observations (Sect. 3.3 and 3.4). It is important to note that this approach does not explicitly represent temporal and horizontal variations in the PSD within the detected cloud layers, which therefore remain a source of uncertainty. However, considering all available CDP measurements within the primary cloud layer (1.2–1.8 km), the median volume diameter (MVD) was $10.5 \pm 1.5 \mu\text{m}$ (mean $\pm$ standard deviation), indicating that the characteristic droplet size remained within a relatively narrow range during the flight.



3.2 Cloud remote observations from airborne radar and lidar

Clouds are often nonuniform along a flight trajectory, so simply applying the reference absorption profile everywhere can lead to large errors. Thus, to relax the assumption stated above, we use data from the NAW radar and AECL to refine the cloud vertical location and extent. The primary cloudy-sky observational scenes were captured between 14:00 and 15:00 UTC during the flight, when the aircraft either flew inside the clouds or below them.

Radar and lidar offer complementary sensitivities for cloud detection because their sensitivities depend differently on PSD, particle number concentration, and particle phase. Radar backscatter is proportional to the 6th moment of the PSD for cases considered in this study where the particle sizes are much less than the wavelength of the radar and is therefore more sensitive to larger particles. Lidar is particularly effective at detecting smaller particles in thin cirrus and non-precipitating water clouds, as scattering and absorption are proportional to the second moment. While lidar's sensitivity to small particles makes it suitable for detecting optically thinner clouds, it is more prone to attenuation, especially in liquid clouds. Integrating radar and lidar measurements leverages their strengths, providing a more robust and comprehensive approach to cloud masking by capitalising on their distinct sensitivities to particle size and the influence of particle number concentration.

One of the key parameters provided by the NAW radar for identifying hydrometeors is the normalized coherent power (NCP), which serves as a qualitative indicator of signal strength. In this study, we use an NCP threshold of 0.2, such that $NCP > 0.2$ indicates the presence of a radar echo. While Dixon et al. (2012) used a threshold of 0.15, we adopted a slightly higher value to improve the separation of atmospheric signal from background noise. At the lower threshold, spurious noise remained in the dataset; increasing the threshold to 0.2 provided cleaner discrimination for our specific case. For lidar observations, we use processed lidar backscatter signals (BS_{lidar}) and identify the presence of clouds when $\log_{10}(BS_{lidar}) > 8$. This threshold was empirically determined to distinguish signal from noise effectively in our dataset.

Figure 4 compares radar- and lidar-detected hydrometeor layers, showing both areas of agreement and discrepancy. In general, they agree on hydrometeor presence in terms of timing and altitude (Figure 4a, b). However, between 14:35 and 14:55 UTC, the radar consistently detects strong echoes near 600 m where the aircraft was flying at the lowest flight leg shown in Figure 1b, while lidar indicates higher base layer (Figure 4a, b). Given lidar's greater sensitivity in detecting cloud base height and in situ visual observations from the crew confirming the aircraft was below the cloud deck at 600 m, we treat the lidar-detected cloud base as the reference.

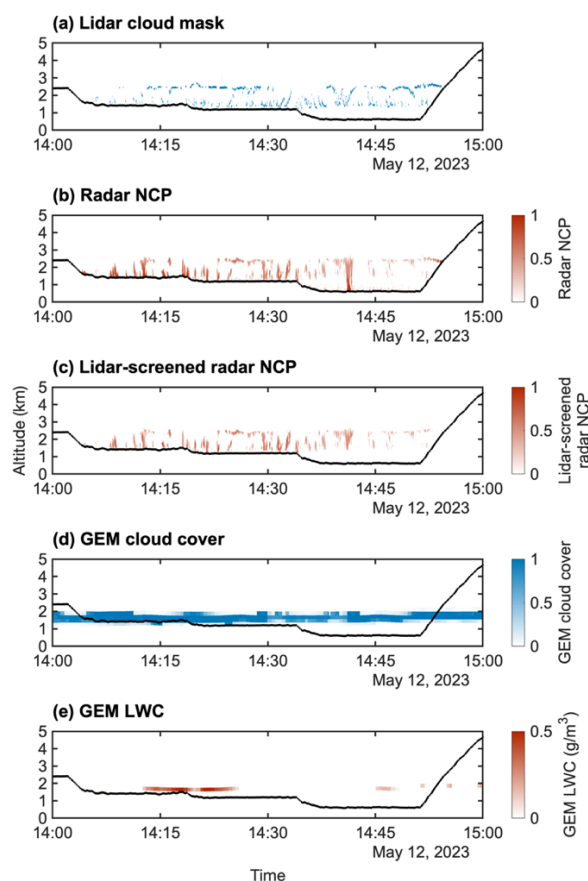
To support the interpretation of radar echoes near the aircraft altitude, we also consider in situ particle observations. Between 14:39 and 14:42 UTC, the 2D-S probe recorded a small number of particles with effective radii reaching approximately 200 μm (Figures S1 and S2), consistent with drizzle-sized droplets. These larger hydrometeors may have contributed to the radar echoes, but their sparse occurrence does not fully explain the persistent, strong echoes in this region. Neither the lidar nor the CDP indicated substantial cloud at this altitude, although droplets larger than 50 μm would exceed the upper detection limit of the CDP. Nevertheless, because the lidar indicated a higher cloud base and visual observations by the flight crew confirmed that the aircraft was below the cloud deck, the lidar-detected cloud base was adopted as the reference for cloud identification.



225 Accordingly, the following adjustments were applied to the radar NCP field to reconcile discrepancies between radar and lidar and to avoid misclassifying radar echoes below the lidar-detected cloud base as cloud layers:

- When lidar indicates clear-sky conditions (i.e., no cloud base detected), radar NCP values are set to 0 at all heights for that time step.
- When lidar detects a cloud base, radar NCP values below the lidar-detected base are set to 0.

230 These adjustments remove radar signals near the lowest observational heights (Figure 4b, c). Subsequently, we combine the adjusted radar and lidar data to pinpoint the precise locations of clouds to account for the inherent spatial and temporal inhomogeneity of clouds. The cloud absorption coefficients (as shown in Figure 3) are retained only at levels where active sensors detect clouds; coefficients at other levels are set to zero. Further details on how we finalize these cloud absorption profiles are provided in Sect. 3.3.



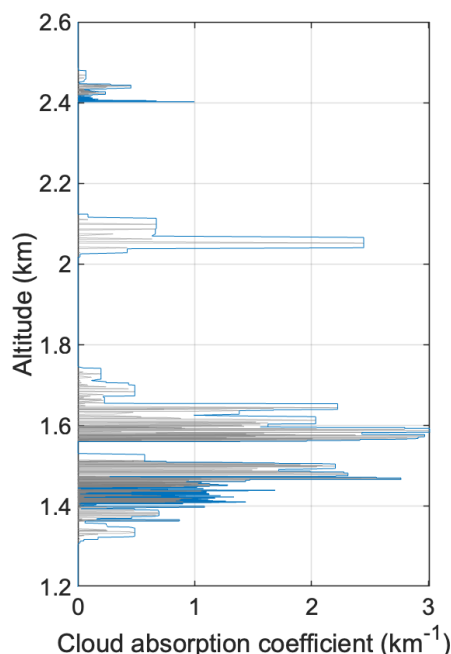
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Figure 4: Cloud information for the flight from airborne radar, lidar, and GEM simulations. (a) lidar cloud mask; (b) radar NCP; (c) radar NCP after lidar-based screening; (d) GEM cloud cover; (e) GEM LWC. A lidar cloud mask value of 1 signifies cloud presence, shown in blue in panel (a). Black lines show the aircraft altitude. Both radar and lidar provide zenith-pointing observations.



240 3.3 Cloud absorption profile treatments

Accurate vertical profiles of cloud absorption coefficients (or optical depths) are essential for all-sky microwave radiative transfer simulations. As previously mentioned, in situ CDP sensors can only provide one reference cloud absorption profile for the entire flight (grey line in Figure 5). Multiple legs were flown at different altitudes, resulting in numerous CDP measurements taken at closely spaced altitudes. This high vertical resolution sometimes reveals thin, broken cloud layers less than 1 m thick. Using such a profile in an unfiltered manner can introduce unrealistic cloud features. Therefore, we apply moving-mean and moving-maximum smoothing techniques to the original CDP-based cloud absorption coefficient profile. Sensitivity tests indicated that the moving maximum generally provided the best all-sky closure (not shown), and it was therefore chosen for further parameter analysis when determining the number of nearby points to use for smoothing.



250 **Figure 5: Vertical profile of cloud absorption coefficients for the flight. The grey line represents the original CDP-derived profile, while the blue line shows the moving-maximum smoothed profile used in subsequent radiative closure analysis.**

The moving-maximum method outperforms the moving-mean one because, between cloud peaks, many low values may be recorded from clear-sky regions at similar altitudes but in different horizontal locations. Averaging these values can weaken or even remove the cloud signal, leading to an inaccurate representation of cloud absorption. In contrast, the moving-maximum method better preserves these peak values, reflecting more realistic cloud conditions. Since the CDP provides accurate PSD observations for liquid clouds, a high concentration of cloud droplets at one level suggests that nearby vertical layers are likely to have similar cloud conditions. Thus, it is assumed that the moving-maximum method more effectively captures the true cloud structure within the atmospheric column.



After screening the radar data based on the lidar-detected cloud base height, we also examined two methods for implementing active cloud instrument data:

1. “Radar and Lidar” method: Mark a level cloudy only if both radar and lidar indicate cloud presence, i.e. $\log_{10}(BS_{lidar}) > 8$ and $NCP > 0.2$.
2. “Radar or Lidar” method: Mark a level cloudy if either radar or lidar detects a cloud, i.e. $\log_{10}(BS_{lidar}) > 8$ or $NCP > 0.2$.

Sensitivity tests were conducted to examine how the REWARDS residuals depend on the cloud detection criterion and moving-maximum window length. Table 2 presents the mean and standard deviation of 94.05 GHz BT bias ($BT_{bias}^{94.05\text{ GHz}}$) from 14:00 to 14:55 UTC for the flight across the tested configurations. When requiring both radar and lidar to detect clouds, more than 200 neighbouring cloud data points (with an average spacing of 0.43 m, corresponding to an approximately 86 m deep layer) are needed to generate smoothed vertical cloud absorption profiles, indicating that this criterion for cloud presence is too strict. Conversely, using only 16 neighbouring data points (~ 7 m) for smoothing, under the condition that either radar or lidar detects clouds, produces the smallest absolute mean REWARDS residual among the tested configurations, with a mean BT bias of 0.12 K and a standard deviation of 24.24 K, and was selected for the subsequent calculations. The residual standard deviation nevertheless remained substantial, indicating that the selected configuration does not fully represent the instantaneous spatial and temporal variability of the clouds.

Table 2: Mean and standard deviation of $BT_{bias}^{94.05\text{ GHz}}$ between 14:00 and 14:55 UTC for the flight under different cloud profile settings.

Cloud Detection Method	MOVMAX (n)	BT bias mean (K)	BT bias std. (K)
Lidar and Radar	1	17.77	27.02
	10	15.23	26.47
	20	14.24	26.48
	50	11.83	27.20
	100	7.59	30.24
	150	3.77	33.92
	200	0.52	37.63
	250	-2.44	41.32
	300	-5.18	44.76
Lidar or Radar	1	14.21	24.22
	5	6.74	22.55
	10	2.69	23.32
	15	0.51	24.09
	16	0.12	24.24
	17	-0.25	24.37
	20	-1.28	24.85
	50	-9.55	30.19



Because the same REWARDS observations were used both to select the cloud profile configuration and to calculate the closure statistics presented later, the REWARDS comparison between observations and simulations is not fully independent. It is therefore interpreted as a closure assessment conditional on the selected cloud representation, rather than as a validation of REWARDS radiometric calibration. In contrast, HiSRAMS observations were not used in selecting the cloud profile configuration and thus provide an independent cross-instrument test of whether the treatment transfers to other microwave frequencies.

Although the mean biases can be reduced with these adjustments, the standard deviations remain relatively high, suggesting that further improvements in cloud representation (e.g., using more detailed airborne cloud sampling or more sophisticated modelling) may be necessary to fully capture the rapid variability in cloud properties.

3.4 Atmospheric states

Vertical profiles of temperature and water vapour along the aircraft trajectory, in addition to the cloud absorption profile, are essential inputs for radiative transfer simulations. While the aircraft provides in situ measurements of temperature and water vapour concentration, similar to cloud PSD measurement, these measurements offer only one reference vertical profile for each variable, which is insufficient to capture the spatial and temporal variability along the trajectory. To address this limitation, we use high-resolution predictions from the pan-Canadian High Resolution Deterministic Prediction System (HRDPS, Milbrandt et al, 2016), developed by Environment and Climate Change Canada (ECCC). HRDPS utilizes the Global Environmental Multiscale (GEM, Côté et al., 1998; Girard et al., 2014) forecast model, which provides detailed profiles of temperature, water vapour, and cloud properties such as liquid water content (LWC), ice water content, and cloud cover across 62 vertical levels with high spatial resolutions ($2.5 \text{ km} \times 2.5 \text{ km}$). The forecast results are saved every 30 minutes.

At each 30-min time step, the GEM vertical profiles nearest to the aircraft trajectory, both horizontally and temporally, are selected to form a “GEM curtain” of these variables along the flight path. This GEM curtain, encompassing all 62 vertical levels, serves as the input to the radiative transfer model. To validate the reliability of the GEM-derived profiles, we perform a sanity check by vertically interpolating the GEM data along the aircraft trajectory to match the aircraft’s altitude (Figure 6a). These interpolated GEM profiles are then compared to in situ observations of temperature, water vapour concentration, and LWC from airborne sensors, as shown in Figure 6b-d.

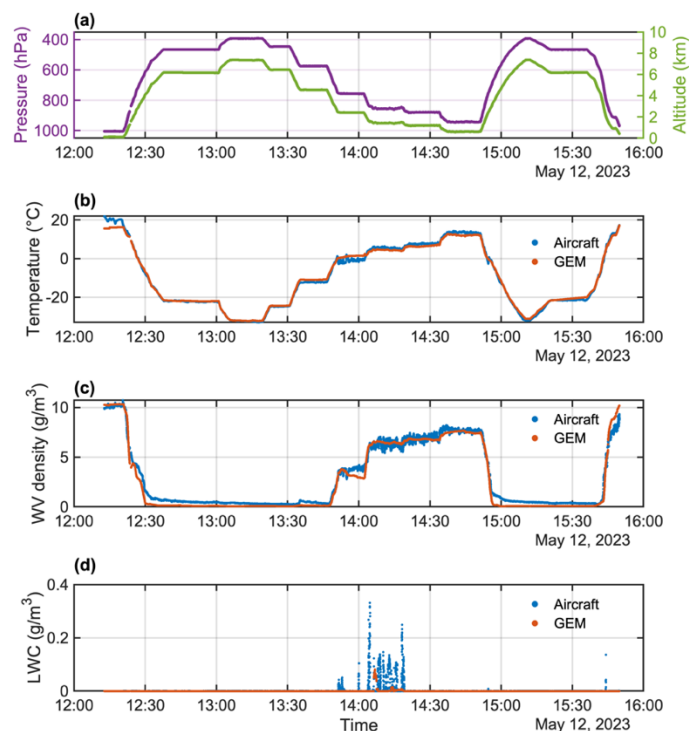


Figure 6: Aircraft in situ measurements and the comparison with GEM outputs for the flight. (a), aircraft altitude and pressure; (b), temperature; (c), water vapour density; (d), liquid water content.

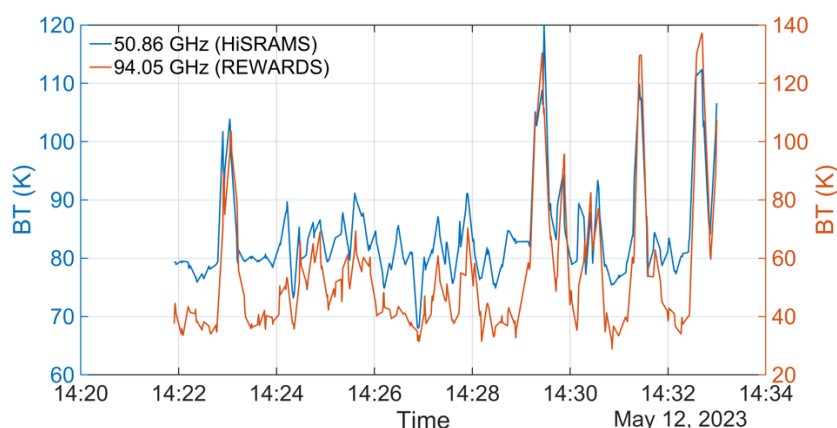
The interpolated GEM profiles generally agree well with the aircraft in situ measurements of both temperature and water vapour concentration, providing a consistency check on the GEM thermodynamic fields used in the radiative transfer calculations at flight altitude (Figure 6b, c). However, this comparison does not independently evaluate the full vertical thermodynamic profiles observed by the radiometers, so errors elsewhere in the atmospheric column remain a source of uncertainty in the forward model. Furthermore, the GEM model identifies the presence of liquid clouds during the flight (Figure 4d, e) at vertical locations consistent with cloud layers observed by the radar and lidar (Figure 4a, c). Given the known limitations of the GEM model, the profiles do not resolve the detailed cloud structure required for all-sky radiative closure analysis. Similarly, the interpolated GEM profiles of LWC do not fully represent the in situ CDP measurements (Figure 6d). In summary, the GEM curtain along the flight path provides the best available temperature and water vapour profiles for the all-sky radiative transfer calculations. Agreement with in situ measurements at aircraft altitude supports their use as model inputs but does not establish the accuracy of the full atmospheric column. In contrast, the GEM cloud fields do not adequately resolve the required vertical cloud structure, emphasising the importance of accurate in situ and remote sensing observations of clouds.



3.5 Microwave radiometer observations

320 The effectiveness of microwave radiometers for all-sky retrievals largely arises from their ability to detect clouds. Both REWARDS and HiSRAMS measure BTs at different microwave frequencies that are sensitive to cloud presence. Figure 7 presents zenith-pointing BT measurements from HiSRAMS at 50.86 GHz and from REWARDS at 94.05 GHz, collected between 14:21 and 14:33 UTC during the flight, when clouds were present above the aircraft altitude (see Figure 4). The high correlation coefficient (0.91) between these two time series shown in Figure 7 not only confirms the consistency of the

325 microwave radiometer measurements but also highlights the consistent impact of clouds on downwelling microwave radiance. Higher BT values indicate optically thick clouds, whereas lower BT values correspond to clear-sky conditions. Intermediate BT values for the two frequencies suggest clouds with varying optical depths.



330 **Figure 7: Zenith-pointing BTs observed by REWARDS and a single channel of HiSRAMS for the flight, between 14:21 and 14:33 UTC on 12 May 2023.**

4 All-sky radiative closure results

4.1 Simulated cloud radiative impact

After establishing the input cloud and thermodynamic profiles, we determined the simulated BT of both HiSRAMS and REWARDS along the flight trajectories. Figure 8 shows the difference between simulated cloudy-sky BT and clear-sky BT.

335 Under cloudy-sky conditions, the clouds have a relatively larger radiative impact on HiSRAMS's weak absorption channels (50–54 GHz in the oxygen band and 176–180 GHz in the water vapour band) than on its strong absorption channels (55–58 GHz in the oxygen band and 182–184 GHz in the water vapour band). This is because, when a channel is already optically thick, the observed BT essentially reflects the air temperature near the instrument, masking signals from clouds at higher altitudes. In contrast, for relatively optically thin channels, more cloud signals can penetrate to the instrument's level. For

340 REWARDS, the clouds have a large radiative impact owing to the low gas optical depth, indicating this instrument is well suited for cloud detection and retrievals. These simulations indicate that both the weak absorption channels of HiSRAMS and



the REWARDS channel can be applied for all-sky cloud retrievals, potentially enabling estimation of parameters such as cloud emission temperature, optical depth, and emissivity.

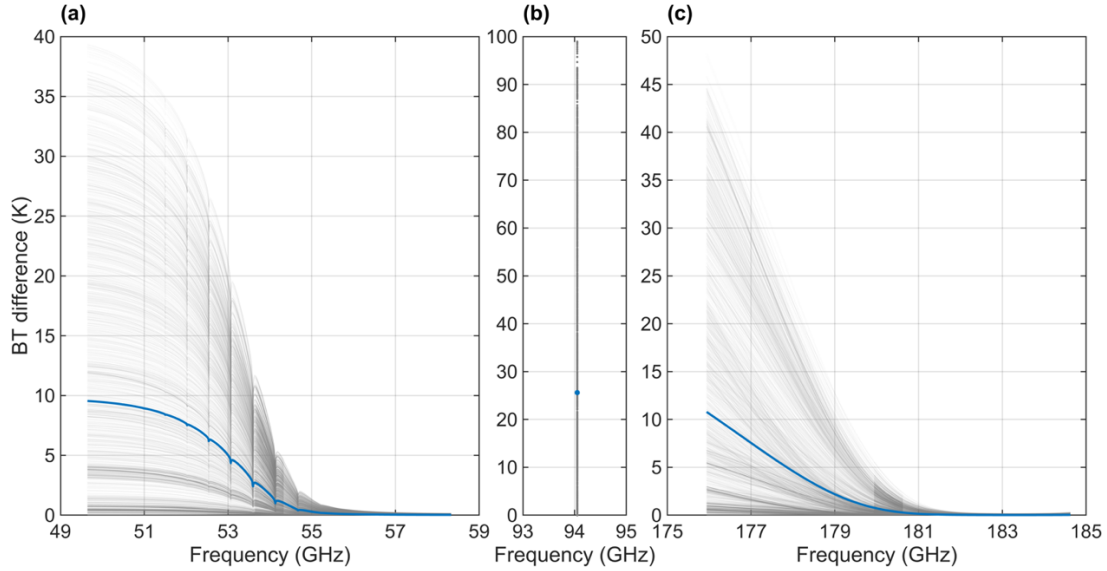


Figure 8: Simulated radiative impacts of liquid clouds on downwelling BT in the HiSRAMS and REWARDS spectral ranges. The BT difference (with cloud minus without cloud) is used to quantify the extent to which liquid clouds modify downwelling BT in each spectral band: HiSRAMS oxygen band radiometer (a), REWARDS (b), and HiSRAMS water vapour band radiometer (c). Grey lines (or dots) represent BT differences at all cloud-present time instances across a range of observational heights, primarily between 500 and 1500 m. Blue lines (or dots) indicate the corresponding mean values.

4.2 Radiative closure uncertainty analysis

The uncertainties in the BT bias, introduced in Eq. 1, are described in Eq. 3. The total uncertainty ($\sigma_{BT_{total}^v}$) arises from the independent uncertainties in both the simulated ($\sigma_{BT_{sim}^v}$) and observed ($\sigma_{BT_{obs}^v}$) BT.

$$\sigma_{BT_{total}^v} = \sqrt{\sigma_{BT_{obs}^v}^2 + \sigma_{BT_{sim}^v}^2} \quad \text{Eq. 3}$$

To characterise the effective observational uncertainty under flight conditions, we calculate the temporal standard deviation of BT within one-minute intervals under clear-sky conditions. For each channel, the median of these one-minute standard deviations is adopted as the representative observational uncertainty (Figure 9). This approach gives an uncertainty of 2.4 K for REWARDS at 94.05 GHz. We use this empirical estimate rather than the nominal NEDT for observational uncertainty because it better represents the uncertainty of the actual in-flight observations. In addition to intrinsic radiometric noise, it may include contributions from calibration or gain variability, residual atmospheric variability, and aircraft or scene-sampling effects. For HiSRAMS, the effective observational uncertainties are larger in weak absorption bands than in strong absorption bands for both radiometers. This is because the colder BTs in the weak absorption bands are farther from the hot and ambient calibration loads used to calibrate the observed BT. The effective observational uncertainties are considered to remain consistent over time.

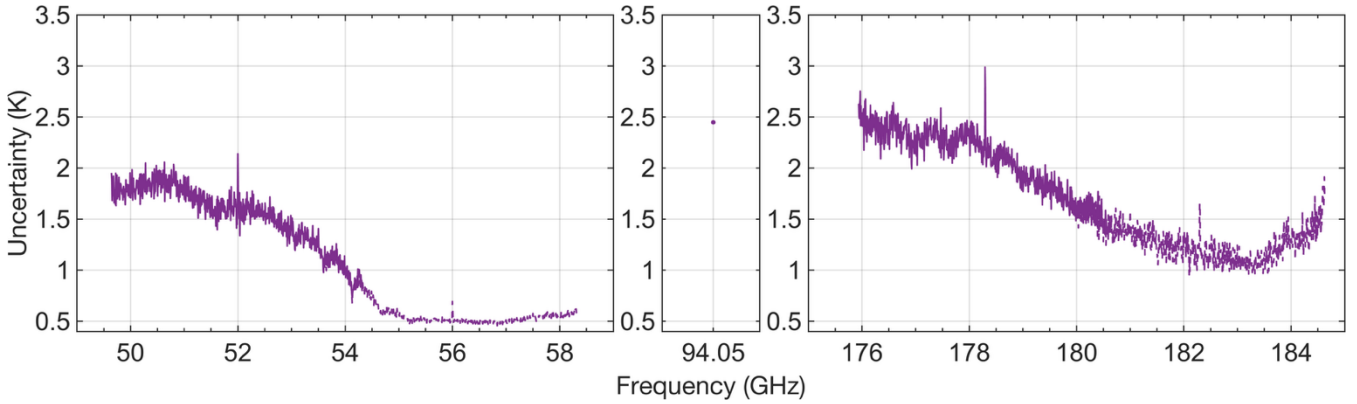


Figure 9: Effective observational uncertainty of HiSRAMS and REWARDS estimated based on the BT measurements under clear-sky conditions. Solid and dashed lines in both HiSRAMS oxygen and water vapour bands represent the two spectrometers, FFT0 and FFT1, respectively.

Uncertainties in our simulations primarily arise from uncertainties in input parameters. In this study, we account for the input uncertainties from temperature, water vapour concentration, and cloud absorption coefficient. For temperature and water vapour profiles, we use the GEM outputs at a 9×9 grid-box resolution to capture spatial uncertainties. For cloud absorption, both spatial uncertainties and uncertainties from gamma-distribution fitting are included. Since only one observed cloud absorption profile is measured, the cloud field inhomogeneity is considered to be the cloud spatial uncertainty, which is accounted for by using the moving 10 s standard deviation of the original in situ cloud absorption coefficient measurements before arranging the in situ values into a vertical profile, ensuring that natural fluctuations within the cloud field are captured. Uncertainty in the gamma-distribution fitting arises from the bin size location in the PSD observations. During the fitting process described in Sect. 3.1, a single particle size is selected as the bin centre for each bin, introducing potential errors. For each time segment, 1,000 random bin-centre distributions are generated, and the corresponding cloud absorption coefficients are computed. The standard deviation of these 1,000 coefficients is taken as the uncertainty. Because the resulting cloud absorption coefficient uncertainty due to bin location is very small (not shown), the bin size uncertainty is deemed negligible. Consequently, only the spatial uncertainty in the cloud absorption coefficient is considered.

The BT uncertainty induced by each input variable is determined using Eq. 4, where x_i represents the i^{th} variable and Δx_i represents its 1σ uncertainty. Since these uncertainties are considered independent of one another, the total simulated BT uncertainty is calculated using Eq. 5.

$$\sigma_{x_i} = \frac{|BT(x_i + \Delta x_i) - BT(x_i - \Delta x_i)|}{2} \quad \text{Eq. 4}$$

$$\sigma_{BT_{sim}^v} = \sqrt{\sum (\sigma_{x_i}^2)} \quad \text{Eq. 5}$$

The radiative closure uncertainties arising from both measurements and simulations are shown in Figure 10 for different frequencies. For cloud-sensitive channels, for example, 94.05 GHz for REWARDS, 50.00 GHz for the HiSRAMS oxygen



radiometer, and 176.00 GHz for the HiSRAMS water vapour radiometer, during cloudy-sky conditions (14:00–15:00 UTC), the total uncertainty is primarily driven by simulation uncertainty resulting from cloud absorption uncertainties. Under clear-sky conditions, however, effective observational uncertainty dominates. For the strong absorption channels in the HiSRAMS oxygen band (e.g., 56.00 GHz), the total uncertainty also stems mainly from effective observational uncertainty. In contrast, for the strong absorption channels in the HiSRAMS water vapour band (e.g., 182 GHz), both water vapour concentration uncertainty and effective observational uncertainty contribute significantly to the total uncertainty. The total radiative closure uncertainties for all HiSRAMS frequencies are shown in Figure 11, and the respective contributions from different variables are presented in the Supplement.

The radiative closure uncertainty analysis demonstrates the critical role of the input cloud profile in all-sky microwave radiative closure, as well as the important role of the input water vapour profile for certain frequencies. It also helps identify suitable channels for future all-sky retrievals of both thermodynamic and cloud profiles.

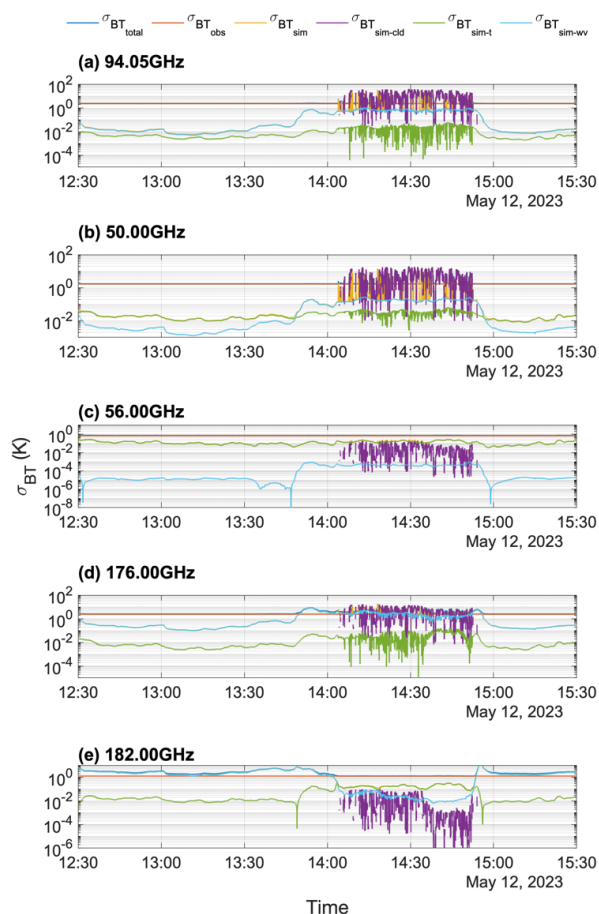
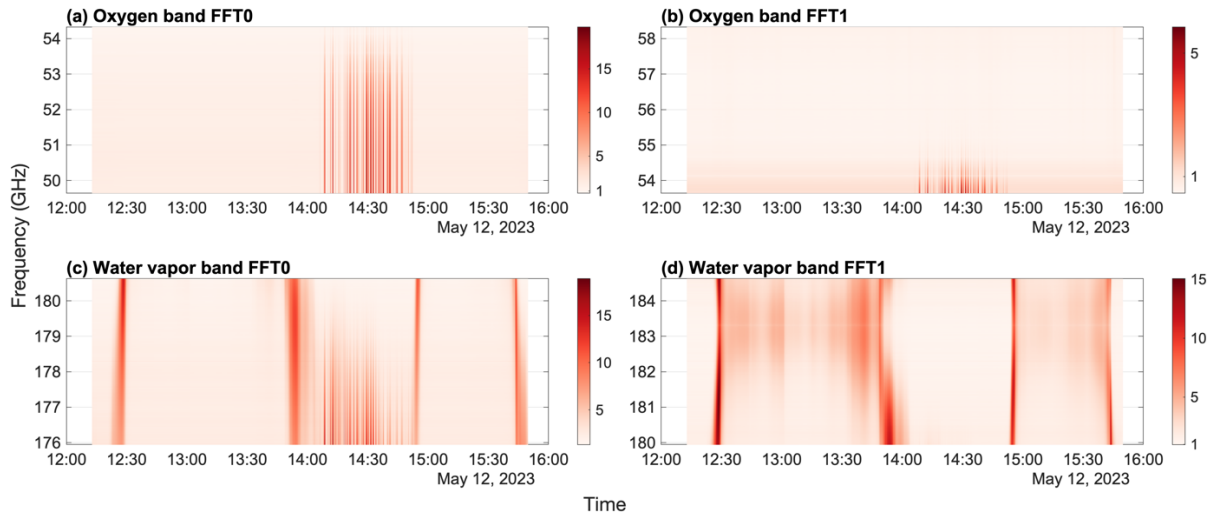


Figure 10: Radiative closure uncertainties at different frequencies for the research flight.



400 **Figure 11: HiSRAMS radiative closure total uncertainties ($\sigma_{BT^v_{total}}$) for the flight. The colour maps are displayed in units of K.**

4.3 REWARDS radiative closure

The REWARDS-observed BTs (blue lines in Figure 12a, b) highlight the instrument's sensitivity to liquid clouds while zenith-pointing. The simulated BTs (orange line in Figure 12a, b), produced by the all-sky absorption-only microwave radiative transfer model, closely match the observations. Because of significant cloud inhomogeneity, both observed and simulated BTs
 405 at cloud-sensitive channels exhibit large fluctuations, i.e. the cloud signals. As described in Sect. 3.3, REWARDS observations at 94.05 GHz were used to select the empirical cloud profile configuration. The results in this section therefore evaluate the consistency between observations and simulations conditional on that selected configuration.

Under clear-sky conditions (e.g., before 14:00 UTC and after 14:55 UTC), the BT biases (blue line in Figure 12c) are close to zero, staying well within the propagated 3σ radiative closure uncertainty range (grey shading in Figure 12c). Between 14:00
 410 and 14:55 UTC, under all-sky conditions, 87.2% of the data points fall within the 3σ uncertainty range. This fraction is used as a consistency diagnostic relative to the estimated scene-dependent radiative closure uncertainty and should not be interpreted as a Gaussian coverage probability. However, it is worth noting that the 3σ uncertainty can reach up to 100 K during certain cloudy periods. For the entire flight, the mean and standard deviation of the all-sky BT biases are 0.85 K and 12.65 K, respectively. Specifically, for clear-sky time instances, these values are 1.50 K and 6.18 K, while for cloudy-sky time instances,
 415 they are -1.94 K and 25.87 K. There are distinct differences in uncertainty behaviour between clear-sky and cloudy-sky conditions, with larger uncertainties indicating cloudy skies. The uncertainty envelope suggests the presence of spatially broken clouds, which is consistent with reports from the flight crew.

The near-zero mean cloudy-sky residual indicates little overall systematic offset, but should be interpreted together with the relatively large residual standard deviation and substantial discrepancies in individual cloudy scenes. These discrepancies
 420 indicate that the empirical cloud profile does not fully capture instantaneous cloud structure and microphysical variability.

Accordingly, the REWARDS results provide an internally constrained assessment of the microwave radiative transfer model and identify limitations in cloud characterisation, rather than providing a stand-alone calibration validation of the radiometer. Overall, the REWARDS all-sky radiative closure analysis showcases the W-band microwave radiometer's efficacy in cloud monitoring. It further emphasizes the pivotal role of accurate cloud profiles, not only for radiative closure analysis but also for constructing prior information in future retrieval applications. Although this study employs multiple airborne sensors to characterise vertical cloud profiles, significant discrepancies at times between simulated and observed microwave radiances highlight challenges in accurately representing cloud properties. In addition to uncertainties associated with representing the cloud absorption profile, residual discrepancies may arise from limitations in the in situ cloud microphysical measurements used to derive that profile, including uncertainties in droplet sizing and sampling, as well as potential environmental influences such as elevated aerosol loading and minor probe icing during portions of the flight. These factors were not explicitly quantified in the present uncertainty analysis but may have affected both the cloud characterisation and the simulated microwave brightness temperatures. Additional uncertainty may also arise from assumptions in the instantaneous cloud profile treatment and from simplifications in the absorption-only radiative transfer model. These findings underscore the need for continued improvements in cloud microphysical characterisation, complementary aerosol observations, and radiative transfer modelling to further reduce uncertainties in all-sky microwave radiative closure analyses.

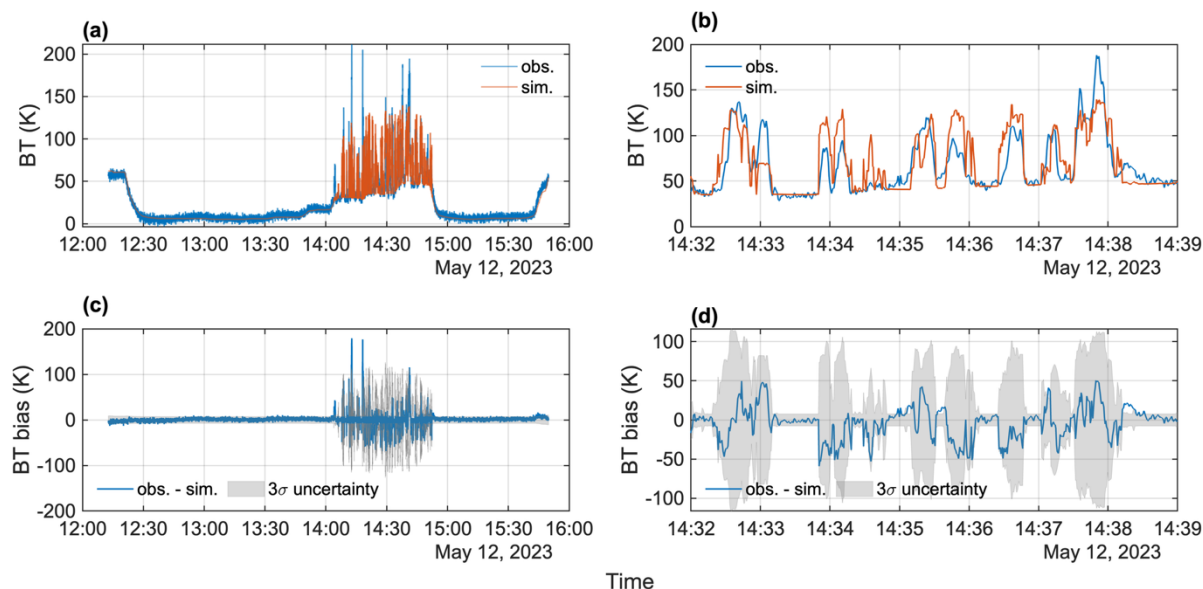


Figure 12: REWARDS radiative closure results during the flight. (a, b) Comparison between simulated and observed zenith-pointing REWARDS BT. Panel b is a zoomed view of panel a between 14:32 and 14:39 UTC, primarily under cloudy-sky conditions. (c, d) BT bias results of REWARDS. The blue lines represent the BT bias, with shading indicating the 3σ uncertainty range of the BT bias. Panel d is a zoomed view of panel c.

4.4 HiSRAMS radiative closure

The cloud vertical profile treatment described in Sect. 3.3 is based on REWARDS observations at 94.05 GHz. Hyperspectral observations from HiSRAMS provide a unique independent opportunity to test this cloud treatment method, leveraging the similar geometric configurations of HiSRAMS and REWARDS during the flight.

Figure 13 presents the radiative closure results at two cloud-sensitive channels of HiSRAMS: 50 GHz in the oxygen band (Figure 13a, b) and 176 GHz in the water vapour band (Figure 13c, d). Because HiSRAMS alternated between nadir and zenith pointing, we performed the radiative closure analysis only on zenith-pointing HiSRAMS observations to maintain geometry consistency with REWARDS. Between 14:00 and 14:55 UTC, HiSRAMS observations at these two frequencies also detect BT fluctuations of varying magnitudes (Figure 12b; Figure 13a, c). These fluctuations represent cloud signals, consistent with the theoretical analysis in Sect. 4.1.

For both selected HiSRAMS frequencies, BT biases remain well within the propagated 3σ radiative closure uncertainty range (Figure 13b, d), with 86.3% and 95.1% of the data points falling within this range, respectively. Signs of spatially broken clouds are observed in Figure 13b and d as well. Notably, the clear-sky uncertainties differ between 50 GHz and 176 GHz, with the water vapour channel exhibiting a larger uncertainty than the oxygen channel. This difference is attributed to greater variability in water vapour concentration and aligns with the clear-sky radiative closure results presented in Liu et al. (2024).

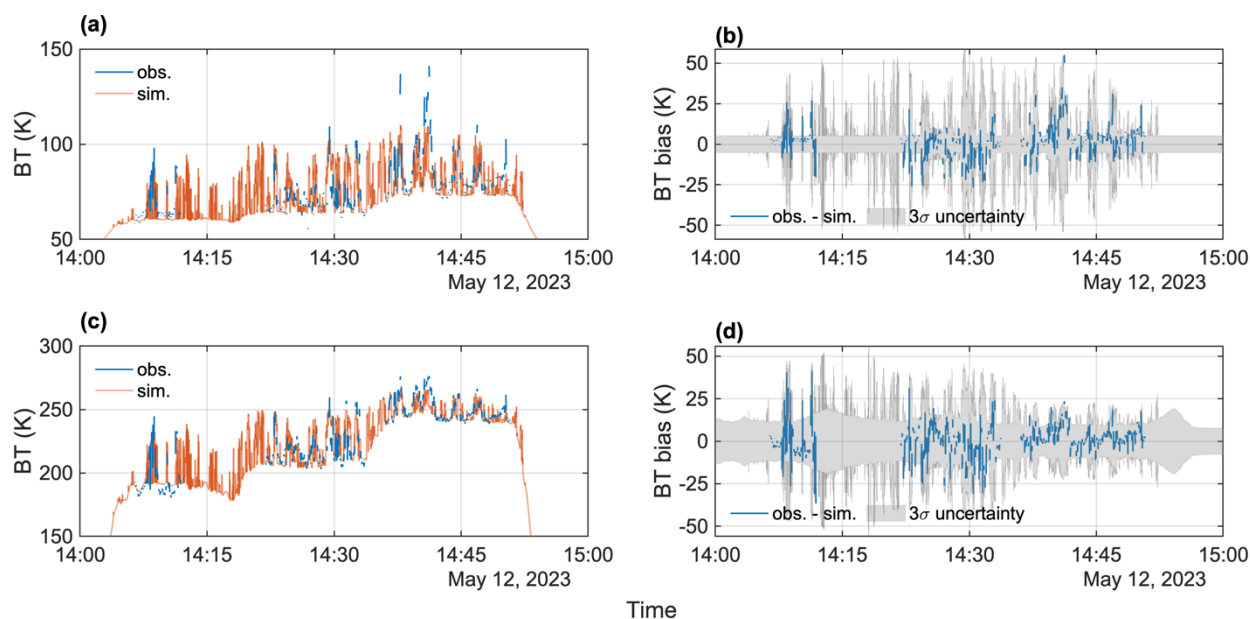


Figure 13: HiSRAMS radiative closure results for 50 GHz (a, b) and 176 GHz (c, d) during the flight. (a, c) Comparison between simulated and observed zenith-pointing HiSRAMS BT at 50 and 176 GHz, respectively. (b, d) BT bias results of HiSRAMS at 50 and 176 GHz, respectively. The blue lines represent the BT bias, with shading indicating the 3σ uncertainty range of the BT bias.

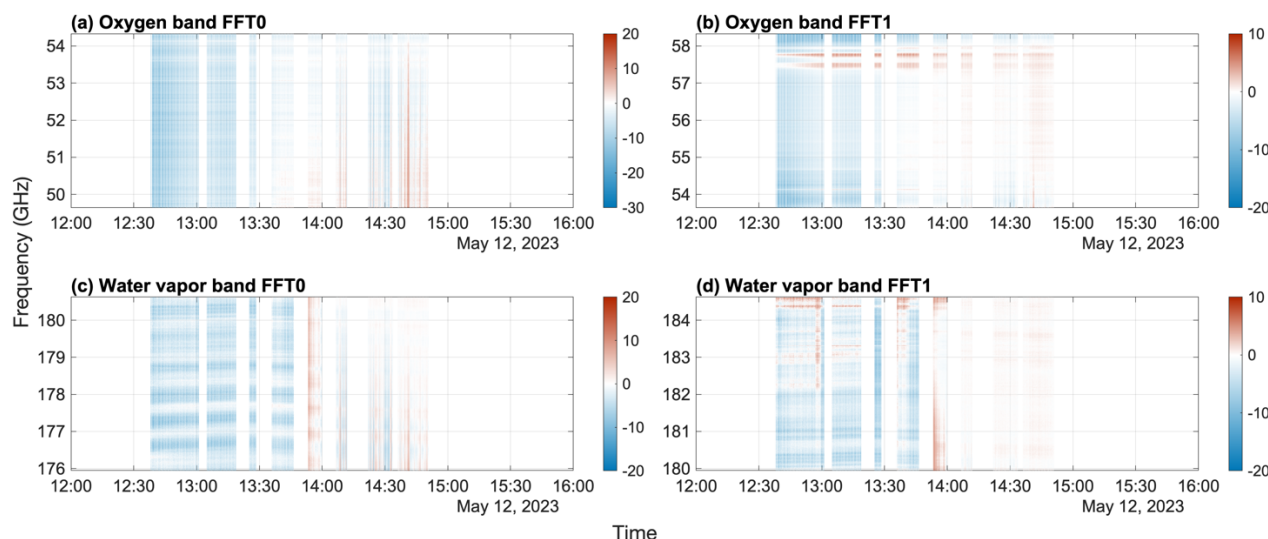


Figure 14: HiSRAMS BT biases for the flight. The colour maps are displayed in units of K.

Radiative biases for all HiSRAMS frequencies are shown in Figure 14. Negative biases are observed before 14:00 UTC under clear-sky conditions for both oxygen and water vapour absorption bands, particularly when the aircraft is at relatively high altitudes. These findings are consistent with the negative systematic bias reported at high altitudes by Liu et al. (2024). Under cloudy-sky conditions (14:00–14:55 UTC), both HiSRAMS radiometers achieve relatively good radiative closure. Overall, the HiSRAMS results provide an independent cross-instrument assessment and support the effectiveness of the REWARDS-constrained cloud treatment across microwave frequencies.

4.5 Radiative closure comparison of REWARDS and HiSRAMS

We evaluated the radiative closure performance of REWARDS and HiSRAMS by examining the percentage of zenith-pointing BT biases that fall within the propagated 3σ radiative closure uncertainty range (Figure 15). For most HiSRAMS frequencies in the oxygen band, more than 80% of the data points lie within this range, whereas for most frequencies in the water vapour band, over 95% lie within the range. These results indicate that both REWARDS and HiSRAMS perform well in terms of radiative closure performance under all-sky conditions.

Certain frequencies within the HiSRAMS oxygen band exhibit poorer radiometric performance. This behaviour is largely due to relatively large negative biases at the upper ends of FFT0 and FFT1 in the oxygen band, a pattern also observed in the clear-sky radiative closure analysis of HiSRAMS (Liu et al., 2024).

Nevertheless, HiSRAMS and REWARDS demonstrate comparable and robust consistency between observations and model simulations under liquid-stratocumulus conditions, with most observed BT biases remaining within the radiative closure uncertainty envelope. Given the different sensitivities of various microwave frequencies to atmospheric variables and the overall robust but variable all-sky radiometric performance, careful channel selection is feasible and advantageous for future all-sky retrieval applications.

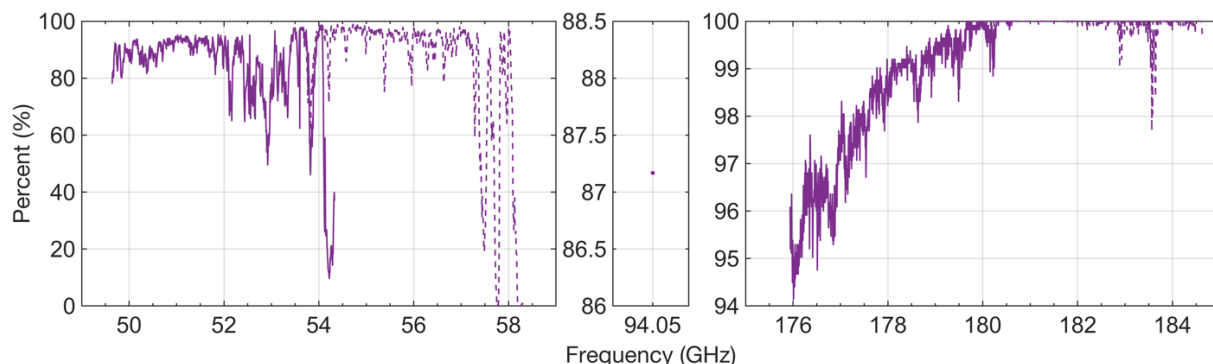


Figure 15: Radiative closure comparison between HiSRAMS and REWARDS, indicated by the percentage of all-sky BT biases within the propagated 3σ radiative closure uncertainty range between 14:00 and 14:55 UTC. Solid and dashed lines in both HiSRAMS oxygen and water vapour bands represent the two spectrometers, FFT0 and FFT1, respectively.

5 Conclusions and discussions

Microwave radiometers, with their ability to see through clouds, hold great potential for both weather forecasting and climate research. Although current passive microwave radiometers typically operate with only a few channels, recent advances in digital polyphase FFT filter banks have enabled the creation of hyperspectral microwave radiometers. Among these, HiSRAMS is one of the first such instruments to be designed and built. Spaceborne W-band observations have been used extensively for active cloud sensing (Stephens et al., 2008; Wehr et al., 2023), and are now being explored for passive sensing. In this study, we performed a radiative closure analysis of both HiSRAMS and REWARDS as a critical test for their all-sky retrieval capabilities. The dataset was collected during an NRC Convair-580 flight on 12 May 2023, during which multiple airborne sensors were deployed to capture cloud properties and atmospheric conditions. An all-sky microwave radiative transfer model that accounts for cloud absorption was developed to simulate BTs, which were compared with those observed by HiSRAMS and REWARDS. Key inputs to this forward model included vertical temperature and water vapour profiles from high-resolution GEM simulations, along with cloud absorption profiles. One key contribution in our approach was the handling of cloud absorption profiles. We began with the reference cloud absorption profile derived from in situ microphysical observations spanning the entire flight. Then, leveraging instantaneous vertical profiles from radar and lidar, we conducted detailed sensitivity tests to “screen” this in situ profile and determine the best possible instantaneous cloud absorption profiles at each time step. This synergy between radar, lidar, and in situ observations, enabled by multiple airborne cloud sensors, refines the cloud inputs used in the forward model and lays the foundation for further radiative closure analysis of REWARDS and HiSRAMS.

Because different frequencies exhibit different sensitivities to atmospheric variables, we performed theoretical analyses to identify cloud-sensitive channels, which include the 94.05 GHz REWARDS frequency, as well as the weak absorption range of both HiSRAMS radiometers. Our radiative closure uncertainty analysis revealed the relative importance of the different input variable at different frequencies across various observational heights in the presence of low clouds below 2 km. Among



these, the vertical profiles of cloud absorption were found to be a major source of uncertainty, especially for cloud-sensitive channels. Additionally, water vapour concentration variability contributed notably to radiative closure uncertainties in the weak absorption channels of the HiSRAMS water vapour radiometer. These findings highlight the importance of accurately representing cloud microphysics and water vapour when simulating radiances in these sensitive channels. At the same time, their strong responses to cloud and water vapour properties indicate that they contain valuable information for atmospheric retrievals.

Under the liquid-stratocumulus conditions, HiSRAMS and REWARDS showed broad consistency between observations and model simulations relative to the estimated uncertainty scales, with over 80% of data points falling within their respective uncertainty ranges. Nevertheless, notable discrepancies remained between simulated and observed BTs under cloudy conditions, reflecting the challenges of accurately representing the spatial and temporal variability of cloud structure, even when multiple cloud sensors are combined. In addition to uncertainties associated with cloud variability, limitations in the in situ cloud microphysical measurements used to derive the cloud absorption profiles, additional potential uncertainty from elevated aerosol loading, and environmental factors such as minor probe icing may also have contributed to the residual differences. These uncertainty sources were not explicitly quantified in the present study but highlight the need for future campaigns that integrate improved cloud microphysical characterisation, comprehensive aerosol measurements, and independent cloud probe intercomparisons to further reduce uncertainties in all-sky microwave radiative closure analyses across a broader range of atmospheric conditions. This study focuses on liquid-stratocumulus cloud conditions. Further studies under a broader range of cloud regimes, including mixed-phase, glaciated, and precipitating clouds, are needed to more comprehensively evaluate microwave radiometer performance.

The radiative closure results, supported by uncertainty analyses, indicate the strong potential of both instruments for retrieving temperature, water vapour, and cloud properties in all-sky conditions. The unique synergy achieved through multiple airborne cloud sensors highlights an important pathway for assessing all-sky radiative closure of radiometers and reducing retrieval uncertainties in future operations. Building on similar multi-sensor data collections, future studies will aim to achieve radiative closure under mixed-phase and glaciated cloud conditions. Ultimately, this work informs optimal channel selection and instrument configuration for advanced microwave remote sensing applications in both operational forecasting and climate monitoring.

Data availability

The field campaign data and the radiative closure data are available from the corresponding author upon reasonable request.



Author contribution

NB, YH, JG, PG, CN, and MW conceived the research. LL, NB, YH, CN, and PG designed the methodology. NB, CN, KR, KB, and LN collected experimental data. LL conducted the primary analysis, with data support from CN (radar), KR (lidar), ZQ (GEM), and PB (2D-S). DS served as the ESA lead manager and oversaw the project. LL led the manuscript writing, with all co-authors contributing to the review.

Competing interests

The authors declare that they have no conflict of interest.

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