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An exploration into the assimilation of sub-millimetre frequencies observed by the Arctic Weather Satellite

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Abstract

The sub-millimetre channels in the 325 GHz band on the Arctic Weather Satellite have been assimilated operationally at ECMWF since July 2025. Prior work has shown they have a positive impact on the forecast when used alongside the 183 GHz humidity-sounding channels, and that they have a greater sensitivity to cloud ice scattering than traditional microwave frequencies. There are other upcoming EUMETSAT missions exploring the sub-millimetre, such as the EPS-Sterna constellation that also covers the 325 GHz band, and the Ice Cloud Imager which extends up to 664 GHz. These higher frequencies are expected to have an even greater sensitivity to cloud ice, motivating an exploration into the assimilation impact of the 325 GHz band. In this report, we investigate whether the sub-millimetre channels remain beneficial when assimilated without the 183 GHz channels, and whether their stronger sensitivity to cloud ice is reflected in the forecast of ice clouds and snow. We perform single-observation experiments to identify potential mechanisms and evaluate the full impact of the 325 GHz channels through four-month Observing System Experiments.

We determine that the information from the sub-millimetre channels is best exploited when used alongside 183 GHz. On the Arctic Weather Satellite, the 183 GHz channels are better at constraining the humidity profile, complementing the additional information provided by the 325 GHz band. We expect that within a data assimilation system, other observations of the 183 GHz band would sufficiently constrain the humidity field, whether or not they are co-registered, facilitating the exploitation of these sub-millimetre frequencies. When these sounding bands are combined, we find an improved characterisation of the cloud ice in the analysis, particularly in regions with strong convection. This leads to improvements in the 12H forecast scores for total column frozen water in these regions, in addition to the improvements to the humidity and wind at longer lead times. This study is the first investigation into the assimilation of sub-millimetre frequencies in all-sky conditions, and highlights the positive impact expected from upcoming satellites observing these frequencies.

1 Introduction

The assimilation of microwave frequencies plays a leading role in [Numerical Weather Prediction \(NWP\)](#) systems due to their strong contributions towards forecast accuracy ([Bormann *et al.*, 2019](#); [Randrianampianina *et al.*, 2021](#)). Recently, this has extended into the sub-millimetre range where frequencies exceed 300 GHz ([Eriksson *et al.*, 2025](#)). These higher frequencies are significantly more sensitive to scattering from frozen hydrometeors than the traditional microwave spectral range which extends up to around 200 GHz. Their inclusion in data assimilation is expected to provide significant information about the properties of cloud ice (ice clouds and snow).

Accurately analysing and forecasting cloud ice is vital as it modulates both radiative and precipitation processes. For example, it's expected that, on average, half of the global surface precipitation is related to cloud ice ([Field and Heymsfield, 2015](#)), and the representation of cloud ice microphysical processes has been shown to influence the spatial and temporal distribution of storm structures ([Milbrandt and Yau, 2006](#)). However, there are a number of barriers to accurately modelling their macro- and micro-physical properties, in addition to the traditional issues in forecasting clouds ([Aumann *et al.*, 2023](#)). This includes quantifying their complex scattering properties, and modelling their varied evolution and formation mechanisms. Within the [European Centre for Medium-Range Weather Forecasts \(ECMWF\)](#) NWP system, there is currently a general underestimation in the global mean ice water path (IWP), particularly for thin cirrus clouds, but an overestimation in parts of the tropics. Furthermore, the cloud ice also struggles to persist later into the forecast ([Delanoë *et al.*, 2011](#)).

There are a number of observations that have been previously or are currently assimilated in all-sky conditions that have some sensitivity to cloud ice, but these observations often have limitations. While

high-frequency radars and active microwave sensors have a greater sensitivity to ice crystals than the sub-millimetre range, they provide limited spatial sampling that reduces their impact within assimilation systems (Janisková and Fielding, 2020). Passive visible and infrared observations are more sensitive to small ice hydrometeors, however, the all-sky assimilation of visible and infrared radiances is not yet operational at ECMWF and is currently under development (Geer *et al.*, 2019; Schomburg *et al.*, 2026). Traditional passive microwave sensors measure at wavelengths that are sensitive only to the largest frozen hydrometeors, and have a significantly lower cloud ice sensitivity than the sub-millimetre range (May *et al.*, 2024; Duncan *et al.*, 2026b). At sub-millimetre frequencies, the extinction of radiation from frozen hydrometeors is dominated by scattering, and so this region provides new information about the amount, size distribution, shape, and orientation of the cloud ice particles (Geer *et al.*, 2021).

The first passive observations of the sub-millimetre have been assimilated at ECMWF since July 2025: three channels in the 325 GHz band. These are new observations from the European Space Agency's Arctic Weather Satellite (AWS), which was launched in August 2024. AWS is a small satellite that carries a single cross-track scanning microwave radiometer. It has channels measuring frequencies near 50, 89, 166, 183, and 325 GHz. The aim of this mission is to demonstrate a prototype for a polar-orbiting constellation of satellites that could provide data for short-term global forecasts and nowcasts. As such, it is a precursor to the EPS-Sterna constellation, which will consist of at least six AWS-like satellites at a given time and is expected to significantly improve the accuracy of NWP models (Eriksson *et al.*, 2025). The sub-millimetre channels from AWS are also a preview of the EUMETSAT Ice Cloud Imager, which will feature even greater cirrus sensitivity as it measures frequencies up to 664 GHz where greater scattering occurs (Eriksson *et al.*, 2020). This report aims to perform an exploratory study into the impact of the sub-millimetre in support of these missions.

The assimilation of the sub-millimetre channels on AWS has been shown to positively impact forecasts when used alongside the traditional humidity-sounding 183 GHz channels (Duncan *et al.*, 2026a). This improvement was most pronounced in short-range humidity forecasts at higher latitudes, but smaller improvements were also seen in temperature and wind. Here, we explore two questions. First, what is the relationship between the 183 and 325 GHz channels within the assimilation? Second, how does the inclusion of sub-millimetre frequencies influence the cloud ice in the analysis and forecast?

The structure of this report is as follows. Section 2 summarises the current setup for the operational all-sky assimilation of AWS at ECMWF. Section 3 performs single-observation experiments using the 183 and 325 GHz channels to explore targeted case studies. Section 4 contains Observing System Experiments (OSEs) that explore the interactions between these channels and impact on the forecasted cloud ice. Conclusions are contained in Section 5.

2 All-sky Assimilation of the Arctic Weather Satellite

The Arctic Weather Satellite (AWS) is a polar-orbiting satellite that carries a single instrument called the Microwave Radiometer. This instrument scans in a cross-track pattern, observing from nadir to 54.5 degrees on both sides, with the scan direction perpendicular to the satellite's ground track (Eriksson *et al.*, 2025). It has 19 channels spanning 50 to 330 GHz that are grouped into four separate feedhorns, all with a QV polarisation. Each feedhorn has a unique geolocation, incidence angle, and swath on the ground. This is accounted for in the preprocessing of AWS data prior to assimilation by superobbing observations onto a common equal-area grid with a resolution of ~ 50 km (Geer and Bauer, 2010). Information about the zenith angle is stored per feedhorn to simulate the observations (Duncan *et al.*, 2025).

The first feedhorn contains the 50 GHz temperature-sounding channels (CH1-8). The second feedhorn

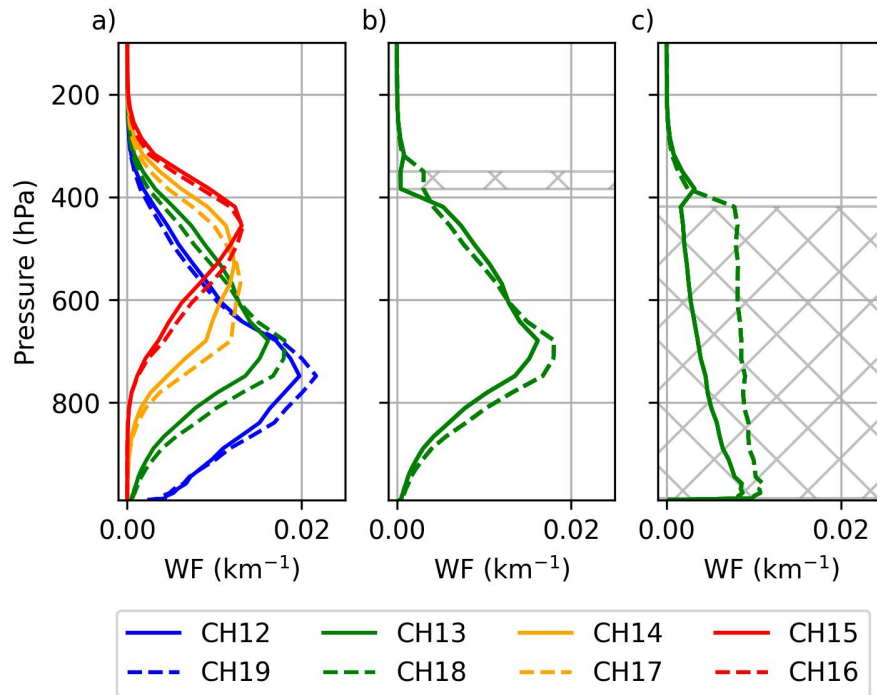


Figure 1: The weighting functions (WF) for the equivalent (solid) 183 and (dashed) 325 GHz channels on AWS in (a) clear-sky conditions, (b) the presence of a thin ice cloud, (c) the presence of a deep snow cloud based on Jeoung et al. (2020). For cloudy cases, only CH13 and 18 are shown for clarity, as CH18 is the lowest peaking 325 GHz channel that is assimilated operationally. Transmittances have been simulated using RTTOVv14 with the default IFS settings for nadir. All examples use the same clear-sky atmosphere with a total column water vapour (TCWV) of 12.6 kgm^{-2} and surface temperature of 280.4 K taken from the ECMWF 137-level diverse profile dataset described in Eresmaa and McNally (2014). Hatched regions show where hydrometeors were included: (b) a cloud $\sim 1 \text{ km}$ thick with cloud top height at $\sim 9 \text{ km}$ and ice water path of 250 gm^{-2} , (c) a deep snow cloud with a snow water path of 500 gm^{-2} and cloud top height at $\sim 7 \text{ km}$.

contains a single 89 GHz window channel (CH9). The third feedhorn contains the 165.5 GHz window channel (CH10) as well as the single-banded 183 GHz humidity sounding channels (CH11-15). The final feedhorn contains the double-banded 325 GHz channels (CH16-19). Each of the sub-millimetre channels were selected to have a clear-sky weighting function that corresponds to one of the 183 GHz channels (Eriksson et al., 2025), as highlighted in Figure 1a. The 183 GHz channels are less sensitive to cloud ice than their counterparts. This is particularly true in the case of thinner ice clouds as shown in Figure 1b. However, Figure 1c shows that they do have some sensitivity to larger frozen hydrometeors, such as snow. Despite this, it is clear that the sensitivity to snow is much greater at 325 GHz.

CH4-7 (50 GHz) and CH11-18 (183 and 325 GHz) are assimilated operationally at ECMWF in all-sky conditions. Full details of the all-sky assimilation system are summarised in Geer et al. (2014), with the treatment of AWS outlined in Duncan et al. (2025), and specifics regarding the 325 GHz channels in Lean and Bormann (2024). Here we provide a brief overview.

At ECMWF, operational weather forecasts are produced using the Integrated Forecasting System (IFS). This system uses incremental 4-dimensional variational assimilation (4D-Var) to combine tens of millions of observations per day with a physics-based model, producing an analysis from which forecasts are run. The control variables are the transforms of surface pressure (a 2D field), relative humidity, wind (vorticity and divergence), and temperature (3D fields) at the beginning of the assimilation window. As of May 2026, the operational version of the IFS is Cycle 50r1 (Polichtchouk et al., 2025).

The forecasted cloud and precipitation are calculated from the wind, humidity, and temperature fields at every time step. The only way to adjust cloud or precipitation during the assimilation window is by adjusting the control variables at the beginning of the window in such a way that the forecast model subsequently produces the required adjustments. Cloud and precipitation are represented in the model using two schemes. The first is the large-scale scheme which represents the sources and sinks of cloud and precipitation through large-scale dynamics. The second is the convection scheme, separated into shallow, mid-level, and deep convection, that represents the vertical movement of a plume of air inside a grid box (Tiedtke, 1993; ECMWF, 2026). Cloud water and ice can be detrained from the convection scheme into the large-scale scheme.

To simulate radiances, the IFS uses [Radiative Transfer for TOVS \(RTTOV\)](#) as its observation operator, with Cycle 50r1 using RTTOVv14 (Saunders *et al.*, 2018). This is a fast radiative transfer code that uses instrument-specific coefficients to increase its operational speed. There are five hydrometeors currently represented within RTTOV: cloud ice, cloud liquid, snow, graupel, and rain, each with different assumed microphysical parametrisations. Within the IFS, snow produced by the large-scale scheme is treated as snow in RTTOV, while snow produced by the convection scheme is treated as graupel to achieve the greater scattering caused by these particles. The treatment of hydrometeor polarisation is currently inactive for cross-track microwave sounders in RTTOV (Geer, 2021; ECMWF, 2026). The radiometric contributions from atmospheric gases and the hydrometeors are combined using the two-column approach and an effective hydrometeor (cloud) fraction. This effective hydrometeor fraction is computed as a layer average of the cloud fractions weighted by each hydrometeor amount.

The AWS radiative transfer coefficients for RTTOV contain variable water vapour and ozone, however the sub-millimetre channels have a sensitivity to the latter on the order of a tenth of a degree (Turner *et al.*, 2022; Barlakas *et al.*, 2022; Eriksson *et al.*, 2025). Given the novelty of the 325 GHz channels, there have been recent studies investigating the ability of RTTOV to simulate this spectral range, with a particular focus on scattering from frozen hydrometeors in Geer (2021), Duncan *et al.* (2025), and Duncan *et al.* (2026b). The surface emissivity for the ocean is simulated using the [SURFace Fast Emissivity Model for Ocean \(SURFEM-Ocean\)](#) model which supports sub-millimetre frequencies (Kilic *et al.*, 2023). The surface emissivity for land is dynamically retrieved for the temperature and water vapour sounding channels using the 50.3 and 89 GHz channels, respectively, making use of their greater surface sensitivity (Baordo and Geer, 2016).

3 Single-observation Experiments

The assimilation of 325 GHz in the IFS has already been shown to have a positive impact on the forecast humidity, temperature, and wind, particularly at higher latitudes (Duncan *et al.*, 2025). It has yet to be determined if these improvements are a result of a stronger humidity sensitivity in cloudy conditions, improved discrimination between cloud ice and humidity signals, or better cloud placement. Here, we explore potential mechanisms underlying these improvements through three case studies using single-observation experiments. The setup of these experiments and methods of analysis are detailed in Section 3.1 with results in Section 3.2.

3.1 Experiment Configuration

Three case studies have been selected to satisfy two criteria. First, we aim to only examine observations that are (a) clear-sky or (b) contain only frozen hydrometeors and so have no liquid cloud or precipitation.

Experiment	Latitude	Time of Observation	TCWV (kgm^{-2})	FWP (gm^{-2})	CI (K)
Clear-sky	66.3	15:56	14.9	0	0.1
Low FWP	36.6	14:12	35.5	50	0.6
High FWP	-36.2	12:41	29.2	781	-5.3

Table 1: The case studies selected to examine the impact of the sub-millimetre channels. Integrated values (total column water vapour (TCWV) and frozen water path (FWP)) are the first-guess values taken from a Cycle 50r1 experiment run at the same resolution as the operational system. The symmetric cloud impact (CI) for the lowest-peaking 183 GHz channel (CH12) is also provided. This is calculated by averaging the difference between the observed and simulated clear-sky brightness temperatures and the difference between the simulated all-sky and clear-sky brightness temperatures.

	Frequency (GHz)	Clear-sky	Low FWP	High FWP
FG Departures (K)	183	2.3	0.2	-2.1
	325	2.3	1.5	-8.4
Observation Errors (K)	183	1.7	1.7	2.2
	325	2.5	4.5	27

Table 2: The mean first-guess (FG) BT departures and assigned observation errors for 183 (CH12-15) and 325 (CH16-19) GHz in each case study.

This is to (a) gain an indication of how the similar clear-sky sensitivity between the 183 and 325 GHz manifests in the assimilation and to (b) see what complications the additional information about cloud ice brings. Second, we aim to isolate cases where the 325 GHz channels have improved the forecast and thus limit cases to those with a [Forecast Sensitivity to Observation Impact \(FSOI\)](#) metric for the 325 GHz channels in the top 50th percentile of all observations in the operational system (Cycle 49r1 at the time of study).

The selected case studies are summarised in Table 1 and include one clear-sky and two cloudy cases that were assimilated in the 12Z analysis on 10th August 2025. Plots of the observed brightness temperatures (BTs) and modelled frozen water path (FWP) for these cases are contained within Figure 2. The clear-sky (Figure 2a-c) and low FWP (Figure 2d-f) cases are over land, while the high FWP case is over ocean (Figure 2g-i) and all have a modelled surface albedo of ~ 0.15 . The cloudy cases were selected to provide examples of typical low and high FWPs that would be detectable in the sub-millimetre channels based on [Duncan et al. \(2026a\)](#). The mean differences between the simulated and observed BTs (the BT departures) for the first guess at 183 and 325 GHz are summarised in Table 2 for each case study alongside the mean assigned observation errors.

In both of the cloudy cases, the observation is at the edge of a cloud. In the low FWP case, the observation is at the northern edge of the cloud, and the cloud moves east and elongates within the 12-hour window. In the high FWP case, the observation is at the southern edge of the cloud, and the cloud drifts southwards into the observation. The symmetric [cloud impact \(CI\)](#) in the lowest-peaking 183 GHz channel (CH12) is also shown for reference. This provides a broad indication of the sensitivity of the 183 GHz channels to the frozen hydrometeors, with larger negative values suggesting greater sensitivity. We would therefore expect that, in the high FWP case, the 183 GHz channels should have some sensitivity to the larger frozen hydrometeors.

For each case, we perform four experiments using the IFS Cycle 50r1 at the same resolution as the operational suite (Tco1279 ~ 9 km resolution with a final analysis increment resolution of ~ 40 km). Unless stated otherwise, the observation errors and quality control are also the same as the operational suite (see Table 11 in [Duncan et al. \(2025\)](#) with observation errors restated here in Table 2). Each experiment is

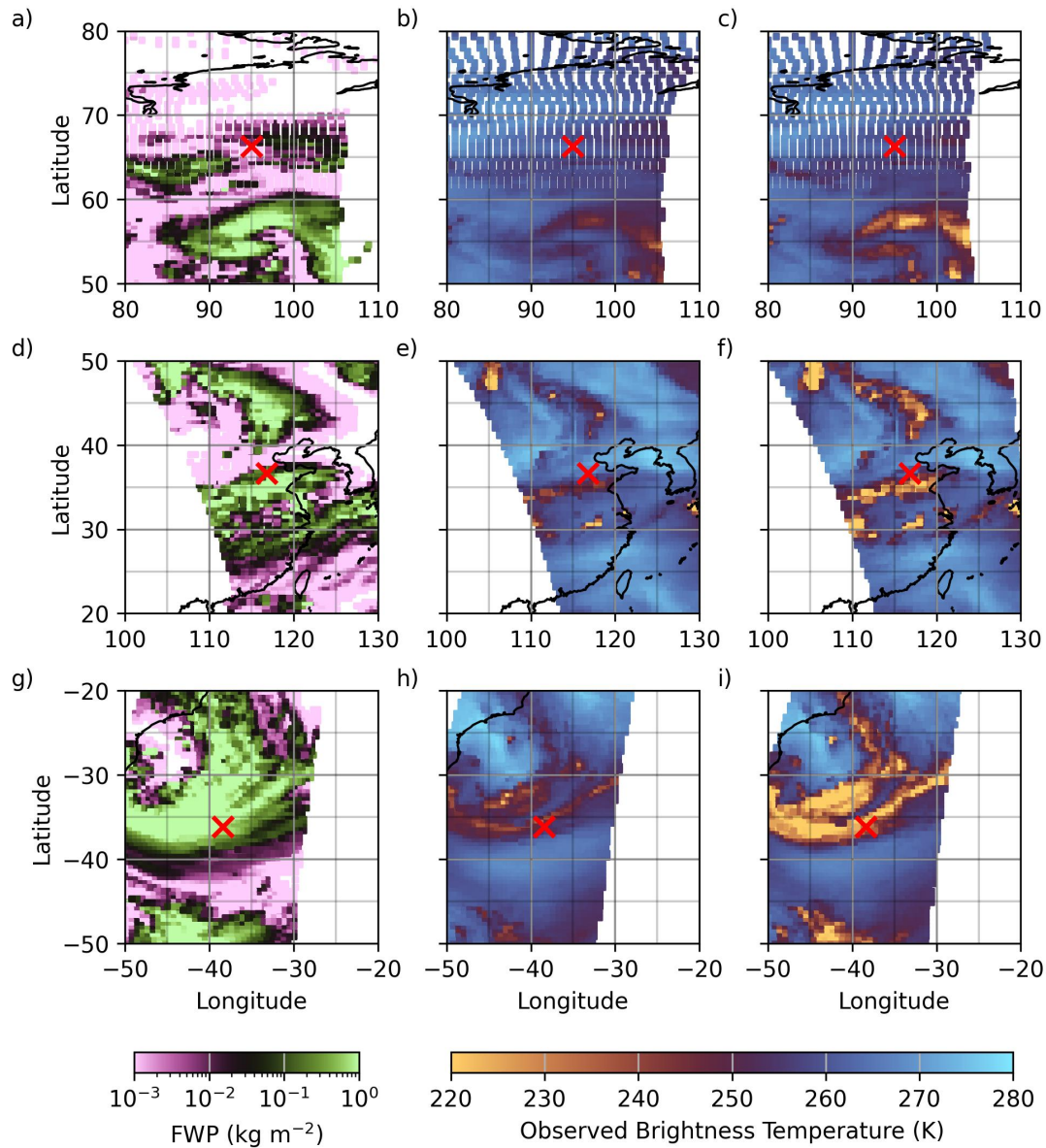


Figure 2: The first column shows the forecast frozen water path (FWP) for each case study. The second and third columns show the observed brightness temperature by AWS CH12 and CH19, respectively. (a-c) clear-sky case, (d-f) low FWP case, (g-i) high FWP case.

run for a single 12-hour cycle, with the analysis and forecast fields for temperature, humidity, and wind output every 3 hours. All experiments use the same background state from a IFS Cycle 50r1 experiment that used the same observing system, resolution, error setup, and quality control as the operational suite. The first three experiments contain a single superobbed AWS observation at the following frequencies: 183 GHz (CH12-15), 325 GHz (CH16-19), and 183 + 325 GHz (CH12-19). The 183 and 325 GHz channels were selected because they have matching clear-sky weighting functions (Figure 1a). The fourth experiment for each case uses the analysis from the full-observing system as a reference, as this can be taken as a best estimate of the true state.

For the clear-sky case, we perform an additional experiment (referred to from here on as the 325* GHz

experiment) to separate the impact of the information available at these sub-millimetre frequencies and their weighting in the assimilation. In clear-sky conditions, the observation errors assigned to the 325 GHz channels are on average 0.8 K ($\sim 50\%$) larger than those assigned to the 183 GHz channels (Table 2). These larger clear-sky observation errors are assigned to the 325 GHz channels due to their greater sensitivity to cloud ice exacerbating the impact of residual cloud on the representation error in clear-sky conditions. This must be accounted for in a global NWP system. However, for this specific case study, the chance of cloud contamination is expected to be smaller, and we see similar first-guess departures between the channel sets, so it poses a good case study to investigate the response of the analysis when the weighting of the two channel sets is the same. Therefore, the 325* GHz experiment also assimilates only CH16-19, but uses the clear-sky observation errors from their corresponding 183 GHz channels.

The study of these single-observation experiments will be divided into two subsections: the first centred on observation space (BTs), and the second centred on model space (analysis increments). Here, we will describe the parameters used to assess both of these aspects.

We will first examine the simulated AWS BTs for each case study in Section 3.2.1. To do this, we will use the root-mean-square-error (RMSE) between the analysis in the full-observing system and the experiments in selected channels:

$$\text{RMSE} = \sqrt{\sum_i^n \frac{(B_{i, \text{single obs}} - B_{i, \text{full obs}})^2}{n}} \quad (1)$$

where B is the BT simulated in the analysis and n is the number of channels. Equation 1 will be used to calculate two parameters: RMSE_{183} using CH12-15 and RMSE_{325} using CH16-19. A lower RMSE value indicates an analysis that is more similar to what was produced by the full-observing system which is assumed to be the best estimate of the true state. It is important to note that while the analysis in the full-observing system includes the 325 GHz channels from AWS, it is dominated by observations of 183 GHz from multiple other microwave sounders. This may potentially limit the representation of cloud ice within the analysis of the full-observing system.

As large-scale cloud variables are prognostic within the IFS, the only way cloud can be altered is by changing the control variables. Therefore, Section 3.2.2 will primarily focus on the analysis increments for temperature, humidity, and wind in these case studies as these are linked to the control variables, before briefly examining the FWP analysis increments. The humidity and wind fields are more significantly affected by cloud (and humidity) observations than temperature (Geer *et al.*, 2017). The relationship between humidity and cloud is more direct as humidity dictates the saturation conditions for a cloud to form. Wind, however, can be altered through 4D-Var wind tracing, where the wind field is adjusted to better fit observations of cloud, precipitation, and humidity (Geer *et al.*, 2017; Zuplotnik *et al.*, 2023). Therefore, while we will examine vertical profiles for local temperature and humidity increments, for wind, we will present 2D maps of the change in wind increments with a focus on increments near the top of the cloud where the sub-millimetre channels should be most beneficial (~ 250 hPa in both cases).

In each case study, the wind components analysed have been selected so a positive change is a reflection of how the cloud moved in the full-observing system. For the low FWP case, we saw the cloud elongate eastwards, and so the zonal wind component is shown. For the high FWP case, we saw the cloud move south and so the meridional wind component is shown. For the clear-sky case, neither wind component was dominant and so we examine the wind speed itself. These components will be compared to what was present in the 183 GHz experiment through the following:

$$p = 100 \times \frac{i_{325 \text{ or } 183+325} - i_{183}}{i_{183}} \quad (2)$$

where p is the percentage change in the increment relative to the 183 GHz experiment, and i is the wind increment at 250 hPa for each experiment within the case study.

3.2 Results

3.2.1 Simulated Brightness Temperatures

We now examine the differences between the simulated BTs in the AWS channels for each observation using the RMSE parameters described in Section 3.1. Table 3 shows the RMSE values between the full-observing system and the first-guess or analysis simulated BTs in each experiment. Plots of the departures from all channels can be found in Appendix A.

First, we consider experiments in which only the 183 or 325 GHz channel sets were used individually. In all cases, using either frequency band improves the RMSE_{183} from the first-guess fit. Assimilating only the 183 GHz channels always yields a better fit of the analysis to the full-observing system in CH12-15 than if the 325 GHz channels were used. Interestingly, the reverse is not true. In the clear-sky and high FWP cases, assimilating only the 325 GHz channels results in a larger RMSE_{325} i.e a weaker fit to the analysis BTs of the full system in CH16-19. In both of these case studies, the 183 GHz channels are expected to be sensitive to humidity and cloud, and so apply some constraint in the assimilation. It is relevant to note that in the full-observing system significantly more observations of 183 GHz are assimilated than observations of 325 GHz as the former is available on multiple microwave instruments. This may lead to a limited representation of the signals captured by the 325 GHz channels in the full-observing system, particularly for these case studies, and contribute towards the larger RMSE_{325} value.

Case	Experiment	RMSE_{183}	RMSE_{325}
Clear-sky	FG	1.34	1.28
	183	0.47	0.51
	325	0.78	0.80
	325*	0.47	0.50
	183+325	0.48	0.48
Low FWP	FG	0.98	0.52
	183	0.60	1.34
	325	0.75	1.12
	183+325	0.56	1.36
High FWP	FG	2.31	10.31
	183	1.83	8.02
	325	2.17	9.60
	183+325	1.76	7.70

Table 3: The RMSE between the simulated BTs in each experiment and those seen in the full-observing system experiment. Note that 325* refers to the experiment where the 325 GHz observation errors are the same as the 183 GHz observation errors. Values are shown for the first guess (FG) for each case, which is consistent between the single-observation experiments, and for the analysis in each experiment. RMSE values have been calculated using Equation 1 in (RMSE_{183}) AWS CH12-15 and (RMSE_{325}) AWS CH16-19 for each experiment. An RMSE value of 0 is indicative that the simulated BTs are identical to what was produced by the full-observing system.

To fairly investigate the impact of these two channel suites, it is also important to consider the difference in their weighting within the assimilation. This is best examined through the clear-sky case study where we expect both channel suites to have a similar clear-sky sensitivity (Figure 1a). In this case, using the 325 GHz channels instead of the 183 GHz channels results in less movement from the first guess, and larger RMSE values. In these experiments, the prescribed clear-sky observation errors are 1.7 and 2-3 K for the 183 and 325 GHz channels, respectively. Therefore, the 325 GHz channels have been given less weight in the assimilation (as justified in Section 3.1). When the 325 GHz channels are assigned the same clear-sky observation errors as the 183 GHz channels (in the 325* GHz experiment), we see comparable $RMSE_{183}$ and $RMSE_{325}$ values to the 183 GHz experiment. This suggests that the larger RMSE values that occur when the 325 GHz channels are used in isolation are a result of the lower weighting in the assimilation, and in clear-sky conditions both channel suites can provide comparable humidity information.

We can now explore the impact of the 325 GHz channels in the presence of cloud ice. The FWP case studies highlight that the 325 GHz channels are particularly impactful in the low FWP case, whereas the added information is more limited in the high FWP case. For the low FWP case, both the 183 GHz and 325 GHz experiments degrade the $RMSE_{325}$ values from the first guess. However, assimilating 325 GHz instead of 183 GHz reduces this degradation by 15 %. This is counteracted by a 25% increase in the $RMSE_{183}$ value. One interpretation is that while the sub-millimetre channels may have some additional information about cloud ice, it is not being correctly separated from the humidity information. Another, is that we may be seeing the bias of the full-observing system towards information from the 183 GHz channels impacting the RMSE values, as previously discussed. For the high FWP case, using the 325 GHz channels produce an $RMSE_{325}$ value that remains close to the first-guess state, whereas assimilating the 183 GHz channels further reduces the $RMSE_{325}$ value. While the 325 GHz channels are more sensitive to FWP, the 183 GHz channels are also sensitive to scattering from large frozen hydrometeors. In this case study, the 183 GHz channels have a symmetric cloud impact of -5.3 K. This suggests that in these higher FWP cases, the 183 GHz channels have some sensitivity to the larger frozen hydrometeors and so the 325 GHz channels are providing a limited amount of extra information.

In all of the cases, combining the 183 and 325 GHz channels results in the best fit relative to the full-observing system from CH12-19. This is least significant in the clear-sky and low FWP cases where the $RMSE_{183}$ and $RMSE_{325}$ values are comparable between the 183 GHz and 183+325 GHz experiments. It is most significant in the high FWP case where combining the channels results in reductions in the RMSE values of the order of 5 % against the 183 GHz experiment. This suggests two things. First, the 183 GHz channels have sufficiently constrained the water vapour profile in each case, and the 325 GHz channels offer little additional information on humidity. Second, the 183 GHz channels are required to constrain the water vapour profile and exploit both the cloud ice and humidity signals in the 325 GHz channels. These inferences will be investigated further through an examination of the analysis increments.

3.2.2 Analysis Increments

We now consider the impact of the observations on the analysis increments for temperature, humidity, and wind in these case studies using the methods described in Section 3.1. Figure 3 shows the median analysis increment for temperature (a-c) and humidity (d-f) in a 1x1 degree box surrounding the centre of the observation. These increments are taken from the 3-hour time slot preceding each observation. For the clear-sky and high FWP cases, this is approximately 1 hour before the observation. For the low FWP case, this is approximately 2 hours before the observation.

In all of the experiments, the channels used have little impact on the temperature analysis increments

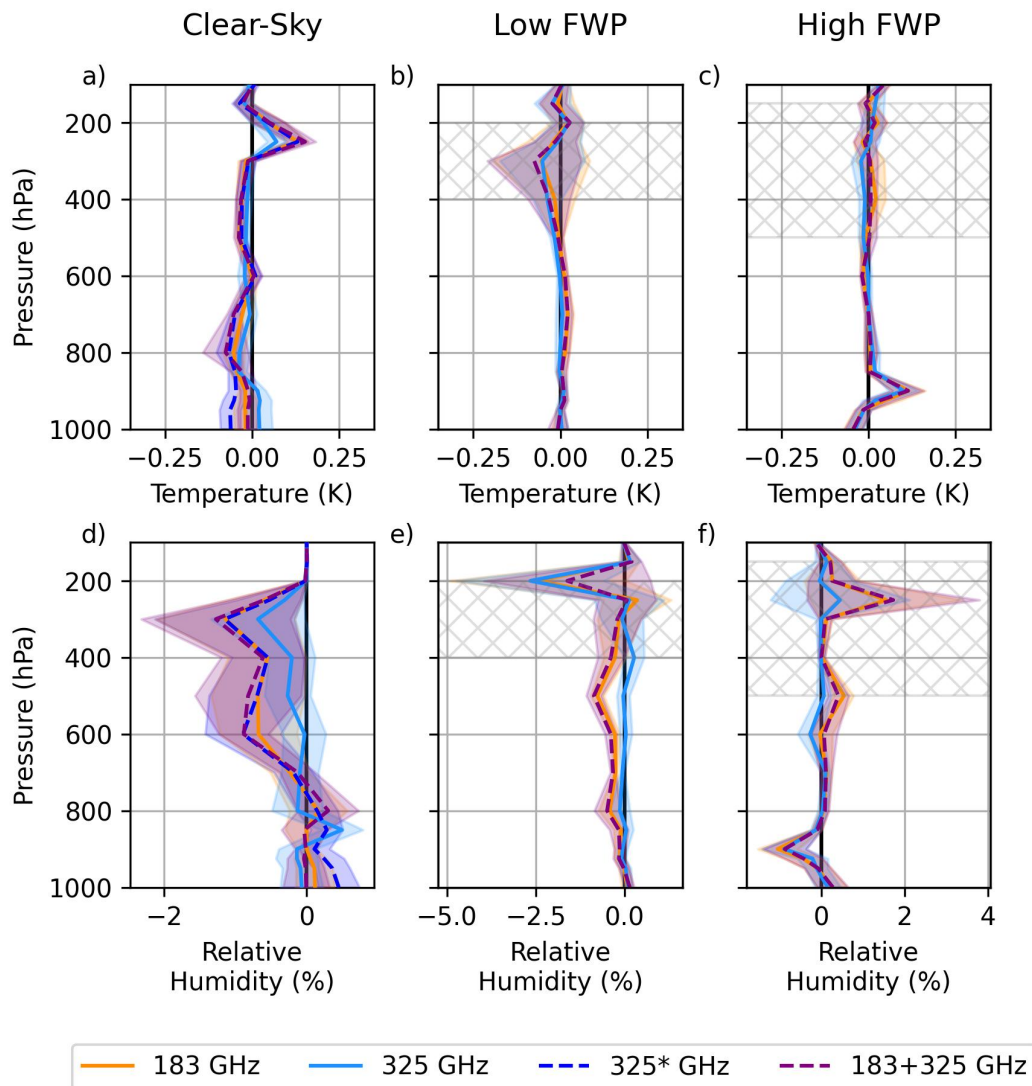


Figure 3: The median analysis increments for (a-c) temperature and (d-f) humidity for a 1×1 degree box around the observation for each of the cases from Table 1. The shaded regions show the median absolute deviation at each pressure i.e the spread of values. The hatched region indicates where modelled cloud ice water content was present. Fields are output every 3 hours on a 0.1 degree grid. The analysis increments shown are for the 3-hourly time slot before the observation: clear-sky at 15Z, low FWP and high FWP at 12Z. For the clear-sky and high FWP cases, this is ~ 1 hour before the observation. For the low FWP case, this is ~ 2 hours before the observation.

(Figure 3a-c), with the largest increments throughout the vertical reaching ~ 0.2 K. In comparison, there is a starker change in the humidity increments between the different channel suites.

We again first consider the differences between the 183 GHz and 325 GHz experiments. In the clear-sky case, the humidity increments generated in the 325 GHz experiment (Figure 3d) are, on average, $\sim 70\%$ smaller than those generated in the 183 GHz experiment. This is prevalent throughout most of the upper and mid-troposphere. When the 325 GHz channels are given the same observation errors as the 183 GHz channels, the increments are more comparable. Similarly, there is also a smaller increment in the high FWP case (Figure 3f), particularly at around 300 hPa. This aligns with the findings from the analysis departures (Table 3); in these cases, the 325 GHz channels do not provide information superior to that of

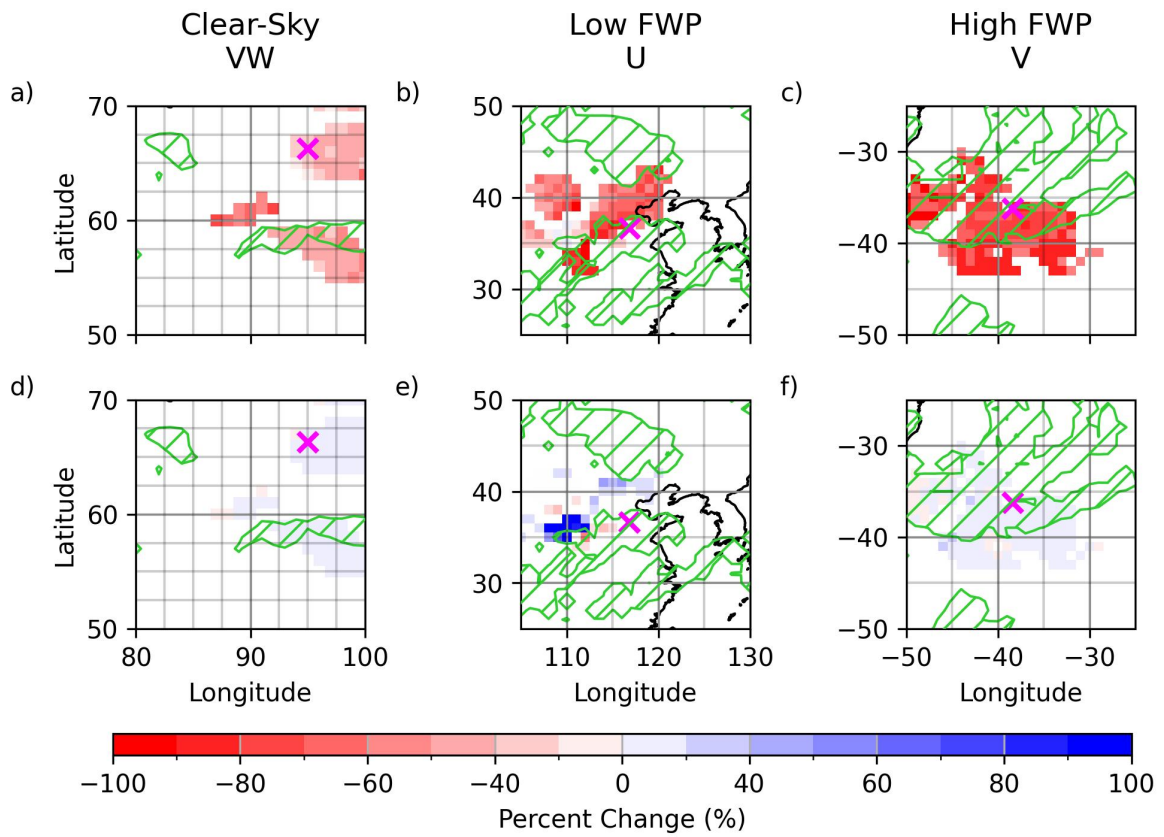


Figure 4: The percentage change in the 250hPa wind analysis increments at the start of the window relative to the 183 GHz experiment for the (a-c) 325 GHz experiments and the (d-f) 183+325 GHz experiments. Changes are shown for each case in Table 1 and for the vector wind (VW), zonal wind (U), and meridional wind (V), respectively for clear-sky, low FWP, and high FWP as described in Section 3.1. Increments are shown at a 1 degree resolution. The green contours show where the cloud ice water content was modelled as 5 mg/kg at 250 hPa and implies the edge of the cloud. The pink cross shows the location of the superobbed observation.

the 183 GHz channels, and for the clear-sky case this is likely due to the larger observation error.

It is only in the low FWP case (Figure 3e) that the 325 GHz experiment produces comparable increments to the 183 GHz experiment. However, this is limited to the top of the cloud. Below the cloud (pressures greater than 400 hPa), the 325 GHz increments are close to zero. This is to be expected given that these higher frequencies are subject to greater attenuation by a lower FWP (Figure 1b as an example). As a result, in this case they provide less humidity information beneath the cloud in the mid- or lower troposphere. This is apparent when the 183 and 325 GHz channels are combined: most of the humidity increments align with those generated by the 183 GHz channels, even in the low FWP case.

We now examine the impact of the different channel suites on the wind increments using the method described in Section 3.1. Figure 4 shows the percentage change in the 250 hPa analysis increments from the 183 GHz experiment at the start of the window for each of the cases. The green outline shows the approximate position of the cloud at the start of the window, and in each case the wind components shown has been selected so a positive percentage change is a reflection of how the cloud moved in the full-observing system (see Section 3.1 for further explanation). The top row shows the change for the 325 GHz experiment, and indicates that in all cases replacing the 183 GHz with the sub-millimetre channels reduces the increment. In the cloudy cases, this reduction suggests that the effect of wind tracing

Case	Experiment	Normalised FWP Increment
Low FWP	183	-0.44
	325	-0.41
	183+325	-0.39
High FWP	183	0.33
	325	0.06
	183+325	0.35

Table 4: The FWP analysis increment (units kgm^{-2}) normalised by the increment in the full-observing system. If the value is 0, it means there has been no change from the first guess. If the value is 1, it means the change matches that of the full-observing system. If the value is -1, it means that the change is of the same magnitude of that in the full-observing system, but is in the opposite direction.

between the 183 and 325 GHz channels is not equivalent. However, in the clear-sky case, the 325* GHz experiment produced wind increments within 5 % of the 183 GHz experiment (not shown), suggesting that in clear skies this weakened wind increment is linked to the lower weighting in the assimilation.

Combining the 183 and 325 GHz channels yields the highest wind speed increments in all three cases closest to what was produced by the full-observing system. For the clear-sky and high FWP cases, there is an increase of ~ 10 % in the wind speeds; however, it is important to note that this magnitude is of the order of 0.01 m/s. In the low FWP case, the increment approximately doubles near the edge of the cloud. This again suggests that adding 325 GHz is most useful in the low FWP case.

Finally, we consider the impact of the different channel suites on the FWP analysis increments for the two cloudy cases at the time and location of their observations. Table 4 shows the FWP analysis increments normalised by the increment in the full-observing system. It is unlikely that a single observation would generate an increment equivalent to that produced by the full-observing system, and this is evident as no normalized increment exceeds 0.5. However, the earlier findings from this section are manifested here: the 325 GHz channels are more beneficial in the low FWP case, but provide little information in the high FWP case, and combining the channel suites results in FWP increments slightly closer to the full-observing system.

Overall, across these examples we see that the 325 GHz channels on their own offer some information, but are not equivalent to the 183 GHz channels in this assimilation configuration. However, when these two sounding bands are combined, there are clear improvements in the humidity and winds. This is least prominent in the clear-sky case as a result of their similar clear-sky humidity sensitivity, with the lower weighting of the 325 GHz channels likely responsible for the reduced positive impact. In the high FWP case, as 183 GHz is already sensitive to FWP, there is a limited change in the analysis increments when the 325 GHz channels are added. The 325 GHz channels appear most useful in the low FWP case as the combined channel configuration results in increased wind increments, alongside FWP increments most similar to the full-observing system (Table 4).

These case studies suggest that the improvements from the 325 GHz channels do not result from an additional humidity sensitivity. When used in isolation, the 325 GHz humidity increments are comparable to or less than the 183 GHz experiments within the cloud (Figure 3e and f). Instead, we theorise that when the channel suites are combined, the 183 GHz channels constrain the humidity profile, enabling the system to distinguish between the cloud ice and humidity signals in the sub-millimetre channels. This leads to a better extraction of the cloud ice signal and better positioning of the clouds, improving the humidity and wind. These findings will be investigated further by conducting experiments that use a depleted version of the operational observing system to determine whether these trends manifest globally.

4 Global Experiments

In this section, we explore the impact of the sub-millimetre channels on a global scale by performing [Observing System Experiments \(OSEs\)](#) using a depleted version of the operational observing system. The experimental setup is detailed in Section 4.1. We then examine the interactions between the 183 and 325 GHz channels in Section 4.2 and determine if they show similar results to the single-observation experiments. In Section 4.3, we focus on the impact of the 325 GHz channels on the cloud ice.

4.1 Experiment Configuration

Four OSEs have been performed using the IFS Cycle 50r1 at Tco399 resolution (~ 27 km resolution with a final analysis increment resolution of ~ 80 km) from 20 May - 30 September 2025. All of these experiments use the same instruments as those used in the operational observing system, excluding AMSUA and MHS from NOAA-15, -18, and -19, as these were decommissioned in June and August 2025. We also exclude any 183 GHz channels not from AWS to isolate the individual contributions of the 183 and 325 GHz channels. Each of these experiments uses a different combination of four channels from the 50, 183, and 325 GHz bands on AWS, and are summarised in Table 5. The four channels at 183 and 325 GHz are the same as those used in Section 3.

Experiment	50 GHz	183 GHz	325 GHz
50	CH4-7	-	-
50+183	CH4-7	CH12-15	-
50+325	CH4-7	-	CH16-19
50+183+325	CH4-7	CH12-15	CH16-19

Table 5: The AWS channels included in each OSE. These experiments were run from 20 May - 30 Sept 2025 using a depleted observing system that excludes AMSUA or MHS from POES, and any 183 GHz channels not from AWS.

4.2 Interactions Between the 183 and 325 GHz Channels

To examine the relationship between assimilating 183 and 325 GHz, we first compare the 50+183 GHz and 50+325 GHz experiments summarised in Table 5. Figure 5 shows the change in the normalised standard deviation of the first-guess departures relative to the 50 GHz experiment for three independent observation groups that are actively assimilated. We see that including the 325 GHz channels improves fits to observations from the [Infrared Atmospheric Sounding Interferometer \(IASI\)](#), [Global Navigation Satellite System radio occultation \(GNSS-RO\)](#), and [Atmospheric Motion Vectors \(AMVs\)](#). This is most obvious in Figure 5a where there are improvements of up to 1% in IASI channels that are sensitive to mid- and lower tropospheric water vapour ($>1100 \text{ cm}^{-1}$) with the inclusion of the 325 GHz channels. This highlights that assimilating sub-millimetre frequencies provides information about tropospheric humidity. Similarly, Figure 5b shows that against the AMVs, the 50+325 GHz experiment slightly outperforms the 50+183 GHz experiment above 500 hPa, likely due to wind tracing. However, this is the only example where including the 325 GHz channels results in an improved short-range forecast relative to including the 183 GHz channels. It is evident across the observations in Figure 5 that relative to the 50 GHz experiment, the 50+183 GHz experiment generally results in a greater improvement to the short-range forecast skill than the 50+325 GHz experiment, particularly in the troposphere. This is most pronounced when evaluating against the IASI tropospheric humidity channels, where using 183 GHz instead of 325 GHz results in an additional 0.5% reduction in the normalised standard deviation.

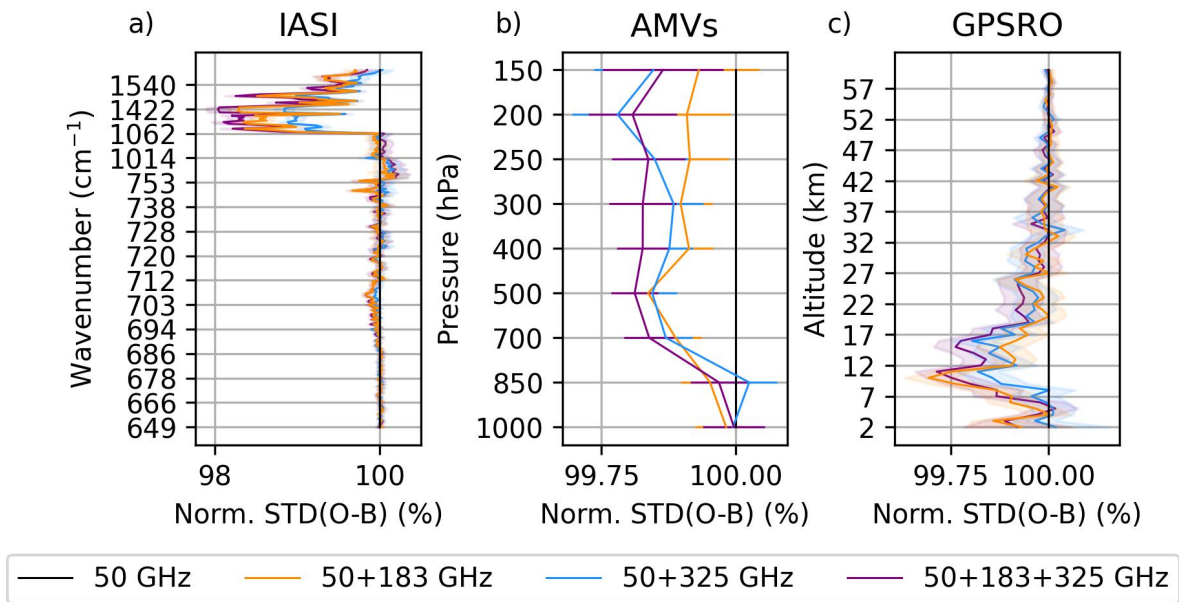


Figure 5: Changes in the $STD(O-B)$ for independent observations from (a) IASI, (b) AMVs, and (c) GNSS-RO. Values are normalised against the 50 GHz experiment. Confidence intervals for 95% statistical significance are given by the shaded regions and horizontal bars following Geer (2016)

Figure 6 shows the change in the RMSE between the forecast and operational analysis (referred to as the forecast score from here on) for relative humidity, temperature, and vector wind at two pressure levels in the troposphere. We see a similar story conveyed here; including the 325 GHz channels improves the forecast scores for all of these variables but including the 183 GHz channels improves them further. This effect is prevalent across the entire troposphere but strongest at the higher latitudes and remains for a lead time of up to 5 days (not shown). These results show a similar signal to the case studies that were examined in Section 3. In these limited case studies, we inferred that the larger modelled clear-sky error in the 325 GHz channels (and so lower weighting in the assimilation) reduced the improvement in the humidity forecast in clear-sky conditions, and the assimilation could not effectively discriminate between cloud and humidity signals when only the 325 GHz channels were used.

Figure 6c and f suggest that at polar latitudes, particularly at the edge of Antarctica, there is an improvement in the winds in the mid- to upper troposphere when the 325 GHz channels are used. This is reflected in the polar AMVs (Figure 7), where improvements extend from 700 hPa up to 300 hPa and, in contrast to the forecast scores, show the 50+325 GHz experiment further improving the fit to AMVs than the 50+183 GHz experiment. This drives the changes seen relative to the AMVs in Figure 5b. The interior of Antarctica is expected to have clouds predominantly composed of ice, so we speculate that this result is driven by the increased sensitivity of 325 GHz to lower FWP, leading to better cloud positioning. The single-observation experiments in Section 3 did not suggest that replacing 183 GHz with 325 GHz would lead to these improvements in wind, but the interior of Antarctica is significantly drier and colder than either of the FWP case studies (Lachlan-Cope, 2010).

Duncan *et al.* (2026a) has already shown that combining the 183 and 325 GHz results in an improved short-range forecast for tropospheric humidity and wind using the previous IFS cycle (49r1). We see similar improvements here using Cycle 50r1. These are shown in Figure 5 and 6 as well as Figure 8 which shows the change in forecast scores for relative humidity, temperature, and wind with the addition of the 325 GHz channels. These improvements manifest mostly at higher latitudes, with the largest

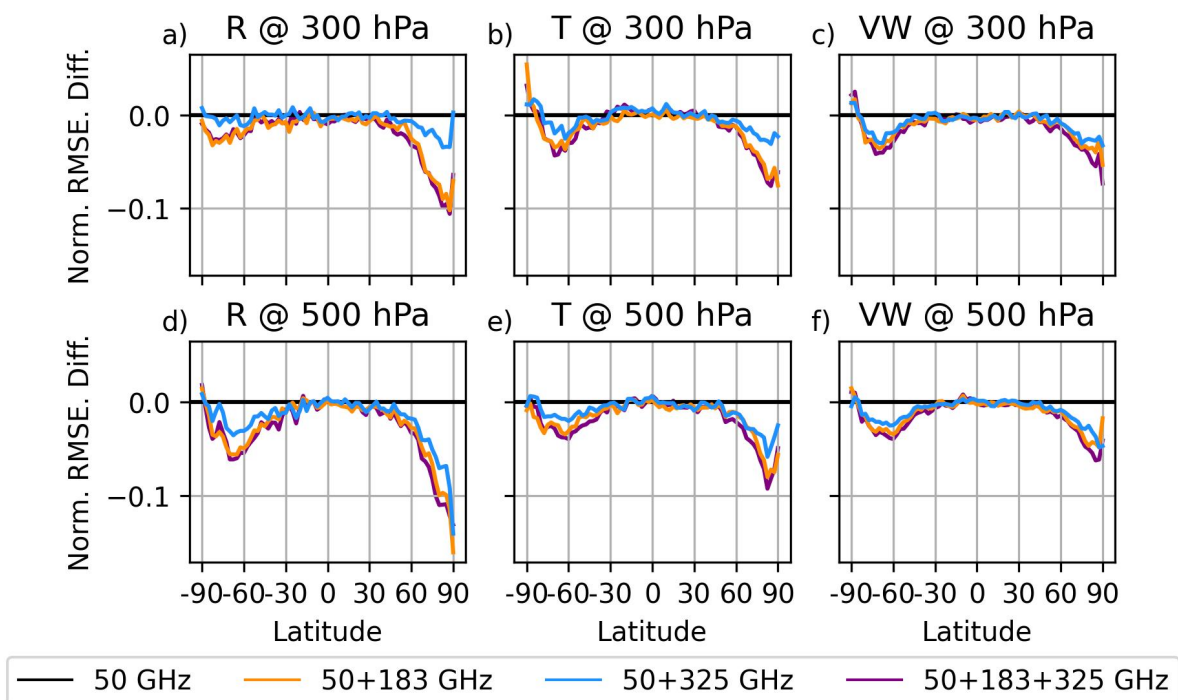


Figure 6: Normalised change in the 24H forecast scores at (a-c) 300 hPa and (d-f) 500 hPa for relative humidity, temperature, and vector wind, between the (control) 50 GHz and the 50+183 GHz, 50+325 GHz, and 50+183+325 GHz experiments defined in Table 5. Forecast scores are the RMSE against the operational analysis (Cycle 49r1 during the experiment period). A negative value shows an improved forecast score.

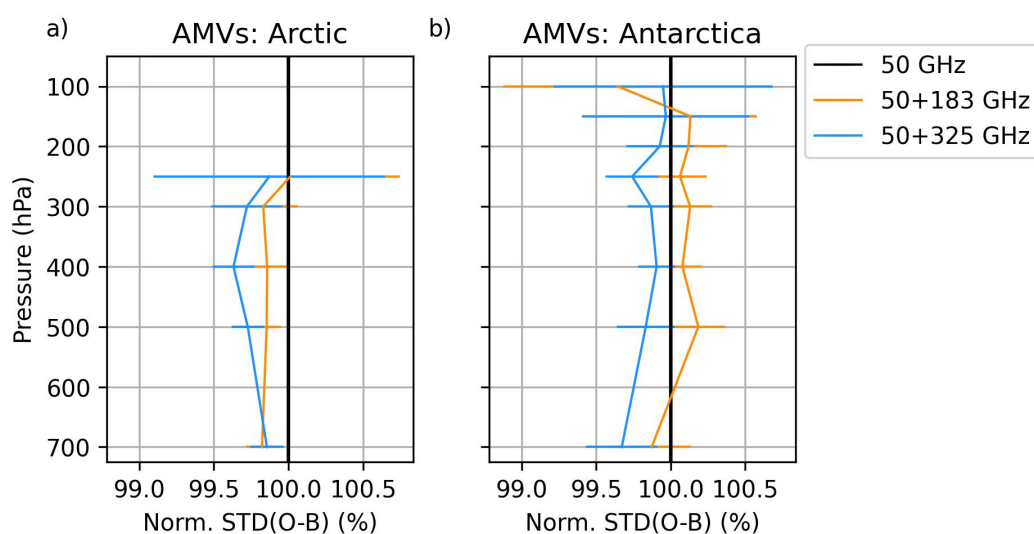


Figure 7: The same as Figure 5b but for the AMVs in (a) the Arctic and (b) Antarctica.

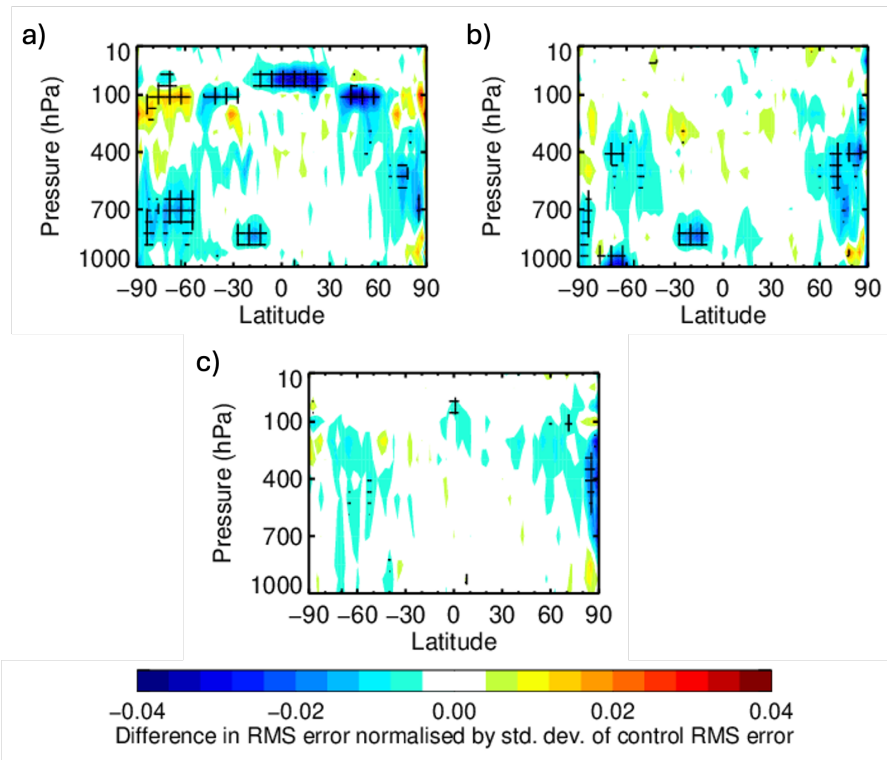


Figure 8: Change in the 24H forecast scores for (a) relative humidity, (b) temperature, (c) and wind, between the (control) 50+183 GHz and 50+183+325 GHz experiments defined in Table 5. Verification against the operational analysis (Cycle 49r1 during the experiment period). A reduction (blue) indicates an improvement in the forecast scores. Hatching for statistical significance at the 95 % confidence level follows [Geer \(2016\)](#).

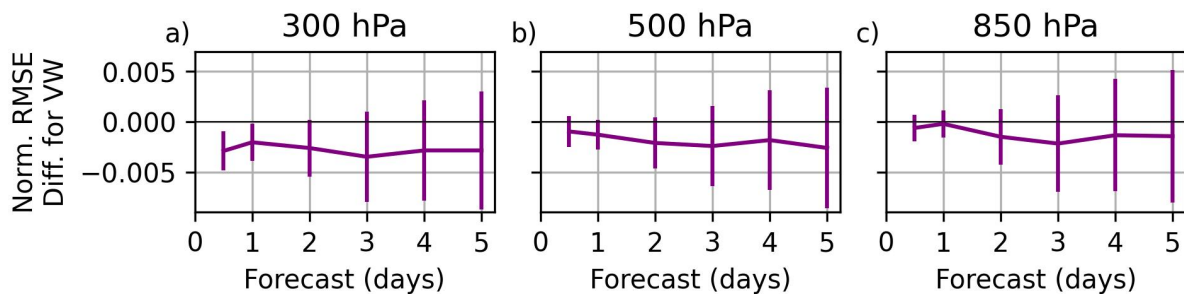


Figure 9: The change in global RMSE of vector winds due to the addition of the 325 GHz channels for the vector winds at (a) 300 hPa, (b) 500 hPa, and (c) 850 hPa, verified against the operational analysis and normalised by the values from the 50+183 GHz experiment. Error bars show 95% confidence range based on [Geer \(2016\)](#).

improvements in humidity and milder improvements in the forecast temperature and winds. The forecast scores in Figure 8a suggest a slight degradation in humidity near the tropopause at higher latitudes, however this is not observed against other independent observations. Some of these improvements persist for up to 3 days in the latitudinal mean of the forecast (not shown). However, Figure 9 shows the change in global RMSE for wind, and illustrates that globally, these improvements are only statistically significant for up to 1 day into the forecast.

There are a number of additional improvements from the sub-millimetre channels that weren't seen in

Duncan *et al.* (2026a). For example, there is a reduced forecast score in the tropics between 700-1000 hPa for humidity and temperature. There are also a number of improvements in the lower stratospheric humidity which are also seen in comparisons against GNSS-RO (not shown), as stratospheric humidity is now included in the analysis in Cycle 50r1 (Polichtchouk *et al.*, 2025).

Overall, it is evident that across these four-month experiments the 325 GHz channels do improve the forecast. Lean and Bormann (2024) found in a simulated study that using either the 183 or 325 GHz channel suites had a broadly similar impact on the forecast. We find that generally, using the 183 GHz channels results in better forecast scores in the troposphere, for all variables except wind over central Antarctica. The results in this section underline the conclusion drawn from the single-observation experiments in Section 3: that the information from the 325 GHz channels is best exploited when used in conjunction with the 183 GHz channels.

4.3 Impact on Ice Clouds and Snow

The next stage of this study is to explore the impact of the AWS sub-millimetre channels on the cloud ice in the analysis trajectory and the forecast. In Section 4.2, we saw that not assimilating the 183 GHz channels resulted in slightly worse tropospheric forecast scores at most latitudes (Figure 6). This was also evident in comparisons against independent observations (Figure 5). Therefore, in this section, we only consider the addition of the 325 GHz channels by examining differences between the 50+183 GHz and 50+183+325 GHz experiments that are summarised in Table 5.

This discussion is divided into five parts. Section 4.3.1 provides a brief evaluation of the current IFS cloud forecast. Section 4.3.2 discusses the impact of the sub-millimetre channels on the frozen water path, with further details of the vertically-resolved changes in Section 4.3.3. Section 4.3.4 then discusses the persistence of these changes to longer lead times, and conclusions are summarised in Section 4.3.5.

4.3.1 Current Forecast of Cloud

As introduced in Section 2, within the IFS, clouds are calculated from the control variables using a physics model within each 12-hour window that contains a large-scale scheme and convection scheme. The IFS currently models cloud using a single-moment microphysics scheme in which the mass (and type) of each hydrometeor is the only microphysical information passed to the assimilation system (Forbes *et al.*, 2011). This is alongside the macrophysical information about the cloud which includes the cloud position and effective cloud fraction.

Figure 10 demonstrates the current limitations in the IFS forecast through differences in the forecast hydrometeor fraction and the hydrometeor fraction derived from Earth Cloud Aerosol and Radiation Explorer (EarthCARE) observations (Wehr *et al.*, 2023). The model vertical columns are sampled along the satellite ground track and matched to the values from the ATLID-CPR-MSI retrieval of Clouds, Aerosols and Precipitation (ACM-CAP) synergistic retrieval product on a common-height grid (Mason *et al.*, 2023; Hogan *et al.*, 2026). It is important to note that while similar, the hydrometeor fractions output by the IFS and derived from EarthCARE are not exactly equivalent and provide only a broad indication of the differences. There are three key biases highlighted by Figure 10: an overestimation of the latitudinal cloud cover up to 200 hPa (blue region), particularly in the tropics; missing thin tropical cirrus at higher altitudes; and an underestimation of cloud at lower altitudes, particularly in the southern hemisphere between 50 to 70 deg S. These are known issues that have been explored in previous work and examples of prior studies include Forbes *et al.* (2009) and Delanoë *et al.* (2011).

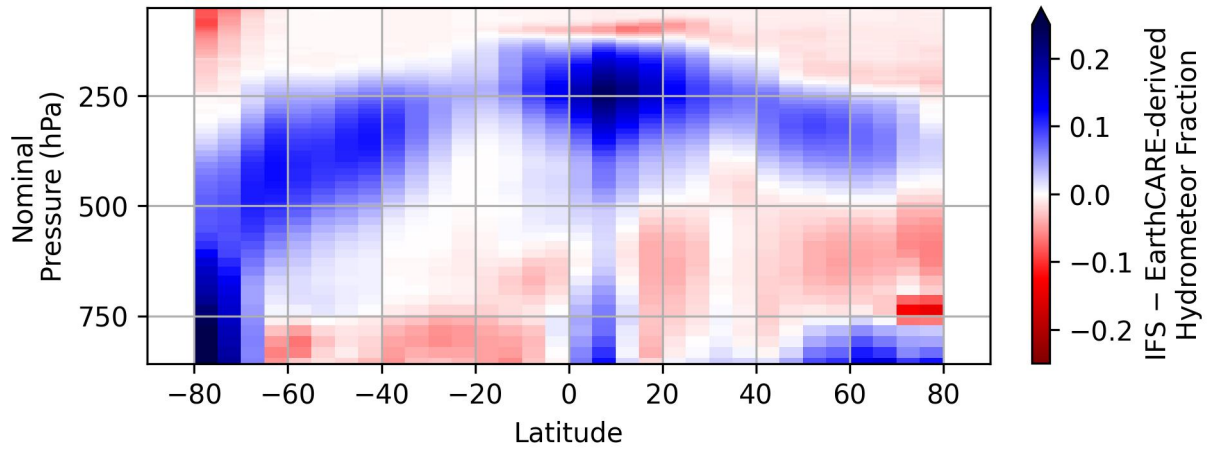


Figure 10: Differences in the hydrometeor fraction between the IFS 12H forecast (Cycle 50r1) and EarthCARE observations, for JJA 2025. Model columns are extracted along the EarthCARE ground track and matched to the ACM-CAP 20 km along-track product on a profile-by-profile basis (Mason et al., 2023). The hydrometeor fraction output from the IFS model is the diagnosed cloud and precipitation fraction (set to zero where both the simulated radar reflectivity is below -35 dBZ and the lidar backscatter is below -57 dB). The hydrometeor fraction from the ACM-CAP radar/lidar retrieval is the fraction of the retrievals in the 20 km length that were valid. Values are zonally averaged in 5° latitude bins between 80° N and S. Data below 1 km are masked due to known near-surface radar clutter (Xu et al., 2026). EarthCARE has an overpass time of approximately 14:00 local solar time.

4.3.2 Change in the Frozen Water Path

Figure 11a and b show the probability density (P) of a given FWP for the analysis and background at the time of each AWS observation across the four-month period. The change in probability density is shown in Figure 11c, with the significance evaluated in Figure 11d using the element-wise Kullback–Leibler divergence ($KL(P_{183}, P_{183+325})$):

$$KL(P_{183}, P_{183+325}) = P_{183} \log \frac{P_{183}}{P_{183+325}} - P_{183} + P_{183+325} \quad (3)$$

where P_{183} and $P_{183+325}$ are the probability densities for the 50+183 GHz and 50+183+325 GHz experiments, respectively, as shown in Figure 11a and b.

The Kullback–Leibler divergence is a non-symmetric metric that measures the difference in information represented by two distributions and is always positive. Here, we show the contribution to the divergence at each point. A value of 0 indicates there is no difference between the two probability density distributions. A larger value indicates a greater difference between two probability distributions, and is biased towards regions of higher probability density. It is important to note that a large change in the distribution is not expected, and this is reflected in the small Kullback–Leibler divergence values in Figure 11d.

There are three obvious changes to the analysis FWP in Figure 11c when the sub-millimetre channels are assimilated. First, there is a slight (0.2 %) reduction in cases with $FWP < 1E-3 \text{ kg m}^{-2}$. Second, there is an increase of ~ 1 % in cloudy cases with $FWP < 5E-2 \text{ kg m}^{-2}$. Third, there is a ~ 3 % reduction in cases with a $FWP > 1E-1 \text{ kg m}^{-2}$. It is important to note that the Kullback–Leibler divergence indicates a lower significance in this last change due to the lower number of cases in this FWP regime. Figure 11c and d show that none of these changes clearly permeate through to the background when averaged globally.

Figure 12a and b show the same breakdown as Figure 11c and d for the analysis FWP but divided into

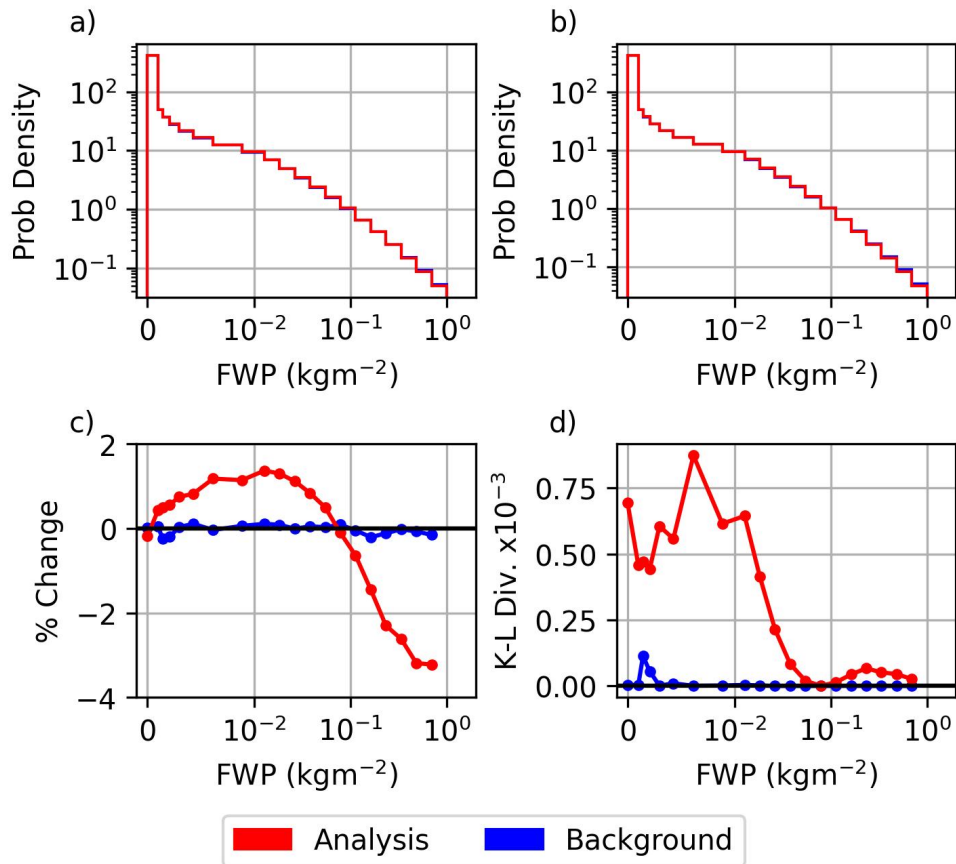


Figure 11: The probability density of the background (short-range forecast) and analysis frozen water path (FWP) at the time of each AWS observation in the (a) 50+183 GHz and the (b) 50+183+325 GHz observing system experiments for 20 May - 30 Sept 2025. Bins increase logarithmically from $10\text{E-}3$ to $10\text{E}1 \text{ kgm}^{-2}$ with a single bin from 0- $10\text{E-}3 \text{ kgm}^{-2}$ to separate clear-sky cases. (c) The percentage change in the probability density upon adding 325 GHz. Points are plotted at the start of each FWP bin. (d) The Kullback–Leibler divergence between the histograms shown in (a) and (b), indicating the significance of the shifts in the distribution.

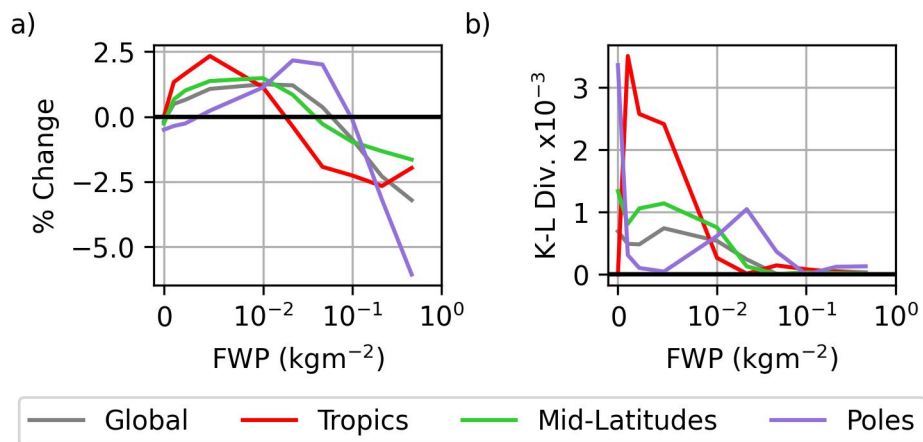


Figure 12: The change in analysis frozen water path in Figure 11c and d but divided into latitudinal regions.

latitudinal regions. All three regions show similar trends, with an increase in the chance of low FWP and a reduction in the chance of high FWP. The largest changes are seen in the tropics and poles. In the tropics, the addition of the 325 GHz channels causes an increase of $\sim 2.5\%$ in the probability density of low FWP clouds peaking between 5 and $10\text{E-}3 \text{ kgm}^{-2}$. This is accompanied by a reduction in the chance of $\text{FWP} > 6\text{E-}3 \text{ kgm}^{-2}$. In the poles, this peak in the chance of low FWP is shifted higher to between 20 - $50\text{E-}3 \text{ kgm}^{-2}$, and we see the largest reduction in the high FWP cases exceeding 5% . There is also a slight reduction (0.5%) in cases with a $\text{FWP} < 1\text{E-}3 \text{ kgm}^{-2}$ that is less prevalent in other regions and drives the change in the global statistic in Figure 11c. There are three possible causes of the shifts in this distribution: there is a reduction in clear-sky cases, an increase in the number of low FWP cases, or a decrease in the number of higher FWP cases. These potential causes will be investigated in the remainder of this section.

Figure 13 shows maps of where the largest changes in FWP are observed for the analysis and background

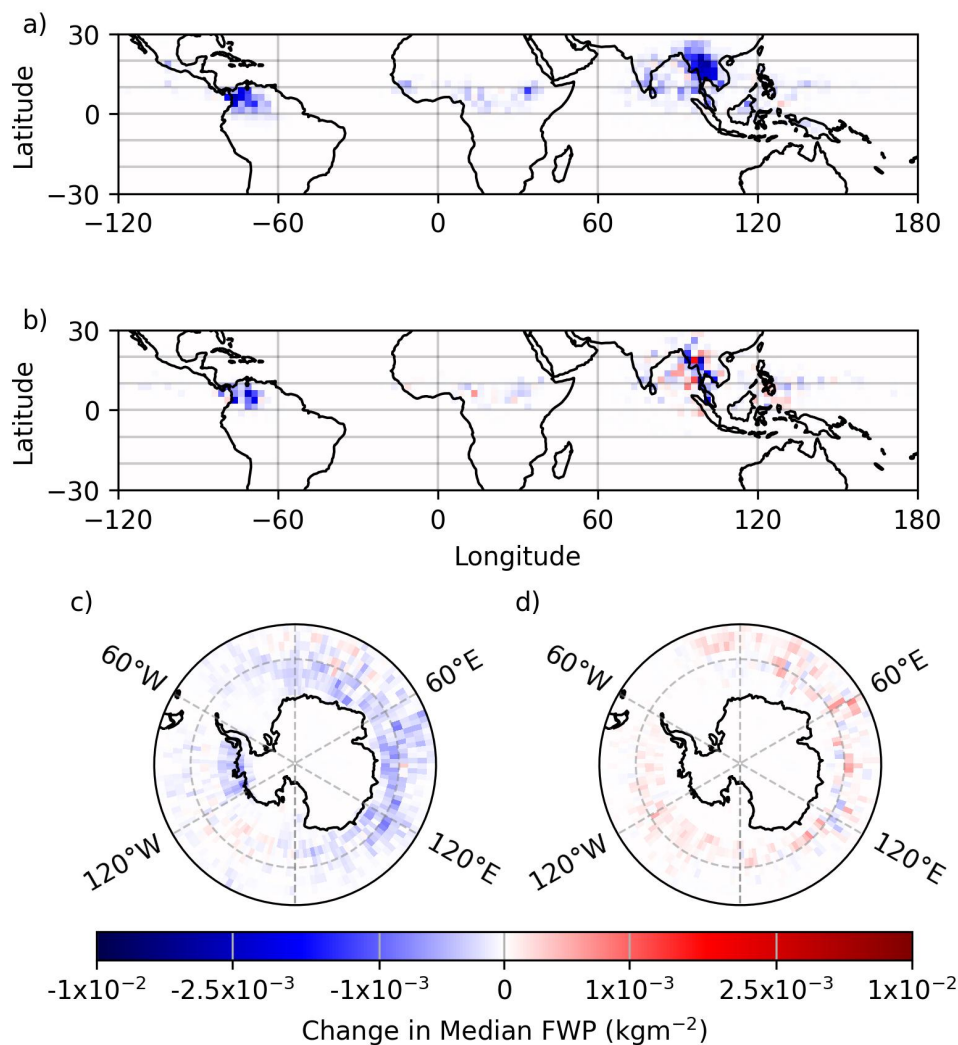


Figure 13: The change in the median frozen water path (FWP) when the 325 GHz channels are added during JJA 2025 for the (a and b) tropics and (c and d) the South Pole for the analysis and background, respectively. Values shown are the modelled FWP interpolated to the location and time of AWS observations, and have been averaged onto a 2.5 degree grid.

at the time of each AWS observation. The largest reductions in the median analysis FWP are in regions of strong convection and are centred along regions of the Intertropical Convergence Zone (Figure 13a) as well as surrounding Antarctica (Figure 13c). In these regions, there is a known diurnal bias, caused by issues representing deep convection. This leads to an overestimation of precipitation and cloud peaking at midday which is also seen in Figure 10 (Tompkins *et al.*, 2007; Lavers *et al.*, 2021). The overpass time of AWS is 10:30 and so while it does not capture the full maximum of this bias, we still see the observations reducing these higher FWP cases produced by the model. This drives part of the shift in the probability density distribution in Figure 11c. This effect is weakened in the forecast for the tropics, as shown in Figure 13b, but remains present over Colombia and Myanmar. Around Antarctica, however, this effect is reversed, with the 325 GHz channels, on average, increasing the FWP in the background.

4.3.3 Change in the Mean Vertical Distribution

Figure 14 shows the shift in the latitudinal mean of the analysis and 12H forecast of frozen water content. In the analysis fields (Figure 14c and d) there are two distinct changes in frozen content: a strong reduction in frozen water content across the main band of ice and snow at all latitudes higher than 85 deg S, and an increase in low-level ice cloud between 50 and 70 deg S. These changes in the frozen water content broadly align with zonal biases in the hydrometeor fraction derived from EarthCARE (see Figure 10), and each will be explored in further detail.

First, we examine the strongest signal - a clear reduction in frozen water content across the main band of cloud ice. This change is between 100 and 750 hPa at all latitudes higher than 85 deg S. These reductions reach up to 5 %, peaking in regions with the strong diurnal bias. This pattern is relatively consistent between the ice and snow water content. At these altitudes, Figure 10 indicates an overestimation in the IFS forecast hydrometeor fraction, and in these same regions we see the assimilation works to reduce the frozen water content. This effect extends down to the surface at higher latitudes for the snow water content but is not mirrored by the ice water content. As with Figure 13b, the strength of these changes does not cleanly transfer into the 12H forecast in Figure 14e and f.

Second, there is a strong increase in low-level cloud ice (particularly ice water content) in the latitudinal mean between 50 and 70 deg S; a region where Figure 10 indicated there was an underestimation of cloud in the forecast in comparison to the EarthCARE-derived hydrometeor fraction. In the analysis, Figure 14c shows a distinct increase in the latitudinal mean at these altitudes, but this increase was not apparent in the median analysis FWP in Figure 13c. This is because the reductions at higher altitudes dominate the integrated signal of the frozen water path, obscuring this increase in low-level content. In contrast, this increase was apparent in the median background FWP shown in Figure 13d. Unlike the reductions in the main band of cloud ice, Figure 14e and f highlights that this increase in low-level cloud ice remains present in the 12H forecast. As a result, we see the integrated variable is dominated by this increase at lower levels in Figure 13d.

We speculate that there are three potential causes for this addition of frozen hydrometeors into the forecast. The first potential cause is that there has been a shift in the vertical cloud position, but this is unlikely given the increase in FWP. The second potential cause is that new cloud is being created, however it is difficult for the assimilation system to do this and it is easier for it to destroy cloud (Geer *et al.*, 2010). The third potential cause is the thickening or widening of existing clouds through the greater sensitivity of the sub-millimetre to smaller frozen hydrometeors.

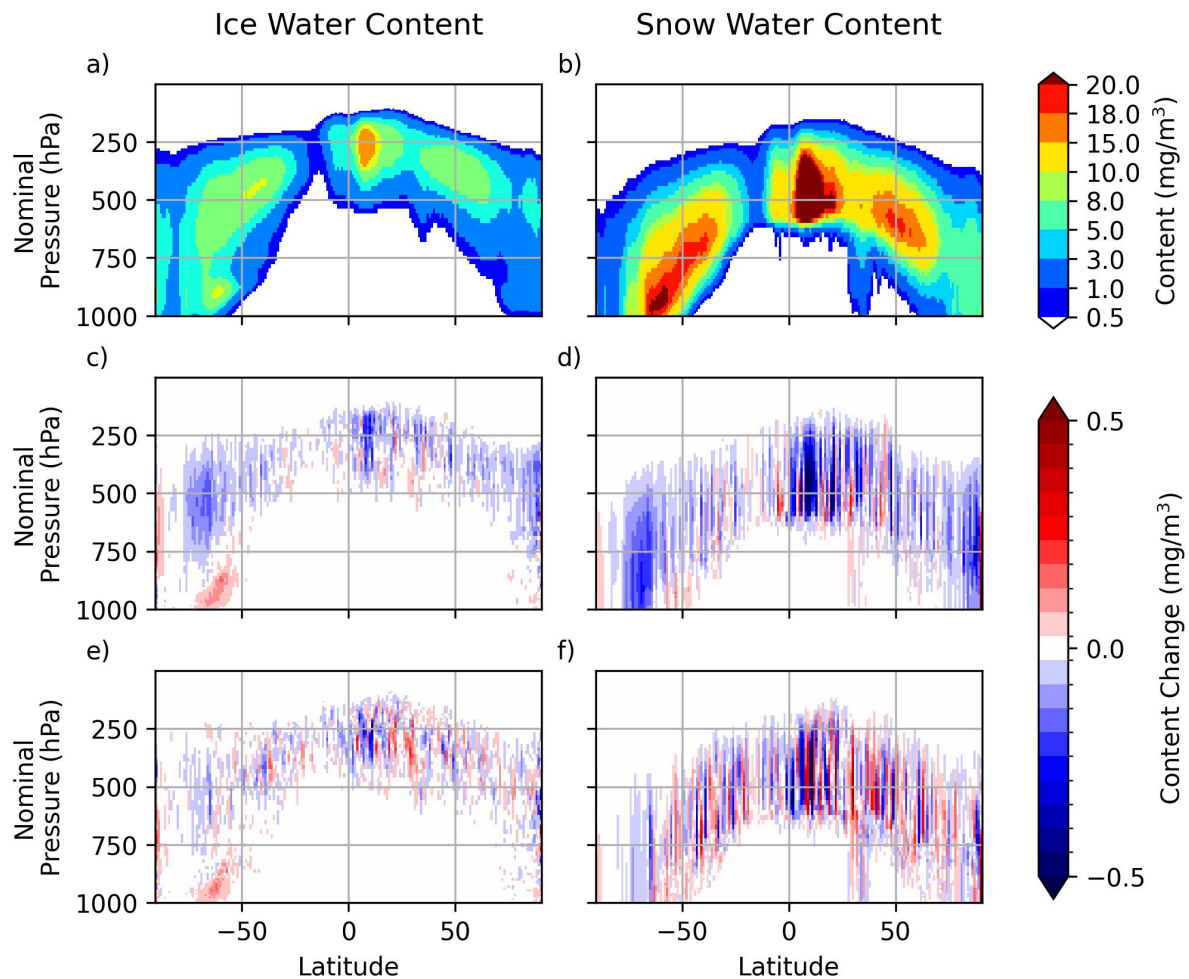


Figure 14: (Top row) The latitudinal mean of the analysis fields for JJA 2025 for the (a) cloud ice water content and (b) cloud snow water content. The impact of including the sub-millimetre channels on the (middle row) analysis and (bottom row) 12H forecast of (left) cloud ice water content and (right) cloud snow water content. Data is output at 0Z and 12Z on a 1 degree grid on 137 model levels and have been converted into nominal pressure.

4.3.4 Persistence in the Forecast

Figure 15 shows the normalised forecast scores for the IWP and SWP in both the tropics and Antarctica for a lead time of up to 5 days. The initial effects discussed here have a statistically significant impact on the forecast scores for only the SWP over Antarctica for the 12H and 1 day forecast. This is to be expected given the transient nature of clouds and their short lifetimes (Geer *et al.*, 2017). It is also, in part, a consequence of cloud being derived from the atmospheric control variables, meaning we are reliant on information being propagated through these control variables and the physics model. We suspect that in the current system, the impact of additional cloud ice information at later lead times is instead apparent through improvements to the humidity and wind forecasts. Using the observed mechanisms with the single-observation experiments in Section 3, we theorise that the better positioning of these clouds at earlier lead times assist in reducing the forecast error for humidity and wind at later lead times. We see an indication of this through the improved forecast scores for wind in Figure 9.

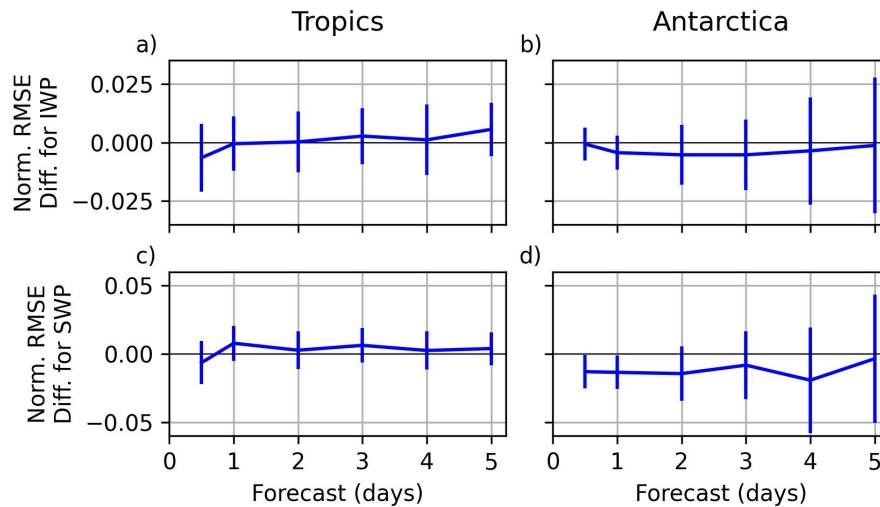


Figure 15: The change in forecast scores with the addition of the 325 GHz channels for the (a-b) ice water path (IWP) and (c-d) snow water path (SWP) over the tropics and Antarctica, verified against the operational analysis and normalised by the values from the 50+183 GHz experiment. Error bars show 95% confidence range based on Geer (2016).

4.3.5 Section Summary

These experiments have shown that including the 325 GHz channels improves the representation of ice clouds and snow in the analysis trajectory. There is a reduction in frozen hydrometeors in the mid- to upper troposphere across most latitudes, where comparisons against EarthCARE-derived hydrometeor fractions suggest there is currently an overestimation, with the greatest changes in the most convective regions. This reduction drives the shift in the probability density distributions in Figure 12a in both the mid-latitudes and tropics. We also see an increase in the low-level frozen water content between 50 and 70 deg S that also aligns with the EarthCARE-derived hydrometeor fraction. This reduces the number of cases with a FWP < 1 gm⁻². We suspect this is caused by a thickening or creation of cloud ice, occurring for less than 1% of AWS observations across the polar regions. This means that the shift in the probability density in the polar region is a combination of a reduction in clear-sky and high FWP cases, as well as an increase in low FWP cases. While there is evidence that some of the largest changes for snow and ice clouds are retained for up to 1 day into the forecast, most of the changes disappear within the first 12 hours, as the model reverts to its preferred climate.

5 Summary and Conclusions

The 325 GHz channels (CH16-18) on the Arctic Weather Satellite (AWS) have been assimilated operationally at ECMWF since July 2025. These channels have a novel sensitivity to cloud ice that has not been assimilated operationally before. When combined with the 183 GHz humidity-sounding channels, the sub-millimetre channels have been shown to improve forecast humidity and wind. In this report, we have conducted a deeper exploration of their role in the assimilation and the mechanisms producing these benefits. First, we have examined whether the information from the 325 GHz channels is comparable to that from the 183 GHz channels. Second, we have explored the significance of their additional cloud ice and humidity sensitivity on the analysis and forecast. To do this, we have performed single-observation

experiments on three different cases to identify potential mechanisms. We have then performed Observing System Experiments over a four-month period using a depleted version of the operational observing system to evaluate these mechanisms globally.

The 325 GHz channels on AWS were found to provide some information about cloud ice and humidity when used on their own, resulting in improved forecasts of humidity, temperature, and wind. However, these experiments had smaller reductions in the forecast scores in the troposphere when compared against the 50+183 GHz experiments, particularly for humidity. Our results indicate that the 325 GHz channels alone are less able to constrain the humidity field and the assimilation cannot separate the humidity and cloud signals from within these observations, likely due to the larger cloud sensitivity. In line with this, we saw in two examples that below the cloud the 325 GHz channels have less information about humidity as they are more strongly attenuated by the layers of frozen hydrometeors.

The best way to exploit the 325 GHz channels was to combine them with the 183 GHz channels. This led to clear improvements in forecast scores in the Observing System Experiments for humidity and milder improvements in temperature and wind, which aligns with prior work. However, it is important to note that these experiments were performed using a depleted observing system, excluding other observations of the 183 GHz band. In the full-observing system other observations of the 183 GHz would assist in constraining the humidity field.

The limited case studies suggested that the addition of these higher frequencies was most beneficial when there was a low frozen water path that could not be detected at the lower frequencies. The clearer delineation of these regions with a low frozen water path led to strengthened wind increments resulting from improved cloud tracing in 4D-Var. In the Observing System Experiments, we saw this manifested through improved fitting to AMVs, and an increased number of cases with a FWP less than 100 gm^{-2} , particularly in the polar regions.

The addition of only four 325 GHz channels has had a statistically significant impact on the frozen water content in the analysis in some regions within this depleted observing system. We see the addition of frozen water content near the southern pole, as well as a reduction in large extremes in regions with strong convection. Both of these improvements were translated into the background, with the latter slightly reduced, however they did not significantly persist past the 12H forecast. While these changes broadly align with comparisons against hydrometeor fractions derived from EarthCARE, it is important to note that the relationship between hydrometeor fraction and cloud content is complex and not equivalent. However, it does provide a loose indication that we are seeing an improved characterisation of cloud ice in the 12H forecast. At longer lead times, there are indications that this additional cloud-ice information is leading to reductions in the forecast error for the humidity and wind. To further exploit these cloud-sensitive observations, it is possible that additional changes to the forecasting system are required to propagate information to later lead times, for which the 325 GHz channels could provide useful guidance. Potential areas of exploration include further model development, such as the inclusion of heterogeneous nucleation, or the use of a cloud control variable to enable the direct modification of hydrometeor mass by 4D-Var.

The work performed here is the first exploration into the impact of sub-millimetre frequencies on the forecast of ice clouds and snow. It highlights the positive impact expected from upcoming satellites observing these frequencies, in addition to improvements in humidity and wind. Currently, the only sub-millimetre frequencies assimilated within the IFS are the 325 GHz channels on AWS. However, the new EPS-Sterna constellation will consist of at least 6 AWS-like satellites and has the potential to further increase the benefits outlined in this report. We also expect that observations of this spectral range could prove useful for the evaluation of cloud ice in Numerical Weather Prediction models and

optimising the existing parameterisations of cloud physics. In particular, the higher frequencies observed by the Ice Cloud Imager will provide further information about cloud ice with a lower frozen water path. We envisage a similar experimentation to that described in this report can be applied to these higher frequencies. Exploiting cloud ice sensitivity from direct radiance assimilation represents a new and potentially impactful extension of all-sky data usage for numerical weather prediction.

A Appendix: Single-observation experiment brightness temperature departures

The differences between the first-guess or analysis and the observed brightness temperatures in each of the single-observation experiments. Details of cases can be found in Section 3.1.

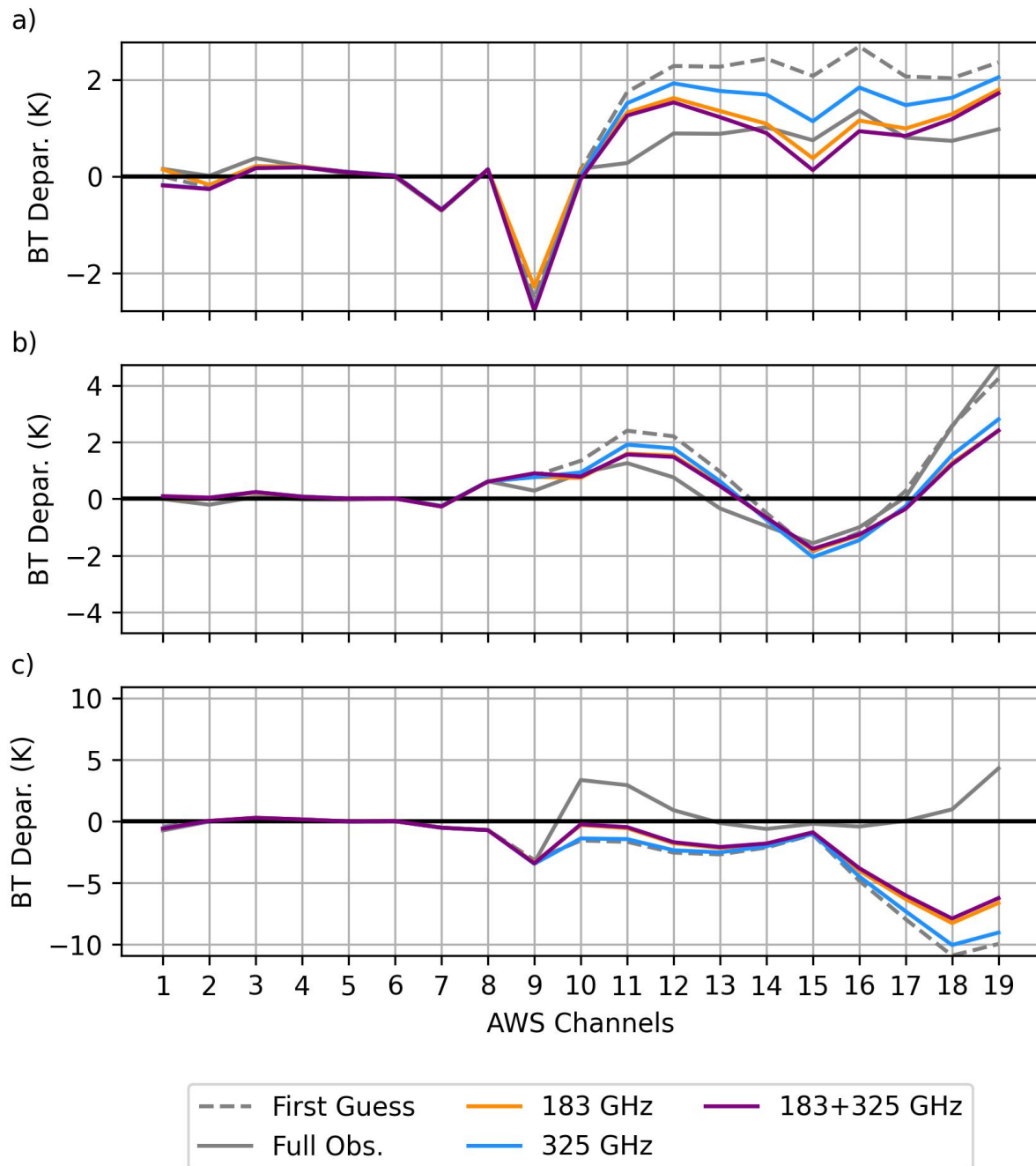


Figure B1: The differences between the first-guess and analysis simulated brightness temperatures and the observed brightness temperature in each of the single-observation experiments. Plots are shown for the following case studies: (a) clear-sky, (b) low FWP, (c) high FWP.

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Acronyms

4D-Var 4-dimensional variational assimilation.

ACM-CAP ATLID-CPR-MSI retrieval of Clouds, Aerosols and Precipitation.

AMVs Atmospheric Motion Vectors.

AWS Arctic Weather Satellite.

BT brightness temperature.

CI cloud impact.

EarthCARE Earth Cloud Aerosol and Radiation Explorer.

ECMWF European Centre for Medium-Range Weather Forecasts.

FSOI Forecast Sensitivity to Observation Impact.

FWP frozen water path.

GNSS-RO Global Navigation Satellite System radio occultation.

IASI Infrared Atmospheric Sounding Interferometer.

IFS Integrated Forecasting System.

IWP ice water path.

NWP Numerical Weather Prediction.

OSE Observing System Experiment.

RMSE root-mean-square-error.

RTTOV Radiative Transfer for TOVS.

SURFEM-Ocean SURFace Fast Emissivity Model for Ocean.

SWP snow water path.

TCWV total column water vapour.

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