RADIOMETER CHANNEL OPTIMIZATION FOR PRECIPITATION REMOTE SENSING

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ABSTRACT

The retrieval errors of cloud and precipitation hydrometeor contents from spaceborne observations are estimated at microwave frequencies in atmospheric windows between 18-150 GHz and in oxygen absorption complexes near 50-60 and 118 GHz. The methodology is based on a variational retrieval framework using a priori information on cloud, atmosphere and surface state from ECMWF short-range forecasts under different weather regimes. This approach was chosen because a consistent description of model state and its uncertainties is provided that is unavailable for other methods. The results show that the sounding channels provide more stable, more accurate and less biased retrievals than window channels, in particular over land surfaces and with regard to snowfall.

1. INTRODUCTION

The retrieval of precipitation profiles from passive microwave radiometric observations is well established and provides the foundation for a large variety of applications. With the launch of the Tropical Rainfall Measuring Mission (TRMM; Kummerow et al. 2000) the first spaceborne rain radar became available providing combined passive-active microwave observations and therefore allowing more detailed analyses of the macro- and microphysical structure of precipitating clouds (e.g. Grecu and Anagnostou 2001). However, due to the large cost of scanning radars onboard satellites, the bulk of rainfall affected satellite observations will still be contributed by passive observations.

Over oceans, physical algorithms that involve realistic observation simulations based on combined cloud-radiative transfer models emerge as the reference (e.g. Kummerow et al. 2001). This is because they have the largest potential of improvement once sufficient microphysical constraints (from models, climatologies, other observations) are provided. Over land, the signal is too complex and the geophysical noise is too large so that constraining information is of little benefit. This explains why purely statistical retrieval techniques remain rather successful over land (e.g. Connor and Petty 1998).

In preparation for the European contribution to Global Precipitation Measurement (EGPM), new options for radiometer channels and new retrieval approaches are investigated that enable a better performance over land surfaces and the specific weather conditions of higher latitudes, namely weak precipitation and snowfall. Only a few experimental studies have been carried out based on airborne measurements of microwave emission near 50 and 118 GHz over precipitating systems. Gasiewski et al. (1990) introduced the differential sensitivity between a single frequency at 53.65

GHz and several channels located near the 118.75 GHz absorption line due to absorption and scattering by clouds and precipitation since cloud extinction increases quadratically with frequency based on measurements of the Millimeter-wave Temperature Sounder (MTS). Using the same instrument, Schwartz et al. (1996) retrieved cloud cell-top altitude based on brightness temperature depressions relative to the clear-sky signal.

Recently, Bauer and Mugnai (2004) presented the first quantitative precipitation profile retrieval analysis employing temperature sounding channels in two different absorption complexes. Three major advantages of this approach are (1) the much lesser sensitivity to surface emission, (2) the possibility of cloud-slicing if sets of several sounding channels are used, and (3) the distinction of cloud and precipitation through differential absorption and scattering between channels in the two absorption complexes. The present study provides a quantitative retrieval accuracy estimation for the EGPM-radiometer for different surface and weather conditions.

Channel No.	Center Frequency	Bandwidth	NeΔT
Window channels:			
1	18.70	0.2	0.5
2	23.80	0.4	0.6
3	36.50	1.0	0.7
4	89.00	3.0	1.0
5	150.00	1.5	1.0
50 GHz sounding channels:			
6	50.30	0.2	0.5
7	51.76	0.4	0.5
8	52.80	0.4	0.5
9	53.75	0.25	0.5
118 GHz sounding channels:			
10	118±8.5	0.5	1.0
11	118±4.2	0.5	1.0
12	118±2.3	0.5	1.0
13	118±1.4	0.5	1.0

Table 1: Radiometer specifications.

2. RADIOMETER

The targeted radiometer has a set of window channels at 18.7, 23.8, 36.5, 89.0, and 150.0 GHz. All window channels have dual polarization, except the 23.8 GHz channels that has only vertical polarization. The sounding channels are located in two oxygen absorption complexes, the first set are single-band channels near 50-60 GHz and the second set are double side-band channels around the 118.75 GHz absorption line. The principle idea behind the combination of two sets of sounding channels is that the higher frequency set is more sensitive to either absorption or scattering by hydrometeors. In precipitating clouds, there will be a significant scattering signature with lower brightness temperatures (TBs) for the higher frequency channel set than for the lower frequency set. This will be distinctively different for non-precipitating clouds.

For optimizing the channel combination between the two sounding channel sets, their sensitivity to clear-sky atmospheric profiles should be as similar as possible. This also minimizes the sensitivity of a retrieval algorithm to errors in the specification of the atmospheric temperature profile that is assumed for each case. The channel specification was based on fixing the 50 GHz channels and then searching for those 118 GHz-channels that match best the 50 GHz channel weighting functions averaged over a large set of profiles. The profile dataset consists of 55,000 profiles that were selected from ECMWF analyses over all areas and seasons (Chevallier 2001). All simulations were carried out for a zenith angle of 53 degrees, i.e. a conically scanning radiometer. The resulting channels are summarized in Table 1.

3. RETRIEVAL METHODOLOGY

The approach for evaluating the retrieval accuracy of hydrometeor profiles over various surfaces using different channel combinations is illustrated in Figure 1 and involves the following steps:

- Profiles of temperature and humidity (**t**, **q**) from short-range ECMWF model forecasts are extracted for selected cases. The model resolution is ~40 km and there are 60 model levels.
- The reference hydrometeor profiles (**w**) are created by applying cloud and convection schemes. Perturbed hydrometeor profiles ($\mathbf{w}_b$) are created in the same way from perturbed temperature and humidity profiles. The temperature and humidity perturbations are obtained from random number generation with the characteristics of the ECMWF model's operational background error covariance matrices, **B**.
- Observations ($\mathbf{tb}_o$) are simulated with a radiative transfer model using the 'true' profiles. The observation error covariance matrix, **R**, contains the radiometer noise (NeΔT) and the geophysical noise due to uncertain surface emissivities on the diagonal.
- The retrieval method is applied to the perturbed hydrometeor profiles and the retrieval accuracy is quantified by comparing the retrievals ($\mathbf{w}_a$) to the reference profiles (**w**).

This approach represents a consistent testing environment because all ingredients, i.e. state variables and observables as well as their error characteristics, are defined. The method is also very well suited for the analysis of instrument performance because retrieval accuracy can be defined as a function of instrument noise, biases, channel cross-correlation and others.

Details of the variational retrieval set-up are outlined in Moreau et al. (2003) and Bauer et al. (2005). The cloud and convection schemes of Tompkins and Janisková (2003) and Lopez and Moreau (2005) are used in combination with the RTTOV (Saunders et al. 2001) fast radiative transfer model that also includes multiple scattering (Bauer 2002).

Land surface emissivity is particularly difficult to simulate due to the complex interaction of electro-magnetic radiation with soil, vegetation and snowcover as a function of a large number of unknown state variables. Therefore, emissivity climatologies produced from SSM/I observations and integrated NWP and satellite products (Prigent et al. 1997) were employed. The climatologies also contain information on temporal emissivity variability over the one-month averaging period which are required for the perturbations in the retrieval study (see below). Data between July 1992 and June 1993 was matched with the corresponding dates of the atmospheric ECMWF model fields to ensure realistic surface conditions.

Since we assume that the climatological variability of surface emissivity is an appropriate measure for emissivity errors in the forward modeling, artificial noise is added to the climatological values for each profile and the variance of this ‘geophyiscal’ noise is added to the diagonal elements of the observation error covariance matrix, **R**.

The variational framework also provides the tools for estimating the signal variability due to noise and due to the variability of the variables to be retrieved. In our case, noise is defined by the radiometer noise and geophysical noise that originates from those parameters that are not the target of the observation but contribute to the measurement. This will be demonstrated in the next section.

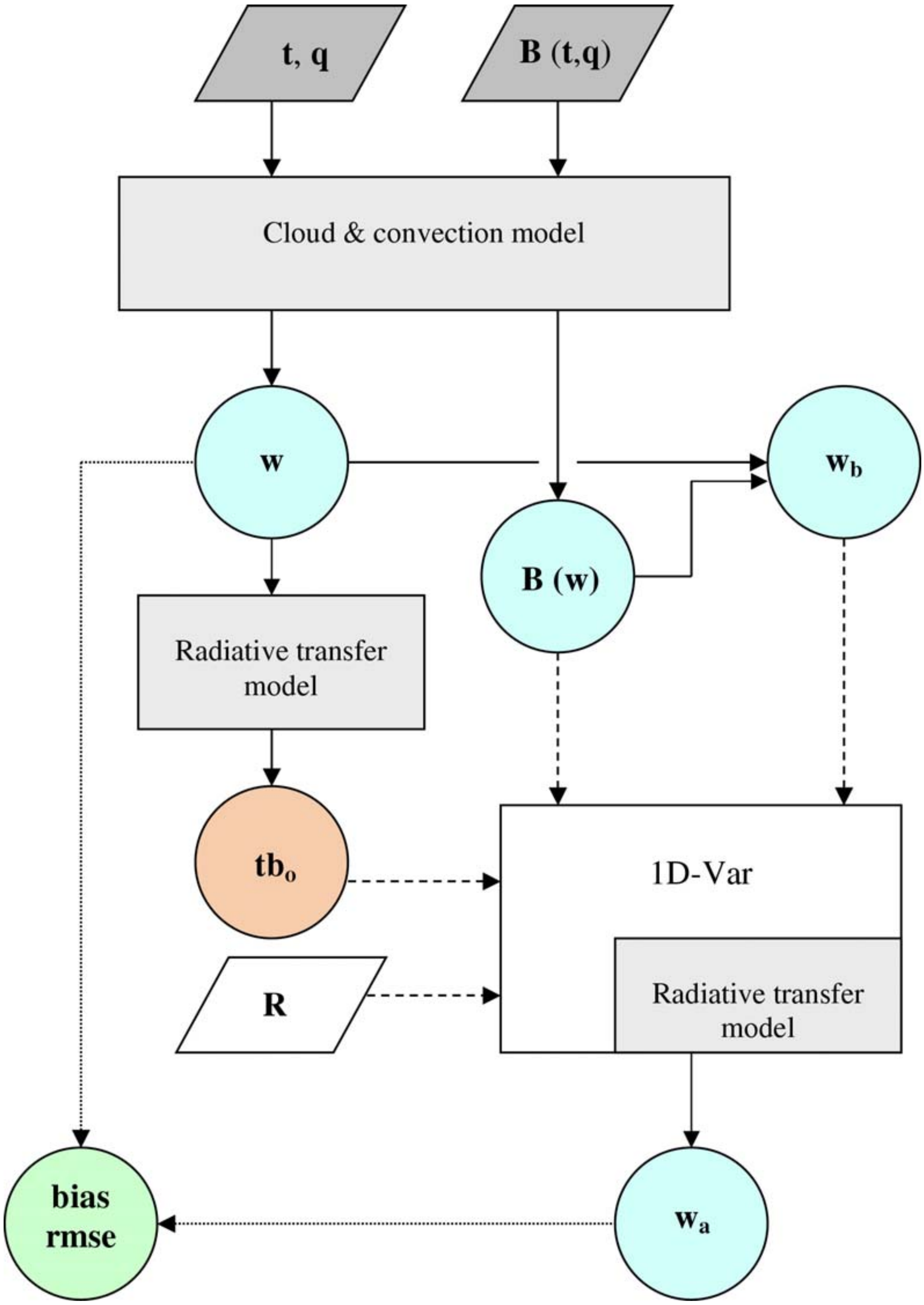


Figure 1: Logical flow of perturbation methodology.

4. RESULTS

4. 1 Sensitivity

The one-dimensional variational (1D-Var) retrieval scheme has been applied to selected profiles from ECMWF short-range model forecasts. The meteorological events represent mainly mid-to-high latitude conditions and weak-to-moderate precipitation intensities with significant amounts of frozen precipitation. Three out of four events are over land and one is over ocean:

1. Western Canadian snowstorm on January 26, 2003, area 1, with heavy snowfall and light rain (n = 78).
2. Same event, area 2, with heavy snowfall and moderate rainfall (n = 46).
3. Northern Atlantic front on January 26 , 2003, with light rain and significant snowfall (n = 88).
4. Scattered Florida precipitation on June 16, 2003, with both light/heavy rain and snowfall (n = 33).

The profiles in cases 1-3 were obtained from 6-hour forecasts initialized at 12 UTC while case 4 was obtained from a 12-hour forecast at 12 UTC. Several 1D-Var retrievals have been performed for each meteorological event, using window channels or sounding channels. For the above selection of situations the most important source of geophysical noise is surface emissivity. For estimating the signal vs. noise characteristics of all radiometer channels, the geophysical variability is translated into radiometric variability by applying the observation operator, i.e., $\mathbf{HBH}^T$, with linearized observation operator that is cloud, convection and radiative transfer model, $\mathbf{H}$.

Figure 2 shows the results of this sensitivity estimation for all channels and the four meteorological situations subdivided into radiometer noise, surface emissivity noise, rain and snow signal, respectively. In case 1, none of the channels show sufficient sensitivity to rainfall due to the very small rainfall amounts. The lower three window channels and the lower four sounding channels show little sensitivity to snow while the remaining channels have similar sensitivity to snow and surface emissivity. The combined retrieval of sounding channels will perform better than the window channel retrieval because the lower three window channels will introduce large noise (and even biases) into the estimate.

For case 2, the situation improves mainly for the window channels at 89 and 150 GHz as well as for the 118 GHz channels. Over oceans (case 3), the lower window channels provide large sensitivity to rain. All the other channels provide similar information on snow as over land surfaces. This suggests that having only window channels, the channels at 89 and 150 GHz provide similar sensitivity over most surfaces with respect to snow but very little sensitivity to rain. Due to the large amounts of precipitating ice in case 4, almost all channels show a large sensitivity.

In summary, depending on the situation, the combination of window and sounding channels provides sufficient sensitivity to both rainfall and snowfall. However, surface contributions are large and may significantly affect the retrieval accuracy. This applies strongly to biases because an aliasing from emissivity to hydrometeor contents may occur in the retrieval. In this case, the window channels are more vulnerable because their sensitivity to surface emissivity is generally large.

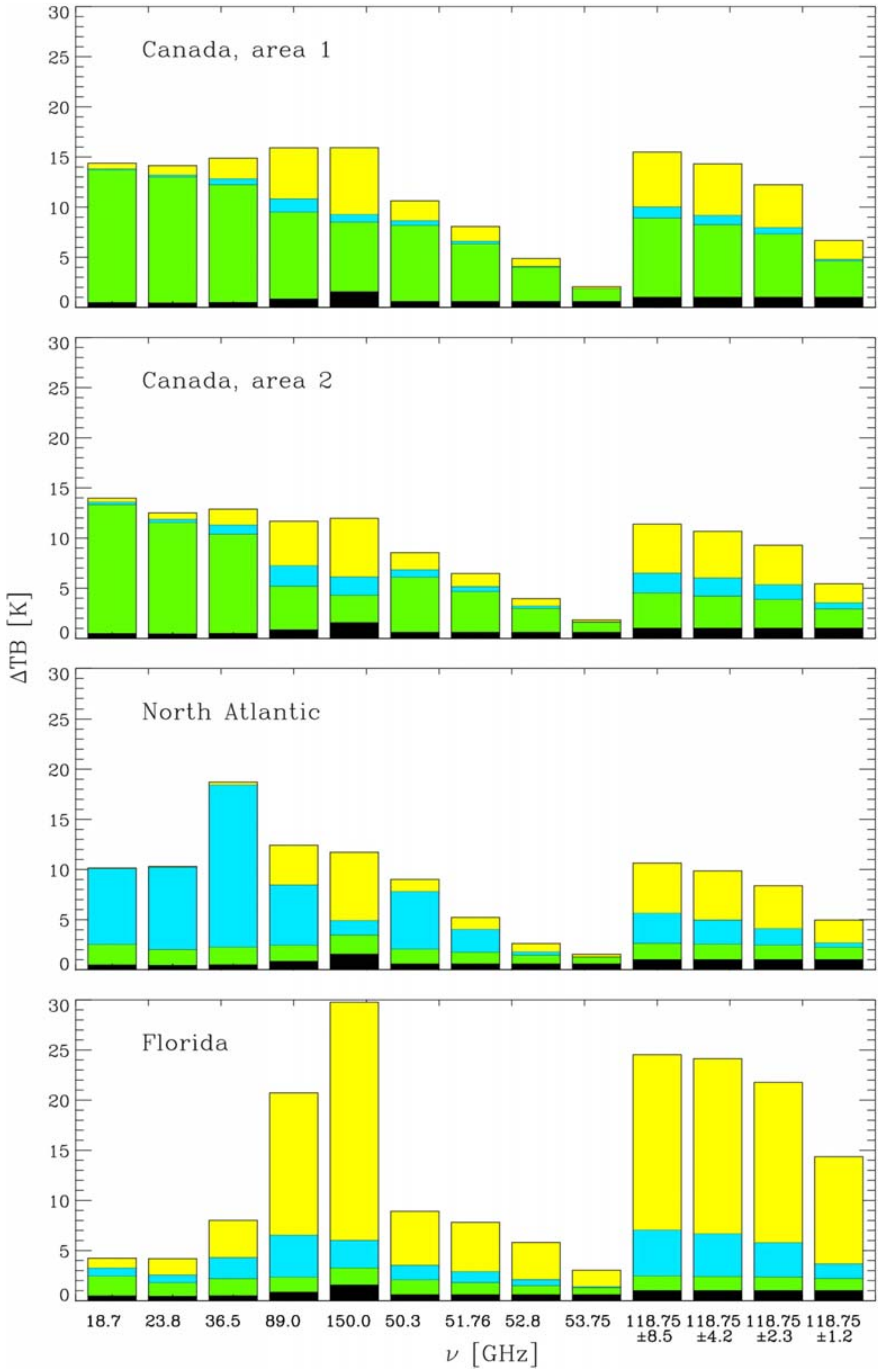
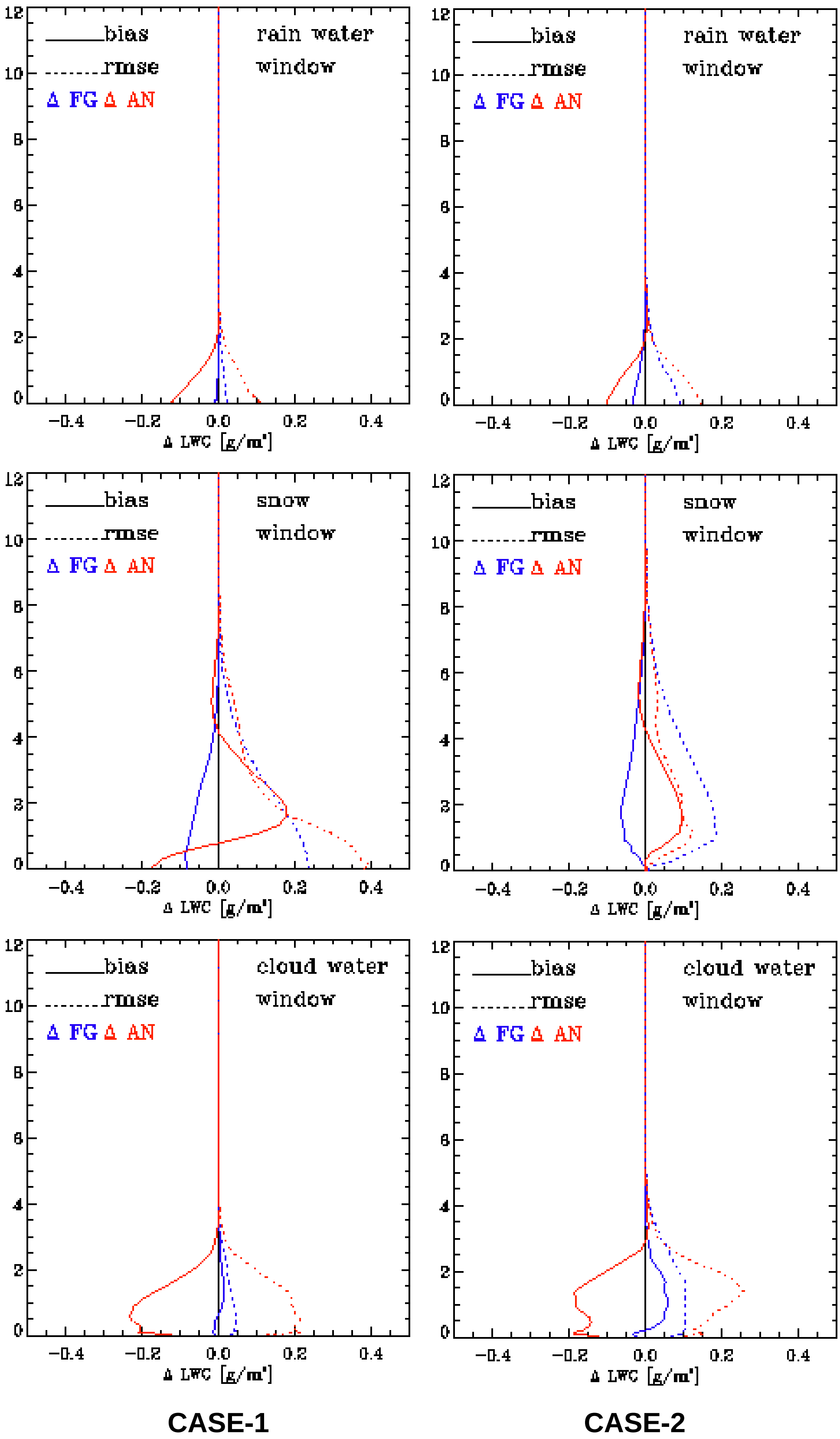


Figure 2: Signal variability for channels in Table 1 from frozen (yellow) and liquid (blue) precipitation, surface emissivity (green) and radiometer noise (black). See text for explanation of cases.


bias
rmse
Δ FG Δ AN
rain water
window
snow
window
cloud water
window
Δ LWC [g/m³]
CASE-1
CASE-2

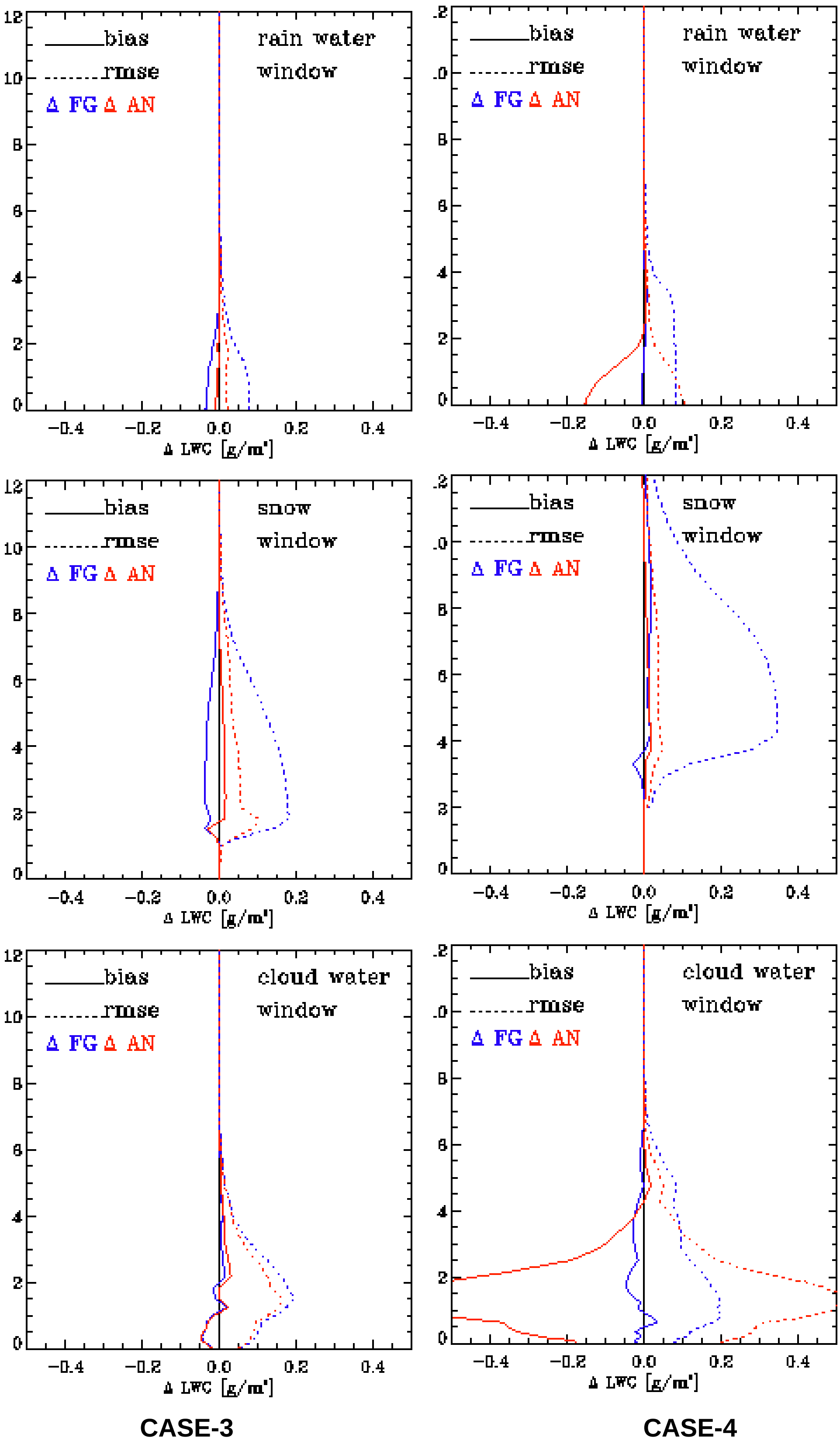


Figure 3: Window channel retrieval FG (blue) and AN (red) departures (bias: solid, rmse: dashed) vs. altitude for cases 1-4 (left-to-right) and rain (top), snow (middle) and cloud water (bottom).

4.2 Retrievals

The contribution of the observations to the retrieval can be evaluated by comparing background (or first-guess, FG) and analysis (AN) departures in terms of equivalent water contents. The AN-departures represent the deviation of the 1D-Var solution from the true state while the FG-departures represent the deviation of the first guess state from the true state and thus are a measure of the accuracy of the first guess (without contribution from the observation). If the AN-departures show improved statistics compared to the FG-departures the observations provided useful information, otherwise they degrade the a priori information.

Figure 3 summarizes the window channel retrieval results for the 4 cases and for rain, snow and cloud water, respectively. The main desired feature is that the AN-departures are smaller than the FG-departures and that no significant aliasing occurs. The former means that the synthetic observations contributed positively to the retrieval while the latter suggest that several hydrometeor types can be retrieved at once. This is not always the case because surface variability may introduce large biases into the retrieval of a hydrometeor type to which the chosen channels are less sensitive.

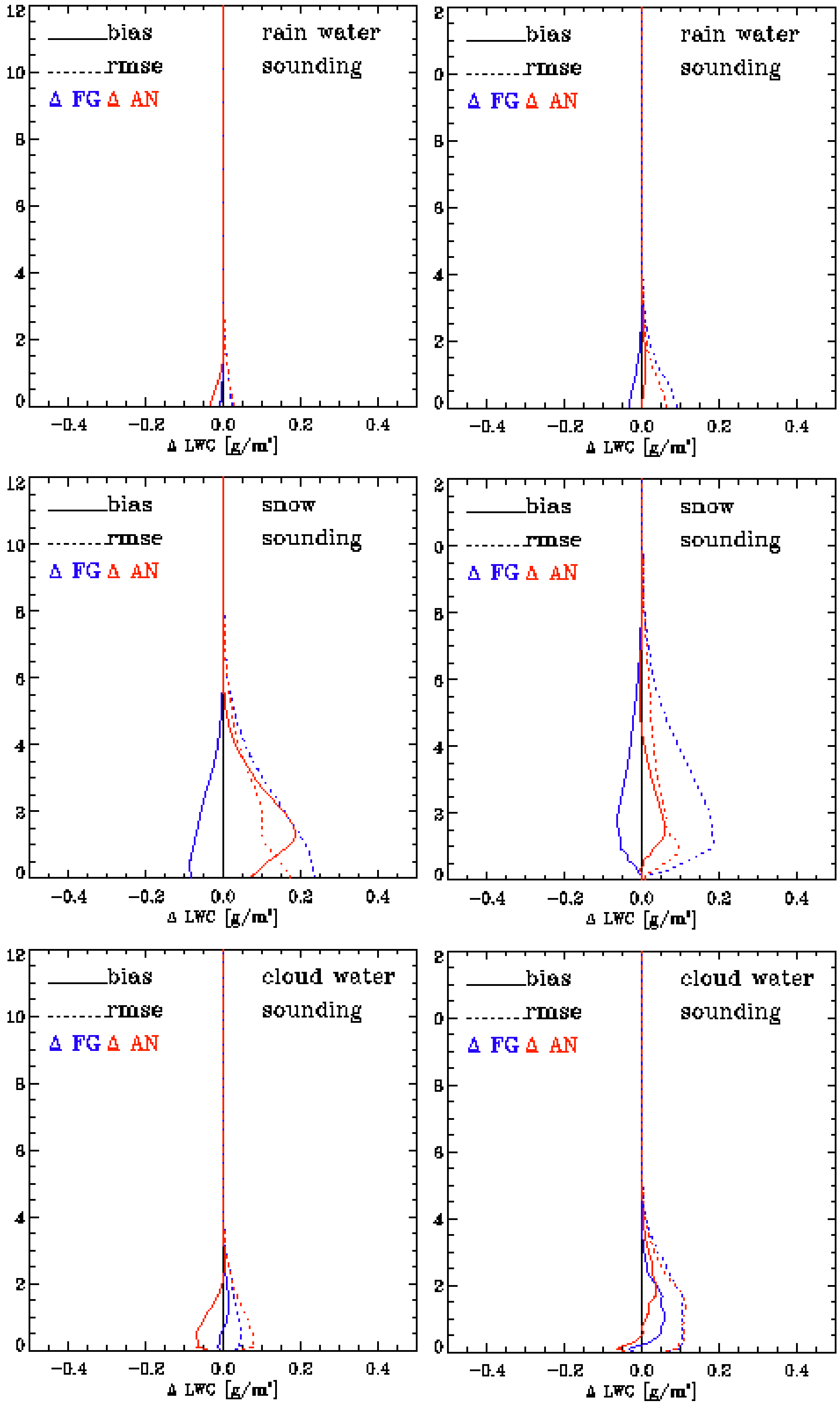
This actually happens for the window channels with regard to cloud water. Over land, cloud water retrieval accuracy deteriorates in most cases. For cases 1 and 2, the window channels do not provide enough sensitivity to produce reasonable retrievals, except for snow in case 2. Biases and root mean square errors (rmse) are large and bigger than those of the initial perturbations. Over ocean, the window channels perform well as expected but even for intense systems over land (case 4) the retrieval accuracy of liquid precipitation contents is questionable.

Figure 4 shows the same statistics for the sounding channels. Here, the cloud water problem is neutralized while for all cases, liquid and frozen hydrometeor content retrievals show improved biases and rmse's. However, the retrieval skill for liquid precipitation over oceans is slightly worse than using window channels. Therefore, these results suggest the general suitability of sounding channels for snow content retrievals under rather different atmosphere-surface conditions.

5. CONCLUSION

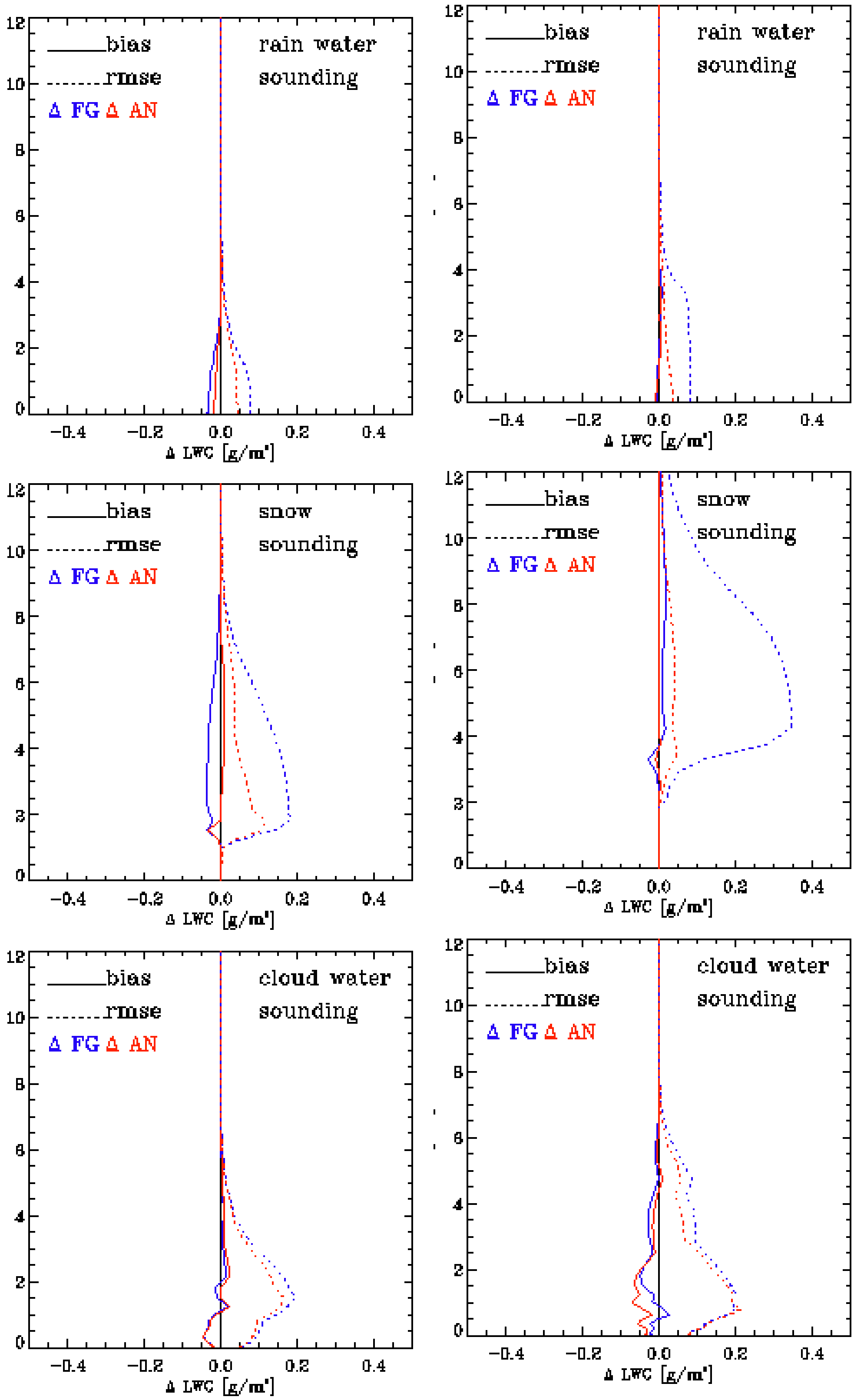
The variational retrieval framework provides a well defined environment for determining geophysical parameter retrieval accuracy using data from existing and future earth observation instruments. In this study, the retrieval errors of rain, snow and cloud water profiles were quantified for various weather conditions, namely a Canadian snowstorm, a North Atlantic front and tropical convection and applied to simulations employing the technical specifications of the instrumentation proposed for EGPM. This consists of a microwave radiometer with several window channels at frequencies between 18 and 150 GHz as well as sounding channels in the 50-60 and 118 GHz oxygen absorption complexes.

ECMWF short-range forecasts of temperature and moisture and the associated operational background error statistics for these parameters were used to create reference and perturbed profiles of hydrometeors. EGPM observations were simulated with a radiative transfer model and a one-dimensional variational retrieval method was applied to retrieve back the reference profiles. Realistic error structures for the observations were provided by estimated radiometric noise and radiative transfer modeling errors as well as geophysical noise contributions from uncertain surface emissivity.


bias
rmse
Δ FG Δ AN
rain water
sounding
snow
sounding
cloud water
sounding
Δ LWC [g/m³]

CASE-1

CASE-2



CASE-3 **CASE-4**

Figure 4: Sounding channel retrieval FG (blue) and AN (red) departures (bias: solid, rmse: dashed) vs. altitude for cases 1-4 (left-to-right) and rain (top), snow (middle) and cloud water (bottom).

The main new development in this study is the application of a variational retrieval framework using operational numerical weather prediction model output for precipitation retrieval. The advantage of this approach is the fairly accurate and consistent description of the meteorological and surface conditions including robust error statistics. This greatly reduces the limitations of existing methods that are based on mesoscale cloud model simulations that only represent very special and in most cases only tropical situations. The requirement of an accurate and consistent description of the entire meteorological setting is in particular important over land surfaces where the relative signal contribution from hydrometeors is comparably small and geophysical noise rather large.

The other new development is the proposal of temperature-sounding channels for precipitation retrieval. It was demonstrated that the differential emission and scattering between co-located channels in two different absorption complexes has great advantages over window channels. While retrieval accuracy over ocean is comparable to that of window channels, the sounding channels outperform window channels for snow and cloud water retrievals and hydrometeor retrievals in general over land surfaces.

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