Recent progress in temperature and humidity profiling in the Arctic using millimeter-wave radiometry

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ABSTRACT

Radiometers operating at millimeter wavelengths show enhanced sensitivity to low water vapor and liquid contents relative to conventional microwave radiometers that operate at longer wavelengths. In the last ten years, it has been demonstrated that this enhanced sensitivity translates in far better accuracy for retrievals of low water vapor and cloud liquid contents. More recently, a One Dimentional Variational (1DVAR) retrieval technique has been developed for obtaining temperature and humidity profiles from observations of the Ground-based Scanning Radiometer (GSR) operating at millimeter-wavelengths. The GSR was deployed in two Arctic experiments held at the Atmospheric Radiation Measurement (ARM) Program in Barrow, Alaska. Temperature and humidity profiles retrieved with the 1DVAR technique are compared with simultaneous radiosonde observations. The 1DVAR retrievals based on GSR observations improves the background up to 5 km, especially in the lower 3 km. The present implementation achieved an rms error with respect to RAOB within 1.5 K for temperature and 0.10 g/kg for humidity profiles up to 5 km height. Using the inter-level covariance definition of the vertical resolution, the 1DVAR retrievals showed < 1 km vertical resolution up to 5 km for both temperature and humidity profiles.

1. INTRODUCTION

Radiometers operating at millimeter wavelengths show enhanced sensitivity to low water vapor and liquid contents relative to conventional microwave radiometers that operate at centimeter wavelengths (below 30 GHz). This sensitivity makes the higher frequency radiometers particularly appealing for accurate observations in the extremely dry and cold conditions typical of the Arctic. For this reason, the Center for Environmental Research (CET) of University of Colorado (CU) designed a 27-channel instrument, called the Ground-based Scanning Radiometer (GSR), spanning the millimeter- and submillimeter- wave spectrum (from 50 to 380 GHz). The set of frequencies was selected for the simultaneous retrieval of atmospheric temperature and humidity profiles, precipitable water vapor, cloud liquid path, and cloud depolarization ratio. The GSR was deployed during the Water Vapor Intensive Operational Period (WVIOP, March-April 2004) and the Radiative Heating in Underexplored Bands Campaign (RHUBC, February-March 2007) both held at the Atmospheric Radiation Measurement (ARM) Program's site in Barrow, Alaska. The GSR joined the resident ARM instrumentation, including a dual channel Microwave Radiometer (MWR) and a 12-channel Microwave Radiometer Profiler; additionally, two other millimetre-wave radiometers were deployed by ARM during RHUBC, the 4-channel GVR and the 15-channel MP183. In particular, the GSR, GVR, and MP183 show several channels located around the strong 183 GHz water vapor band, which are useful for ground-based water vapor measurements in very dry conditions.

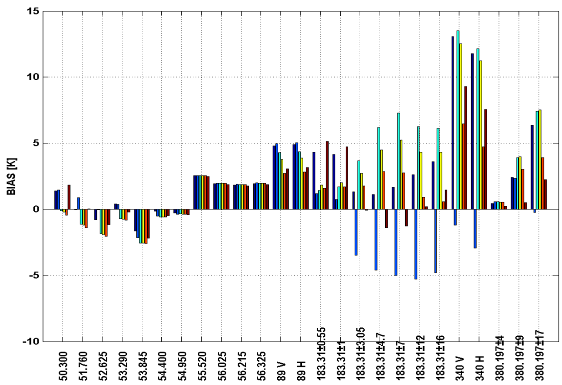

Figure 1. *Observed minus simulated Tb residuals during the WVIOP 2004.*

2. EXPERIMENTAL SET-UP

The GSR is a 27-channel instrument that is able to scan almost continuously from zenith to 3.5 optical air masses on both sides (16.6 to 163.4° elevation) [1] . A quantitative analysis of the scattering from non-precipitating spherical liquid and ice particles for the range of conditions during RHUBC showed that this contribution can be considered within the instrumental noise level for most but not all of the GSR channels [2]. In fact, the scattering contribution becomes significant for higher frequency channels (above 200 GHz). In order to keep the implementation of the 1DVAR technique simple and time-effective, we neglect the scattering contribution and thus avoid the use of higher frequency channels. Consequently, we consider only the 20 lower frequency GSR channels. These include 11 channels in the low-frequency wing of the 60 GHz oxygen complex, a window channel at 89 GHz and 7 channels around the strong 183.31 GHz water vapor line. Using the set of radiosondes and GSR brightness temperature (Tb) observations collected during the WVIOP2004, we computed the observed minus simulated Tb residuals for the GSR channels (Fig.1).

At the ARM NSA site, two daily operational radiosonde are launched routinely. During the three weeks of

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RHUBC, the operational radiosonde observations (RAOBs) were complemented by a large number of additional radiosondes that were released only during clear sky and very low integrated water vapor content (IWV ≤ 2 mm) as detected by near real time GSR retrievals [2]. A total of 94 radiosondes were launched during day and night time, of which 38 were later judged as clear sky according to simultaneous ceilometer data. All radiosondes launched during RHUBC are RS92 manufactured by Vaisala.

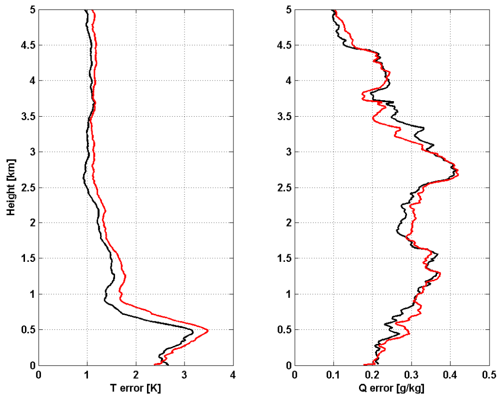

Figure 2. *Diagonal terms (square root) of the Background error covariance matrices B of temperature (left) and humidity (right) profiles from ECMWF (red) and NCEP (black) global forecast near the ARM NSA site in Barrow (computed from 77 forecast-RAOB match-ups during the WVIOP 2004).*

3. 1DVAR RETRIEVAL TECHNIQUE

The 1DVAR method developed here builds on earlier work [3,4,5]; the major difference is indeed the use of millimeter-wave channels that should improve the accuracy for humidity retrievals in dry conditions. Moreover, multiangle observations are used in the retrieval of both temperature and humidity for improving the vertical resolution and the signal-to-noise ratio. A detailed description is given in [6].

The 1DVAR technique requires the output of a numerical weather prediction (NWP) model as background knowledge of the state vector. For the ARM NSA site we have access to the output of two NWP models, the European Center for Medium-scale Weather Forecast (ECMWF) and the National Center for Environmental Prediction (NCEP) global forecast. In Fig.2, we show the square root of the diagonal terms of the background error covariance matrices of temperature and humidity profiles from ECMWF and NCEP forecast in Barrow, as computed from a set of simultaneous and colocated forecast-RAOB data collected during the WVIOP. The two models show comparable errors both for temperature and humidity profiles. Therefore, we only show retrievals using the background from NCEP global forecast. The NCEP global forecast is initialized every 12 hours and released over a 3-hour temporal grid and 81 height levels; the levels cover the vertical range from 0 to 20 km, although they are concentrated near the surface.

The state vectors we use are profiles of temperature and total water (i.e. total of specific humidity and condensed water content). As discussed in [3], the choice of total water has the advantages of reducing the dimension of the state vector, enforcing an implicit correlation between humidity and condensed water including a supersaturation constraint. Moreover, the natural logarithm of total water is used, which creates error characteristics that are more closely Gaussian and prevents unphysical retrieval of negative humidity.

The observation vector is defined as the vector of Tb measured by GSR at a number of elevation angles, plus the surface temperature and humidity. The forward model was run at the GSR equivalent monochromatic frequencies; typical errors with respect to band-averaged Tb are within 0.1 K and were accounted for in the forward modeling component of the observation error. The number of channels and elevation angles actually used was selected as a trade-off between the number of forward model computations and the expected vertical resolution. This trade-off lead to 6 channels (54.4 to 56.325 GHz) and 6 elevation angles (from 1.0 to 3.5 optical air masses) for temperature retrievals and 8 channels (89 to 183±16 GHz) and two angles (1.0 and 1.5 optical air masses) for humidity retrievals.

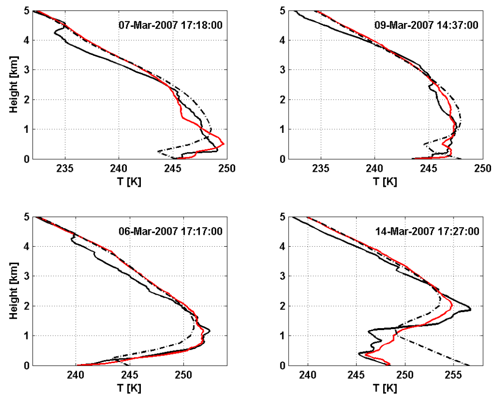

Figure 3. *Examples of background (dashed) and 1DVAR temperature retrievals (red) vs. RAOB (black) temperature profiles.*

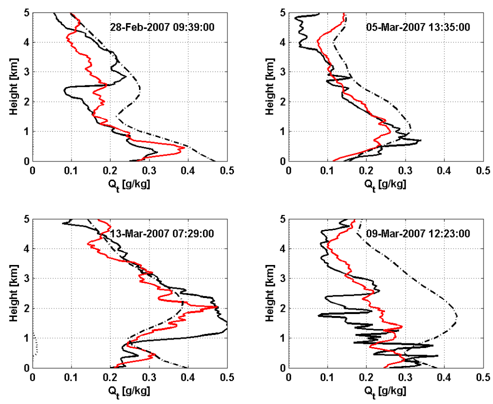

Figure 4. *Examples of background (dashed) and 1DVAR humidity retrievals (red) vs. RAOB (black) specific humidity profiles. Note that for the case of 13-Mar-2007, the 1DVAR technique estimated a cloud from 0.5-1 km (dotted).*

4. RESULTS

The 1DVAR retrieval technique with the settings described in the previous section were applied to GSR data collected during the 3 weeks duration of RHUBC. These observations were found to be consistent with simultaneous and colocated observations from the other two independent millimeter-wave radiometers, generally within the expected accuracy [7].

Examples of temperature and humidity retrieved profiles are illustrated in Fig.3 and 4, respectively, obtained from the GSR brightness temperatures observed within 10 minutes from the radiosonde launch time. As a comparison, we also show the background NWP profiles that were used as a first guess, and the in situ observations from the radiosonde. Considering just the retrievals computed at the time of radiosondes ascents (total of 94 RAOBs), the convergence rate was 100% for both temperature and total water. The solution usually takes 3 to 10 iterations to converge.

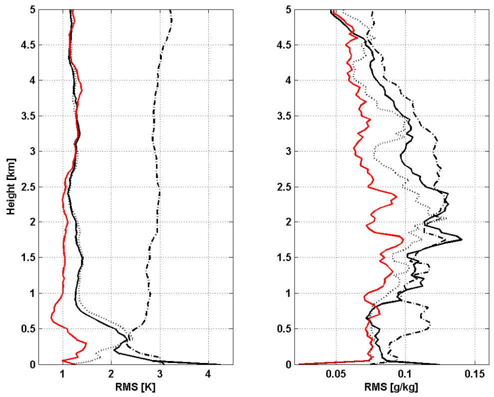

Figure 5. *Profiles of rms error (solid) of background (black) and 1DVAR retrievals (red) with respect to RAOB for temperature (left) and humidity (right). The dotted line indicates the rms error of retrievals obtained coupling the background with surface temperature and humidity only. The dash-dotted line indicates the variability (in terms of std) of the 94-RAOB set launched during RHUBC.*

The statistical comparison of background and retrievals vs. RAOB resulted in the rms errors in Fig.5, which also shows the rms error of retrievals obtained using surface temperature and humidity only, i.e. without radiometric observations. Therefore, the rms error reduction of 1DVAR retrievals with respect to (a) background and (b) to background plus surface measurements demonstrates the benefit of adding radiometric observations to (a) the forecast and (b) to the forecast coupled with surface temperature and humidity sensors only. 1DVAR retrieval rms error with respect to RAOB remains within 1.5 K for temperature and 0.10 g/kg for humidity. The integrated water vapor (IWV) values computed from background and retrieved humidity provide an rms error of 0.27 and 0.10 kg/m2 with respect to RAOB.

Fig.6 shows the vertical resolution for 1DVAR retrievals, computed using the inter-level covariance definition [8]. For temperature retrievals, the vertical resolution degrades roughly linearly with height, from 50 meters near the surface to 1 km at 1.5 km height and remains within ~1 km up to 5 km; for humidity retrievals the resolution slowly degrades with height, from a few hundreds of meters near the surface to ~1 km at 5 km height.

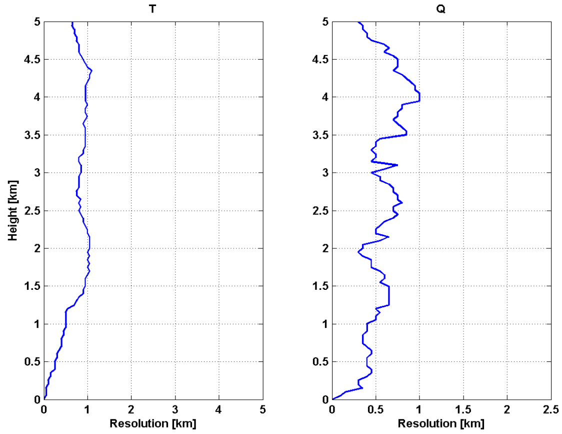

Figure 6. *Vertical resolution for temperature (left) and humidity (right) profiles as estimated using the inter-level covariance definition.*

5. SUMMARY

A 1DVAR retrieval technique has been developed to combine in an optimal way ground-based millimeter-wavelength scanning radiometric observations with the background from a NWP model. The 1DVAR technique has been used to retrieve profiles of temperature, humidity and liquid water content (through the control variable total water). Error analysis has shown that the 1DVAR retrievals based on GSR observations improves the NWP background up to 5 km, especially in the lower 3 km. With the present implementation, we achieved an rms error with respect to RAOB within 1.5 K for temperature and 0.10 g/kg for humidity profiles up to 5 km height, with 2.9 and 2.0 degrees of freedom for signal, respectively. Using the inter-level covariance definition of the vertical resolution, our 1DVAR retrievals shows vertical resolution within 1 km up to 5 km for both temperature and humidity profiles. Water vapor burden obtained by integrating the retrieved humidity profiles showed rms accuracy with respect to that obtained by RAOBs within 0.10 kg/m2.

The 1DVAR method is flexible and suitable for data assimilation in NWP models. The method may be easily adapted to work with other microwave radiometers and for running operationally. These characteristics make the 1DVAR method ideal for a distributed use in a network of operational microwave radiometers, such as MWRnet (http://cetemps.aquila.infn.it/mwrnet).

REFERENCES

[1] Cimini D. et al, 2007: The Ground-based Scanning Radiometer: A Powerful Tool for Study of the Arctic Atmosphere, IEEE TGRS, 45, 9, pp. 2759-2777.

[2] Cimini D. et al., 2007: Ground-based millimeter- and submillimiter-wave observations of low vapor and liquid water contents, IEEE TGRS, 45, 7, pp. 2169-2180.

[3] Hewison T., 2007: 1D-VAR Retrievals of Temperature and Humidity Profiles From a Ground-Based Microwave Radiometer, IEEE TGRS, 45, 7, pp. 2163-2168.

[4] Löhnert, U., S. Crewell, C. Simmer, 2004: An Integrated Approach toward Retrieving Physically Consistent Profiles of Temperature, Humidity, and Cloud Liquid Water. J. Appl. Meteor. 43, 1295–1307.

[5] Löhnert, U. et al., 2007: Accuracy assessment of an integrated profiling technique for operationally deriving profiles of temperature, humidity and cloud liquid water, J. Geophys. Res., 112, D04205.

[6] Cimini D. et al., 2009: Temperature and humidity profiling in the Arctic using ground-based millimeter-wave radiometry and 1DVAR, IEEE TGRS, in press.

[7] Cimini D. et al., 2009: Comparison of ground-based millimeter-wave observations and simulations in the Arctic winter, IEEE TGRS, in press.

[8] Smith, W.L. et al., 1999: The retrieval of planetary boundary layer structure using ground-based infrared spectral radiance measurements, J. Atmos. Oceanic Technol. 16, 323–333.