4-DIMENSIONAL VARIATIONAL ASSIMILATION OF GROUND-BASED MICROWAVE OBSERVATIONS DURING A WINTER FOG EVENT

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1. Introduction

To measure the vertical profiles of temperature and water vapor that are essential for modeling atmospheric processes, radiosondes are traditionally the privileged way to obtain upper-air information. Radiosondes, however, present certain limitations. It typically takes 40 minutes for a radiosonde to ascend through the troposphere and about 2 hours to ascend to full height. Cost and other practical considerations further limit the temporal sampling interval (i.e. launch frequency) to one or two a day. As a result, radiosonde networks, which are already very coarse in spatial distribution, are inadequate to temporally and spatially resolve mesoscale features.

In contrast, ground-based remote sensors, such as Lidar, RASS or Microwave Radiometer Profilers can provide atmospheric profiles with less vertical extension (2~10km) and sometimes less resolution (100m) but at much finer temporal resolution and reporting interval (about 10 minutes) than radiosondes.

For modeling studies, vertical resolution is generally not an issue as models have usually much poorer vertical resolution and the radiosonde data have to be averaged over the vertical layers of the model. More serious, however, is the limitation of ground based remote sensor to operate under specific weather conditions (nightly, clear sky, etc.). The TP/WVP-3000 developed by Radiometrics Corporation is a ground-based microwave profiler capable of providing continuous, real-time vertical profiles of temperature, water vapor and limited-resolution cloud liquid water from the surface to 10 km in nearly all weather conditions.

To assesses the impact of such high frequency measurements on mesoscale weather forecasts, we have conducted several numerical experiments of 3-dimensional and 4-dimensional variational assimilation of radiometer profiles into a high-resolution (10km) version of the 5th generation of the NCAR/Penn State mesoscale model (MM5) for a case of winter fog.

In the following section, we briefly introduce the microwave profiler. In Section 3 we describe the meteorological situation for the case study. The assimilation experiments are defined in Section 4. Short-term forecasts (3~6hr) obtained from the different assimilation strategies are presented and compared in Section 5. Concluding remarks are given in Section 6.

2. Microwave Radiometer Profiler

The Radiometrics TP/WVP-3000 microwave radiometer profiler is comprised of two separate receivers in the same cabinet that share the name antenna and antenna pointing system (Figure 1).

Figure 1*: Radiometers on the roof of the Radiometrics facility in Boulder, Colorado. Note the steep terrain, which tends to strengthen upslope updrafts leading to deeper cloud.*

A highly stable synthesizer permits tuning to a large number of frequencies within the receiver bandwidth. The temperature-profiling receiver measures sky brightness temperature emissions at seven frequencies corresponding to a complex of oxygen absorption lines between 51 and 59 GHz. The humidity-profiling receiver uses five frequencies extending from the center of the water vapor line at 22 GHz out to 30 GHz.

Surface meteorological sensors measure air temperature, barometric pressure and relative humidity. To improve the measurement of water vapor and cloud liquid water profiles, cloud base altitude information is obtained with an infrared thermometer. The calibration of the water vapor-profiling receiver is maintained by continuous tipping curves. A liquid nitrogen-cooled blackbody target is used to calibrate the temperature-profiling receiver. A detailed description of the instrument and calibration procedures can be found in Solheim. (1998a).

Profiles of temperature, water vapor and cloud liquid water are obtained at 47 levels: from 0 to 1 km above ground level at 100 m intervals, and from 1 to 10 km at 250 m intervals. The profiles are derived from the measured brightness temperatures with neural network retrieval algorithms.

The neural network was trained with brightness temperatures calculated using a microwave radiation transfer model for ten years of radiosonde profiles Denver. The accuracy of the retrieved profiles estimated against radiosonde measurements is about 0.6 K near the surface and less or equal to 1.6 K up to 7 km in summer and 4 km in winter.

For water vapor, the corresponding values are 0.2-0.3 g/m^3 near the surface and 0.8-1.0 g/m^3 from 1 to 2-km altitude (Güldner and Spänkuch, (2001). The neural network retrieval and alternative retrieval methods are discussed by Solheim et al. (1998b).

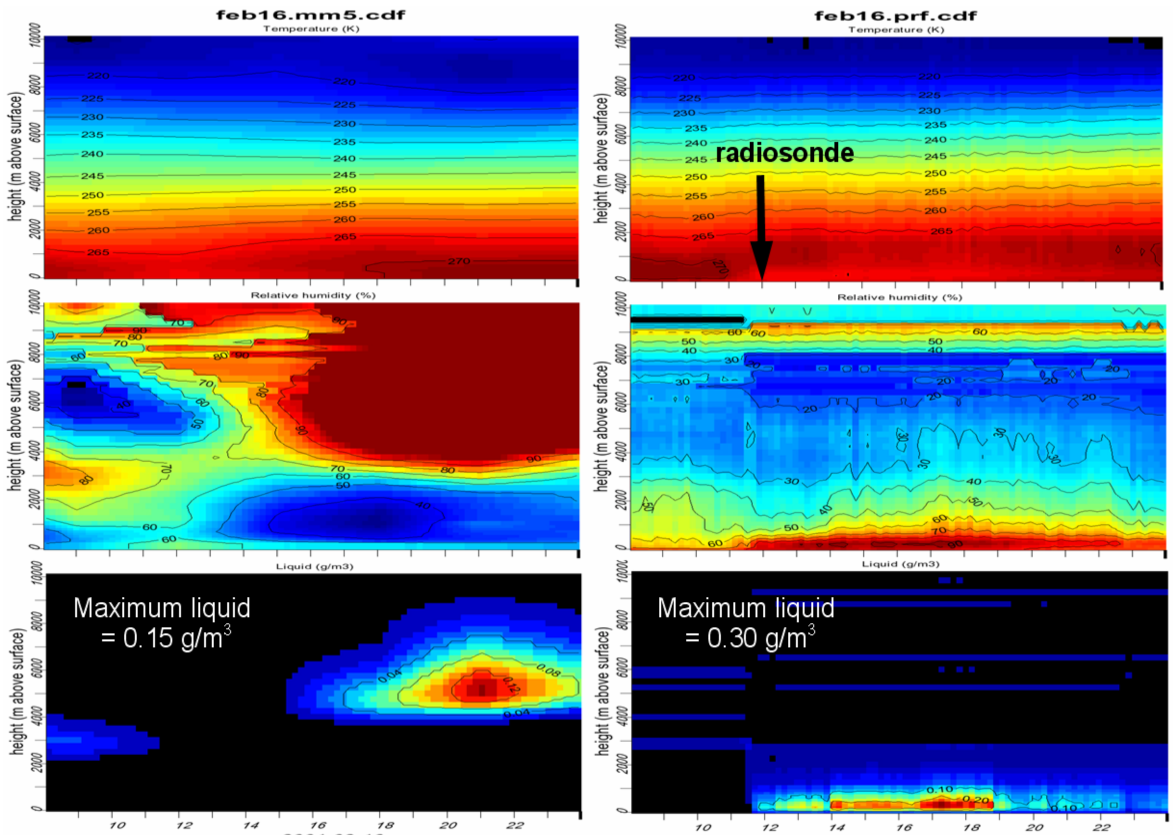

***Figure 2**: Time series of MM5 forecast (left) and radiometer observations (right) at Boulder CO on 16 Feb 2001 for temperature (top panel), relative humidity (middle panel) and liquid water (bottom panel).*

3. Winter Fog Event

Upslope events occur along the front range when warm moist when humid air from the Gulf of Mexico from the east blows across the high Plains and up the slopes of the eastern side of the Rocky Mountains. As air flows along the rising terrain it expands and cools causing fog, clouds, rain, or snow. The condensation can be amplified at the surface, when the ground temperature is much colder. Such an event occurs on February 16, 2001 on the Colorado front range over a period of four days. As a result of these conditions Denver International Airport diverted several hundred flights during an 18 hour period.

A TP/WVP-3000 radiometer was operating in Boulder, Colorado and captured very well the onset of upslope and fog conditions that followed. Figure 2 shows time series of the profiles of temperature, humidity and liquid water observed by the radiometer and predicted by the MM5 real-time system ran twice daily at NCAR <http://www.mmm.ucar.edu/mm5>.

The model resolution is 30 km, 10 min profiles are interpolated at Boulder from 3 hr model outputs. The observed and forecast temperature, relative humidity and liquid profiles are significantly different. The observed temperature profile is warmer by up to 5 K.

The relative humidity forecast shows saturation after 1600 UTC above 4 km height, in contrast with the observation which shows saturation below 0.5 km. Similarly, cloud liquid with 0.15 g/m^3 maximum density is forecast at 5 km height at 2100 UTC compared to radiometric observations of 0.3 g/m^3 at 200 m height just after 1700 UTC.

Supercooled fog, an aviation hazard, was cleary detected by the radiometer but was not forecast by the model.

4. Assimilation Experiments

To study the impact of radiometer data on numerical weather forecasts, 3D-VAR and 4D-VAR assimilation of radiometer temperature and moisture profiles was carried out. A high-resolution (10 km) version the MM5 modeling system is used as forecasting model.

The model is integrated over a 600 km x 600 km domain centered at Boulder. The boundary conditions are provided by the real-time MM5 ran at 30 km over the continental US. Figure 3 shows the domain with the terrain elevation and the location of the main source of observations.

There are 10-min temperature and moisture profiles from the radiometer in Boulder (BLDR), 30-min integrated water vapor content from GPS ground receivers associated and 1 hr wind profiles from Medicine Bow (MBWW), Wyoming, and Platteville (PLTT) and Granada (GDAC), Colorado.

The assimilation experiments aim at producing 3-hr forecasts and begin at 12Z, as the fog forms over Boulder, and is continued until 18Z. In the 4D-VAR experiment, all observations available between 12Z and 15Z are assimilated at the exact time they have been recorded. The use of the adjoint model allows recovery of the optimal initial conditions valid at 12Z from which the model is freely integrated to produce a forecast at 18Z. This is typically how 4D-VAR data assimilation is performed in operational centers. In the 3D-VAR experiment, observations valid at 12Z are assimilated to initialize the model from which a 3-hr forecast is calculated.

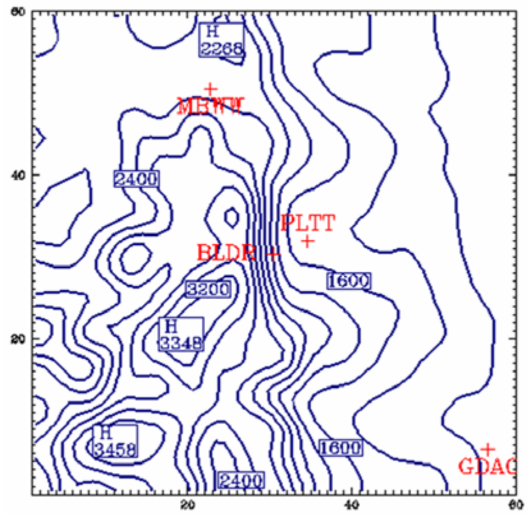

***Figure 3**: MM5 domain with terrain elevation and observations locations*

Next, the observations valid at 15Z are assimilated using the 3-hr forecast as first guess to re-initialize the model at 15Z. The model is integrated between 15Z and 18Z to produce the final forecast. The sketch in Figure 4 summarizes the observation distribution for the assimilation experiments.

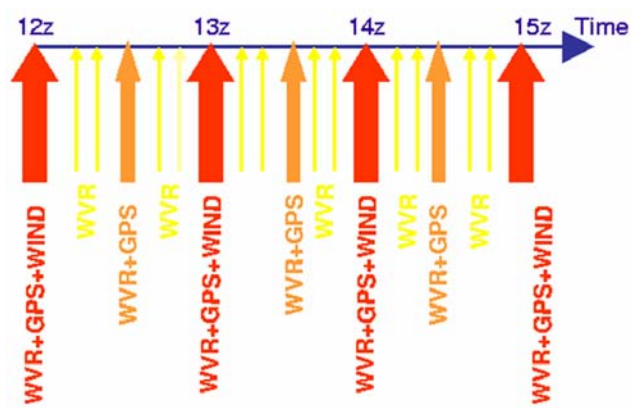

***Figure 4**: Type and time distribution of observations assimilated in the 4D-VAR*

experiment. Observations valid at 12Z and 15Z only were used in the 3D-VAR experiment.

The NCEP ETA model, after assimilation of conventional radiosonde sounding and surface observations, provides the first guess at 12Z for both experiments. Although, more observations are assimilated during the 4D-VAR assimilation experiment, the time constraints for data arrival is the same for both experiments. Thus, the framework is well suited to compare both approaches in an operational environment. Finally, a free 6-hr forecast is computed as control run. In all forecasts, the same models physical options are used (bulk PBL scheme, shallow convection and large scale precipitation). These options are not the best suited for this particular problem, but they are the only ones available from in MM5 4D-VAR.

4. Numerical results

Temperature and humidity profiles have been generated at the radiometer time and location by interpolation of hourly model outputs. Figure 5 shows the time series of relative humidity for the observations and the MM5 runs.

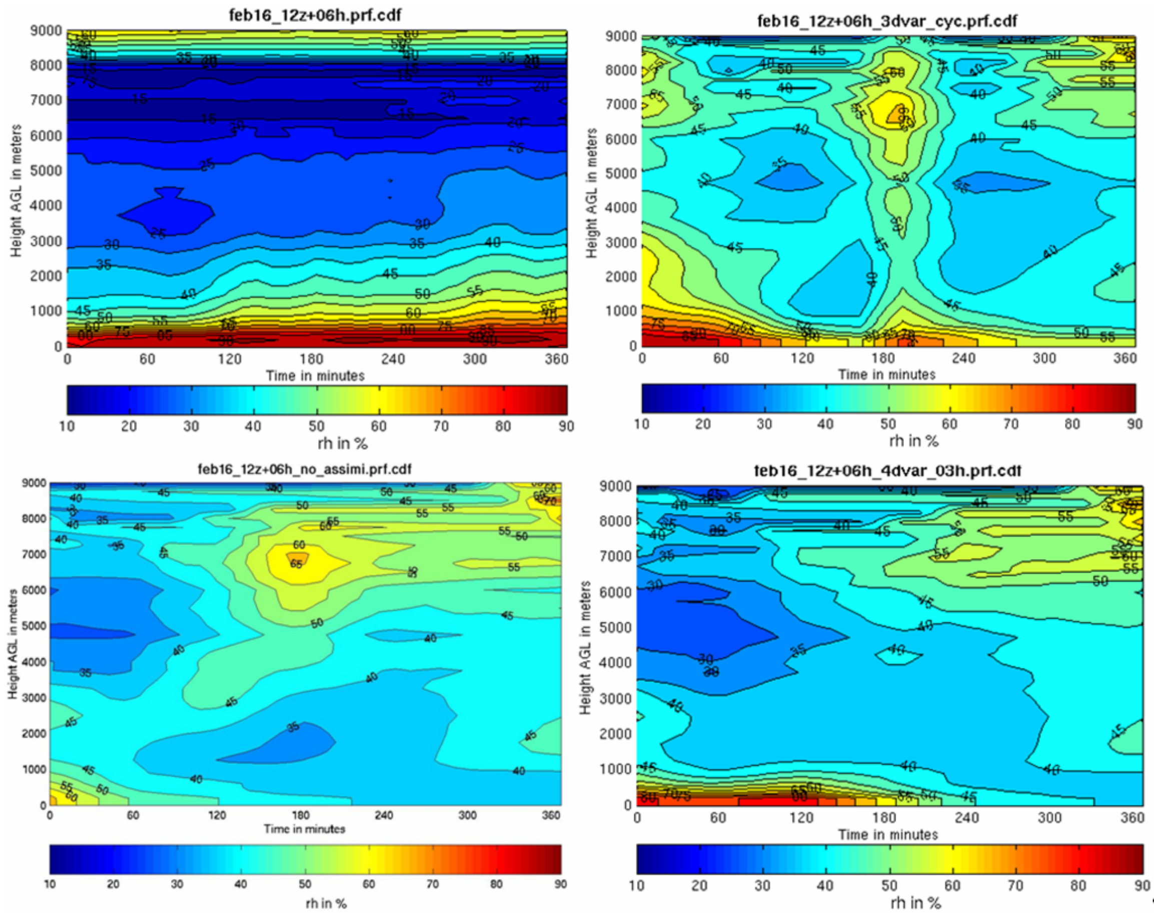

***Figure 5**: Relative humidity profiles for Boulder between 12Z and 18Z on February 16: Radiometer observations (top left), MM5 without assimilation (bottom left), MM5 with 3D-VAR assimilation at 12Z and 15Z (top right), MM5 with 4D-VAR assimilation between 12Z and 15Z (bottom right).*

The 4D-VAR assimilation is able to generate the fog all along the assimilation time window (12Z-15Z). The benefit is rapidly lost, however, during the free forecast (15Z-18Z). Conversely, the 3D-VAR assimilation cannot reproduce the fog after 14Z but the benefit of the new assimilation cycle at 15Z can still be felt at 18Z. To quantitatively verify this graphical result, we have computed the root mean square error between the model forecasts valid at 18Z and the radiometer observations. The results are given below.

Forecast Type	Temperature rms (K)	Mixing Ratio rms (g/kg)
No Assim	3.50	4.6
4D-VAR	3.50	4.7
3D-VAR	3.02	4.4

The quantitative impact of the assimilation can be barely felt at 18Z; however the 3D-VAR assimilation provides the best forecast. One reason is the existence of a bias, due to the ground temperature. Surprisingly, the biggest contribution to the cost function was from the temperatures. In fact the models had the moisture almost correct, but were too warm by 2 K at the surface, which prevented the air to saturate and the fog to form. A better forecast is expected in the absence of the surface temperature, since variational assimilation is not designed to correct for bias.

6. Conclusions

Temperature and humidity profile data observed by a microwave radiometer profiler were used along with radar and lidar data to successfully forecast a major winter upslope storm that was not forecast using traditional data. For historical reasons, the MM5 4D-VAR and MM5 3D-VAR data assimilation systems are very different and it is difficult to draw definitive conclusions on their relative merits from these preliminary comparative assimilation experiments. A new parallel version with updated physics of the MM5 4D-VAR has been recently developed and will soon released to the user community. It will be interesting to re-run the comparisons with this new version once the ground temperature bias fixed in the model.

7. References

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