Thermodynamic and wind profiling for high-resolution dispersion, precipitation and fog forecasting

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ABSTRACT

Abstract. Thermodynamic profiling provides continuous temperature, humidity and cloud liquid profiles during clear and cloudy conditions. The thermodynamic profiler radiometrically observes microwave radiation intensity at multiple frequencies, along with infrared and surface meteorological measurements. Historical radiosonde and neural network or regression methods are used for profile retrieval. Wind profiling radar provides horizontal winds. We compare radiosonde, thermodynamic and wind soundings to evaluate continuous profiling accuracy. Forecast and observed thermodynamic profiles are also compared. Thermodynamic profiling, particularly when combined with wind profiling radar and advanced assimilation methods, provides continuous soundings needed for improved local high resolution modeling and forecasting. We also describe "slant" observations of integrated GPS signal delay and their potential to extend local forecast improvements to regional scale. Applications include improved forecasting of high resolution dispersion and transport, short-term precipitation and fog.

1. INTRODUCTION

Thermodynamic profiling provides temperature and humidity soundings up to 10 km height and low resolution cloud liquid soundings. The radiometer (Figure 1) observes 12 frequencies in a region of the microwave spectrum dominated by atmospheric water vapor, cloud liquid water, and molecular oxygen emissions. Observation frequencies were selected using eigenvalue analysis to optimize profile retrieval accuracy[1]. Vertical infrared and surface temperature, humidity and pressure observations are included to improve profile retrieval accuracy.

Figure 1. Thermodynamic profiler <http://radiometrics.com>.

The water vapor absorption line at 22 GHz is pressure broadened with decreasing height. By observing radiated power at selected frequencies in this region the water vapor profile can be determined. The molecular oxygen absorption band centered at 60 GHz is relatively strong, limiting observed emission to several hundred meters above the radiometer. Moving away from band center, the absorption decreases and emission can be observed at increasing height. By observing radiated power at selected frequencies in the oxygen band, the temperature profile can be determined. Liquid water emission in the microwave spectrum increases approximately with the frequency squared. By observing radiated power in this region, low resolution cloud liquid profiles can be determined. Cloud base temperature is derived from the zenith infrared observation. Cloud base height can be determined using cloud base temperature and the temperature profile retrieval.

Historical radiosondes are used with regression or forward modeling and neural network methods to derive tropospheric profiles at a particular site from the microwave, infrared, and surface meteorological observations. Neural network and regression methods are discussed by Solheim et al.[1] and Güldner and Spänkuch[2], respectively. We discuss thermodynamic profiler accuracy and reliability, and compare thermodyanmic soundings with radiosonde and forecast soundings. We also describe (1) mobile thermodynamic and wind profiling systems with applications in high resolution mesoscale forecasting; (2) advanced assimilation methods; and (3) use of GPS slant delay observations to extend local forecast improvements to regional scale.

2. EXAMPLE OBSERVATIONS

Thermodynamic (radiometer) soundings at Boulder, Colorado, are compared with Mesoscale Meteorology model (MM5) <http://www.mmm.ucar.edu/mm5> forecasts in Figure 2.

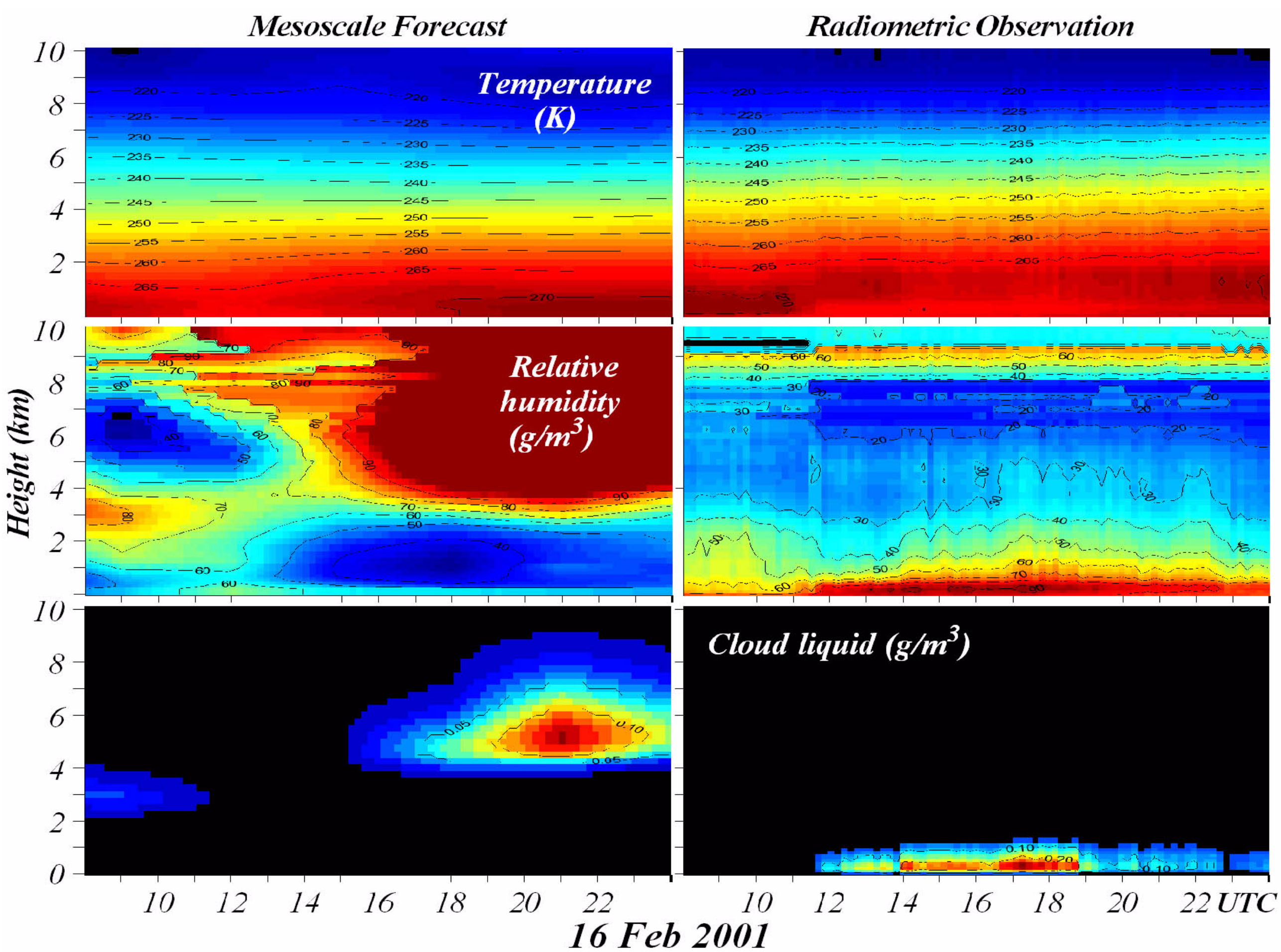

Figure 2. Forecast and radiometric observations (neural network retrieval at Boulder, Colorado). The radiometer accurately sensed fog that was not present in the forecast.

The 3-hr 10-km MM5 forecasts shown in Figure 2 are based on the 16 Feb 2000 UTC analysis. It is seen that the observed temperature, relative humidity, and liquid profiles are significantly different than the forecast profiles. For example, the temperature profile observation is warmer than the model by up to 5 K. Further, the relative humidity observation shows saturation below 0.5 km height, whereas the forecast shows saturation above 4 km height. Finally, the cloud liquid profile observation shows 0.3 g/m^3 maximum density at 200 m height whereas the forecast shows 0.15 g/m^{3}at 5 km height. The observations were taken during the onset of upslope and fog conditions that occurred along the Colorado front range over a period of four days. Continued fog conditions resulted in diversion of several hundred flights from Denver International Airport (DIA) during an 18 hour period. Assimilation studies by one of the authors (Vandenberghe) showed that 3DVAR and 4DVAR assimilation of radiometric soundings improved fog forecasts at DIA during this period. Radiosonde soundings in Denver during this period showed saturation below 300 meter height consistent with radiometer observations of fog in Boulder.

3. ACCURACY AND RELIABILITY

The radiometer K-band channels (22-30 GHz) are calibrated by tipping[3]. The V-band (51-59 GHz) calibration uses a cryogenic blackbody target. Tipping and cryogenic calibrations are automatically transferred to a temperature stabilized noise source. An internal mirror points to any elevation angle and an azimuth drive enables pointing to any sky direction. Radiated power observations are used directly in profile retrieval based on regression and radiosonde observations. Instrument accuracy in brightness temperature determination is 0.5 K rms. The radiometer design has proven its reliability during more than one million hours of operations in locations including the arctic, mid-latitudes, and the tropics. Additional information on radiometer design, performance, and applications are provided by Ware et al.[4].

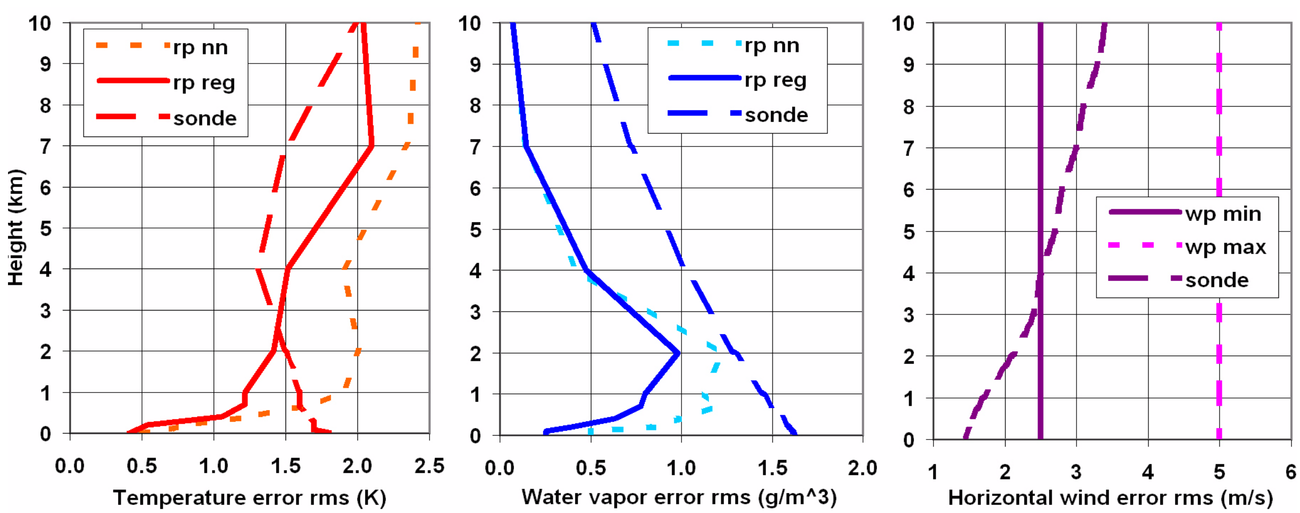

Figure 3. Radiometric profiler (rp) retrieval accuracy based on statistical comparison with radiosondes[2] Radiosonde (sonde), neural network (nn) and regression (reg) root mean square differences are shown. Wind profiler (wp) and radiosonde wind measurement errors are also shown.

The German Weather Service is evaluating the use of radiometric and wind profilers for use in operational forecasting. Comparisons between several hundred radiosondes launched at six hour intervals at Lindenberg and the radiometric profiler are shown for the summer months are shown in Figure 3. For the regression retrieval, the temperature error is less than 1 K below 1.5 km height and less than 2 K below 6 km, and vapor density error is less than 0.8 g/m^3 below 1 km and less than 1.1 g/m^3 below 7 km. Güldner and Spänkuch[2] provide details on the radiosonde and radiometer sounding comparisons. Neural network retrieval errors include radiometer calibration and errors in line shape assumptions used in forward modeling. Radiosonde sounding errors up to 10 km height are estimated to be 1.3 to 2 K (temperature), 0.5 to 1.6 g/m^3 (vapor), and 1.4 to 3.4 m/sec (wind) by the U.S. National Center for Environmental Prediction <http://

lnx21.ncep.noaa.gov/oberr/reanl-obs.html>. Figure 3 shows that the magnitude of thermodynamic and minimum wind sounding errors are roughly comparable with radiosonde errors. Taking volumetric and temporal sampling effects into account, continuous thermodynamic and wind soundings are well suited for high-resolution mesoscale modeling.

4. MOBILE PROFILING

Skill levels of 1-12 hour weather forecasts are notoriously poor. Reasonably accurate forecasts can be obtained during the first hour by assuming no change in weather. However, forecast skill rapidly degrades until initialization with new radiosonde observations, typically 12 hours later. Short-term forecast skill can be improved with thermodynamic and wind soundings[5]. Further improvements are expected if radiometric brightness temperature and wind radar moments are directly assimilated into models. Direct assimilation avoids errors associated with profile retrievals. In addition, wind radar moments contain moisture gradient information that can improve thermodynamic sounding accuracy[6]. Mobile thermodynamic and wind profiling systems are shown in Figure 4.

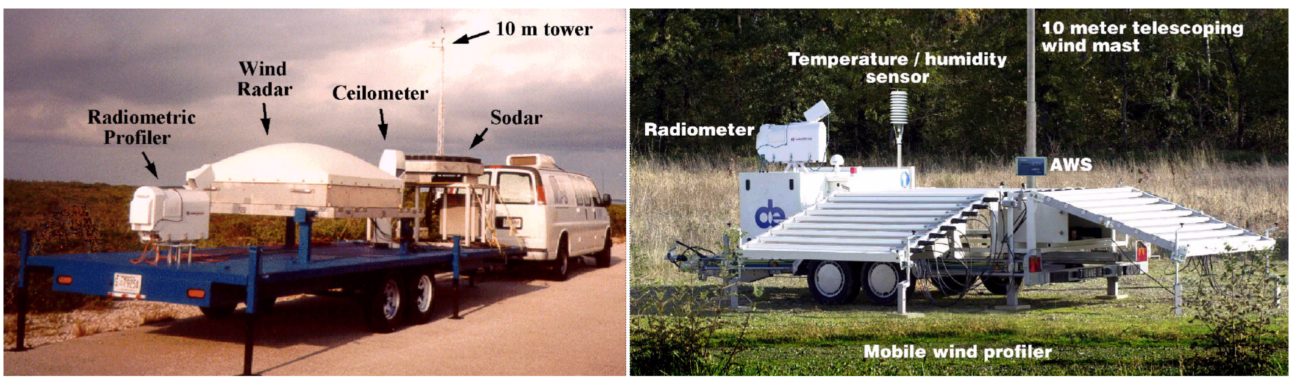

Figure 4. Mobile thermodynamic and wind profiling systems designed for high-resolution modeling and forecasting. Professor Kevin Knupp at the University of Alabama, Huntsville developed the research system shown at left <http://vortex.nsstc.uah.edu/mips>. Degreane, Inc., <http://www.meteo.degreane.fr> is marketing the commercial system shown at right.

5. GPS SLANT DELAYS

Delays induced by water vapor along GPS ray paths can be accurately measured[7,8]. These *slant wet delays* provide strong horizontal constraints for water vapor analysis[9]. When GPS slant wet delays are combined with water vapor soundings from radiometric profilers, high-resolution three dimensional water vapor analysis can be obtained[10]. An example high resolution water vapor analysis of a dry line and convective storms at 750 meter height is shown in the left-hand panel of Figure 5. The three dimensional water vapor field, including the location and magnitude of convective storms, is recovered from 3DVAR assimilation of simulated GPS slant wet delays and radiometric water vapor soundings. Large-scale convective storms are not seen in the Barnes analysis derived from radiosonde soundings.

MacDonald et al.[11] also showed that high resolution winds can be recovered if wind profiler observations and total GPS slant delays are included in the 3DVAR analysis. The wind fields are derived from pressure fields that contribute to total slant delays. At angles below 2 degrees elevation, GPS slant delays are accurate to 2% or better. Slant delays at these low elevation angles extend for distances of 100 km or more in the boundary layer[12]. Slant delays can be used to extend local constraints based on thermodynamic and wind profiler observations to regional scales.

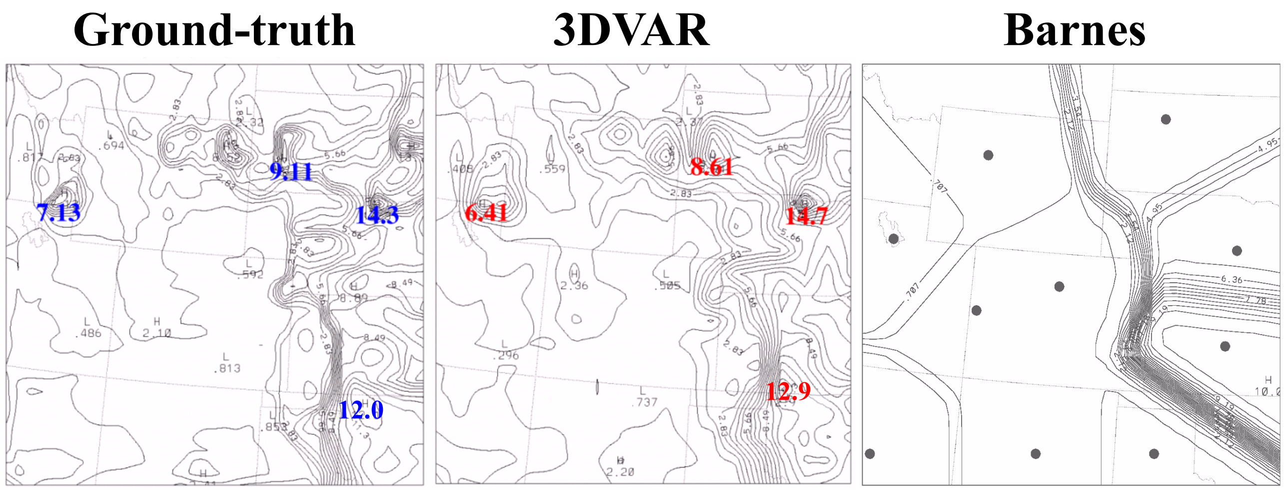

Figure 5. Water vapor analysis in a 12-state region in the central US at 750 m height including a dry line and convective storms (left). Locations of major convection are marked by their maximum water vapor density. Analysis based on simulated slant GPS and radiometric soundings (center) recovers the magnitude and location of convective storms[10]. The convective storms are not seen in the Barnes analysis based on radiosonde soundings at locations marked by black dots (right).

6. CONCLUSIONS

We have provided an overview of thermodynamic profiling and its use with wind profiling and slant GPS methods. In summary, thermodynamic profiling with microwave radiometry provides accurate and reliable temperature and humidity soundings up to 10 km height in clear and cloudy conditions, and low resolution cloud liquid soundings. Continuous thermodynamic soundings can be used to improve local high-resolution forecasting. Results can be further improved by assimilating wind profile observations. If slant GPS observations are also assimilated, three dimensional water vapor and wind analysis on regional scale can be obtained. Applications include forecasting of high resolution dispersion and transport, short-term precipitation and fog.

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