Use of Wind Profiler Estimates of Significant Moisture Gradients to Improve Humidity Profile Retrieval

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12 February 1996 and final form 22 April 1996

ABSTRACT

A method is presented to obtain a high-vertical-resolution humidity profile if the location and strength of only a few significant segments of the humidity gradient profile are known. The method is based on a previously developed statistical inversion technique coupled with moisture gradient information derived from wind profiler and the radiosonde temperature measurements. An existing retrieval algorithm uses an independent historical radiosonde-derived dataset and data from a two-channel microwave radiometer, standard surface meteorological instruments, and a lidar ceilometer. In this study, the possibility of constraining the statistical retrieval using measurements of significant moisture gradients derived from wind profiler signals and radiosonde temperature observations is investigated. An example is given to illustrate the method: on 26 May 1994 the 449-MHz wind profiler/RASS at Erie, Colorado, detected a strong humidity gradient at 4.9 km MSL. A statistical inversion algorithm constrained to the radar-measured gradient at 4.9 km was used to estimate the moisture profile. Results from this example show that an improvement in retrieved humidity profiles in particular, in the strength and location of a shallow layer, can be obtained if only significant radar-sensed humidity gradient information is added to other ground-based remote sensing measurements.

1. Introduction

Remote profiling of atmospheric variables such as wind, temperature, and humidity has undergone rapid development during the past decade. The profiling of wind up to 16 km above ground level (AGL) has been shown to be successful (Strauch et al. 1987). The National Oceanic and Atmospheric Administration (NOAA) Wind Profiler Demonstration Network, which covers a large part of the midwestern United States, is operational and provides continuous profiles (up to 16 km AGL) of wind speed and direction every 6 min from unattended instruments (Schlatter and Zbar 1994). A radio acoustic sounding system (RASS) provides high vertical and temporal resolution virtual temperature profiles up to 5.6 km (Martner et al. 1993). Combining RASS with the space-based remote sensing measurements to obtain temperature profiles comparable to the radiosonde measurements was successful in two studies. Schroeder et al. (1991) used a simple inverse covariance weighting method to extend RASS measurements with the temperature profiles retrieved from the Television and Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) data. Stankov (1996) combined RASS with Aeronautical Radio Incorporated (ARINC) Communications Addressing and Reporting System (ACARS) temperature data and TOVS brightness temperature observations using a coupled statistical and physical retrieval technique to obtain temperature profiles equivalent with those observed by radiosondes in both clear and cloudy conditions. Operational humidity profiling, however, is still far from realization.

Microwave radiometer data have been used to recover humidity profiles (Skoog et al. 1982; Westwater 1993); however, it is necessary to incorporate measurements from other instruments to obtain humidity profiles that can describe detailed vertical humidity structure. By combining data from RASS, a microwave radiometer, ACARS, a lidar ceilometer, and TOVS, Stankov (1996) used a coupled statistical and physical retrieval technique to obtain humidity profiles in addition to temperature profiles for 119 soundings from a two-month experiment designed to test this retrieval method. For cloudy conditions, Stankov et al. (1995) derived accurate humidity profiles from surface measurements, K-band radar cloud-base and cloud-top height measurements, and microwave radiometrically observed path-integrated water vapor using a physical

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retrieval method. Han and Westwater (1995) used RASS, a two-channel microwave radiometer, surface meteorological instruments, and a ceilometer to derive humidity profiles by coupling a statistical classification technique with a physical retrieval algorithm and showed good agreement with radiosonde measurements for a yearlong dataset.

Although the above methods generally produce humidity profiles that accurately represent the mean atmospheric structure, they are unable to detect thin layers and large gradients in the humidity profiles. Gossard et al. (1982, 1995) showed that the vertical gradients of the mean potential refractive index can be inferred from wind profiler measurements. In addition, they demonstrated that if the potential temperature gradient is known (e.g., from RASS), the vertical gradient of mean specific humidity can be inferred using

$$\frac{dQ_0}{dz} = \frac{1}{b}\left(\frac{d\phi_0}{dz} + a\frac{d\theta_0}{dz}\right), \qquad (1)$$

where Q_0 is the specific humidity, θ_0 is the potential temperature, ϕ_0 is the potential refractive index, and d/dz is a vertical derivative. The parameters a and b are functions of the mean temperature and humidity (Kerr 1951) and for the standard atmosphere can be considered constants equal to about 1 and 7, respectively. If the turbulent structure of the lower atmosphere is adequately represented by an inertial subrange, the vertical gradient of radar potential refractive index, can be expressed in terms of the turbulence structure parameters of the refractive index and vertical velocity fields, (i.e., C_n^2 and C_w^2, respectively), which can be estimated from the received power and from the spectral width of the Doppler velocity spectrum (e.g., Gossard et al. 1982, 1995). The resulting radar estimates of significant vertical gradients of humidity and their location in height can be used as an additional constraint in a humidity profiling retrieval algorithm.

In this note, we propose a technique to improve the detailed vertical structure of humidity profiles by using information on significant humidity gradients obtained from wind profiler/RASS measurements. At the time of this study, however, there were no such simultaneous datasets. Thus, we have used wind profiler data coupled with temperature gradients inferred from a nearby radiosonde ascent as a proxy to RASS. Consequently, this note demonstrates a feasibility of the proposed technique and not a direct application.

2. Measurements

The Environmental Technology Laboratory (ETL) of NOAA has, since 1981, operated a suite of ground-based remote sensing instruments and surface meteorological instruments that measure temperature, dewpoint, and pressure at Stapleton International Airport in Denver, Colorado. The measurements from these instruments and from National Weather Service (NWS) radiosondes and a lidar ceilometer at Stapleton are collected in ETL's databases and are available for use in near-real time. In addition, ETL operates a 449-MHz wind profiler at Erie, Colorado, some 60 km away from Stapleton. Typically data are recorded every 2 min for the two-channel microwave radiometer and the surface measurements, half-hourly for the wind profiler radar at Erie, every 30 s for the lidar ceilometer measurements, and every 5 min for the ACARS reports. Data sampled at a higher rate are all averaged to 20 min, surrounding the time of the half-hourly data.

a. *Two-channel microwave radiometer*

The ETL ground-based, zenith-pointing microwave radiometer systems observe radiation emitted by the atmosphere and measure the brightness temperatures in the 20.6-GHz and 31.65-GHz frequency channels. Those channels respond to radiation from both water vapor and liquid water. Measured brightness temperatures are converted to path-integrated water vapor and path-integrated liquid water using a simple statistical estimation algorithm (e.g., Hogg et al. 1983). Radiometrically derived integrated water vapor values agree with the radiosonde-observed vertically integrated values to an rms accuracy of about 1 mm (Hogg et al. 1983; Martner et al. 1993).

b. *Wind profiler*

Long-wavelength wind profiler radars were designed to primarily measure winds in all weather conditions (Strauch et al. 1987; Martner et al. 1993). They detect signals backscattered from turbulence-induced refractive index fluctuations with a scale of half the radar wavelength. As the turbulent eddies drift with the mean wind, their translational velocity provides a direct measure of the mean wind vector. Typically, profilers are designed to operate in two modes, one for low-altitude sampling with high vertical resolution and another for higher-altitude sampling with reduced vertical resolution. The 449-MHz (λ = 0.67 m) wind profiler at Erie has 900-W peak power, antenna size of 18 m^2, two-way beamwidth of 5.7°, first height at 255 m, height spacing of 180 m, and 32 heights.

c. *Laser ceilometer*

The NWS routinely operates a laser ceilometer at Stapleton International Airport. It is a model CT12 K, manufactured by Vaisala. This instrument measures the cloud-base height every 30 s and has a vertical resolution of about 15 m; measurements are taken from the surface to 3.6 km AGL.

d. *Radiosonde*

The NWS radiosondes are routinely launched twice a day at 1100 and 2300 UTC. The accuracy of radiosonde soundings is described by Pratt (1985) and Wade (1994). A 5-yr-long historical dataset of radiosondes from Stapleton for May 1981–85 was used for statistical information.

e. Surface meteorological instruments

A standard surface meteorological station measures surface pressure, temperature, and relative humidity providing 2-min averages as a part of the ETL suite of instruments at Stapleton. The accuracy of the surface pressure measurement is 0.5 mb, surface temperature accuracy is 0.5°C, and surface relative humidity accuracy is 5%.

3. Technique description

We used a linear statistical inversion technique mathematically described by Strand and Westwater (1968), applied to the six-channel microwave radiometer measurements by Hogg et al. (1983), and applied to the RASS virtual temperature measurements by Schroeder (1990). Stankov (1996) extended this technique to combine several individual ground-based remote sensing measurements with in situ ACARS and surface meteorological measurements to retrieve temperature and humidity profiles.

This technique is also well suited to incorporate radar-observed humidity gradient measurements into the retrieval. The technique estimates atmospheric humidity from a linear combination of measurements as

$$\hat{q}(z) = c_0(z) + \sum_{i=1}^{m} \mathbf{c}_i(z)\mathbf{x}_i , \qquad (2)$$

where $\hat{q}$ is the humidity estimate, z is the height coordinate, m is the number of measurements, $\mathbf{x}_i$ is the measurement vector, and $\mathbf{c}_i$ is the retrieval coefficient vector. An a priori radiosonde dataset for a 5-yr period that is independent of the measurement vector determines the retrieval coefficient vector $\mathbf{c}_i$. This a priori dataset characterizes the site climatology; it consists of Stapleton radiosonde ascents for May and June 1981–85. Typically the measurement vector $\mathbf{x}_i$ would consist of surface meteorological data, ceilometer, and two-channel microwave radiometer measurements. In this study, we include radar-observed measurements of humidity gradients aloft in the data vector. This retrieval method falls into the category of a priori linear statistical methods where the moisture profile is estimated by Eq. (2). A detailed discussion of statistical inversion as applied to the temperature–humidity profiling is described by Westwater (1993). Random noise is added to all components of the data vector; the rms values of the noise vector correspond to experimentally determined accuracies. The regression coefficients obtained from the least squares fit at the chosen altitudes make up the retrieval coefficient vector. Here we chose 70 levels between the surface and 300 mb and 27 additional levels between 300 and 0.1 mb.

4. 26 May 1994 case

On 26 May 1994, Gossard et al. (1995) conducted an experiment to test if the wind profiler can observe the humidity gradients at Erie, Colorado, from the measurements of the zeroth, first, and second moments of the clear-air Doppler spectra, from which C_n^2, the horizontal wind (u, v), and C_w^2, respectively, can be inferred, and temperature from radiosonde. The radar detected a large humidity gradient at 1720 UTC and 5.1 km MSL. The Denver radiosonde released some 60 km away and several hours later, at 2300 UTC, showed a strong humidity gradient at 4.9 km AGL. The 200-m difference in height of the radar-observed and the radiosonde-observed humidity gradients could be explained by the difference in the observation times and the spatial difference between the sites. At the time of the Denver radiosonde ascent intermittent low-level clouds were present.

Figure 1 displays the results obtained for this case using the retrieval method described in section 3 with the radar-observed humidity gradient information included as an additional constraint in the dewpoint profile retrieval. For comparison we also include retrieved humidity profile without gradient information and separate the effect of cloud on the retrieval.

Figure 1a shows the observed radiosonde profile and the retrieved dewpoint profile when only two-channel microwave radiometer measurements and the temperature profile are known. The radiometer reported 0.082 mm of liquid and 1.50 cm of vapor present in a column of air. Integrating the radiosonde-observed humidity profile gave 1.81 cm of precipitable water vapor, and the integral of the retrieved humidity profile gave 1.68 cm.

Figure 1b shows the retrieved humidity profile when in addition to measurements used in Fig. 1a, the cloud boundaries (Politovich et al. 1995; Stankov et al. 1995) were included as constraints in the retrieval method. Precipitable water vapor obtained by integrating the retrieved humidity profile was 1.88 cm.

Figure 1c shows the radar-observed and the radiosonde-observed vertical humidity gradient profiles (Gossard et al. 1995). The radiosonde humidity gradient was computed at the vertical resolution of the radiosonde measurements, but the results were interpolated onto the height of the radar-observed gradients for comparison. The agreement in the location of the most significant humidity gradient is quite good, but the maximum value obtained from radiosonde measurements is -13.39×10^{-3} g kg^{-1} m^{-1}, which is significantly larger than -9.98×10^{-3} g kg^{-1} m^{-1} observed by the radar.

Figure 1d shows the retrieved humidity profile when only the radar-observed humidity gradient information

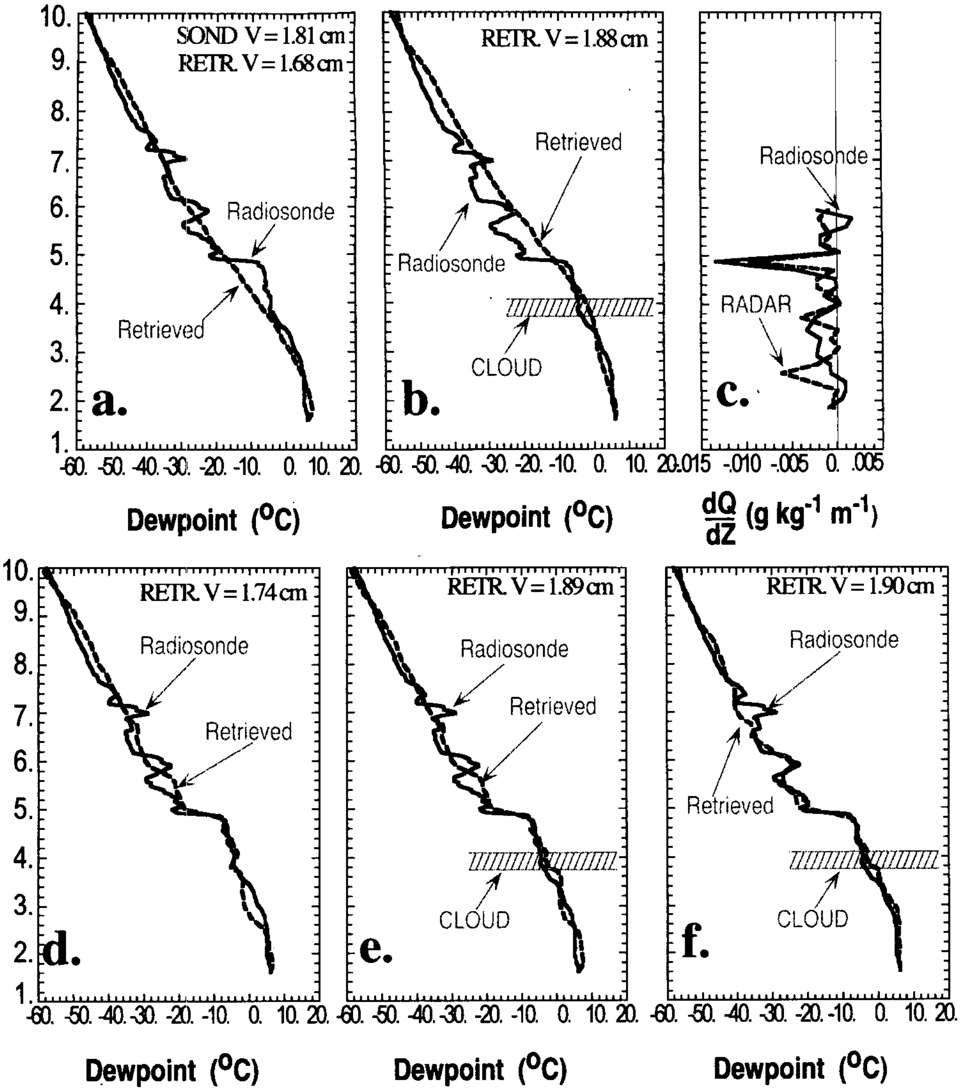

FIG. 1. Retrieved dewpoint profile obtained at 1720 UTC 26 May 1994, (a) radiosonde-measured dewpoint temperature and retrieved dewpoint temperature based on two-channel microwave radiometer measurements only; (b) radiosonde-measured dewpoint temperature and the retrieved dewpoint temperature based on two-channel microwave radiometer measurements and cloud boundary information; (c) vertical gradient profile of dQ/dz (g kg^{-1} m^{-1}) observed by the radar and computed from the radiosonde-observed humidity and interpolated onto the radar-observed heights; (d) radiosonde-measured dewpoint temperature and the retrieved dewpoint temperature based on two-channel microwave radiometer measurements and the radar-observed humidity gradient information; (e) radiosonde-measured dewpoint temperature and the retrieved dewpoint temperature based on two-channel microwave radiometer measurements, cloud boundary information, and the radar-observed humidity gradient information; and (f) radiosonde-measured dewpoint temperature and the retrieved dewpoint temperature based on two-channel microwave radiometer measurements, cloud boundary information, and the humidity gradient information computed from the radiosonde measurements.

was added to the measurement vector of Fig. 1a as constraints in the retrieval method. Precipitable water vapor obtained by integrating the retrieved humidity profile was 1.74 cm.

Figure 1e shows the retrieved humidity profile when both the radar-observed humidity gradient and the information on cloud boundaries were added to the measurement vector of Fig. 1a as additional constraints in the retrieval method. Precipitable water vapor obtained by integrating the retrieved humidity profile was 1.89 cm.

Figure 1f is similar to Fig. 1e, except that the humidity gradients obtained from the radiosonde ascent were used as constraints in the retrieval instead of the radar-observed humidity gradient profile. The precipitable water vapor obtained by integrating the retrieved profile was 1.90 cm.

The top row of Fig. 2 shows the height dependence of the dewpoint difference from the radiosonde (retrieved radiosonde), and the bottom row shows scatter diagrams of the retrieved and radiosonde dewpoint profiles for the retrievals corresponding to Figs. 1a,b,d,e,f. Including just the cloud boundaries (Fig. 2b) did not improve the overall retrieval with respect to Fig. 2a. However, including the radar-observed humidity gradient observations (Fig. 2c) reduces the mean of the differences (M) to 0.38°C and the standard deviation (S) of the differences to 2.64°C. The correlation coefficient remains 0.99 for all the cases. Combining cloud and gradient information (Fig. 2d) increases the mean and reduces the standard deviation, while using the humidity gradient information computed from the radiosonde ascent gives best results (Fig. 2e), with $M = 0.18$°C and $S = 2.08$°C.

Adding more remote sensor observations to the retrieval (in particular, wind profiler–derived moisture gradients) and, therefore, imposing constraints on the smooth humidity profile obtained from the microwave radiometer measurements and the site climatology, reveals more and more significant details in the humidity profile.

5. Summary

We have presented a method for enhancing the height resolution of humidity profiles obtained using data from suites of remote sensors. In particular, we examined the possibility of detecting sharp moisture gradients using the height and magnitude of significant humidity gradients detected by a wind profiler/RASS (Gossard et al. 1995). All the required measurements are routinely available from NOAA's 915-MHz prototype wind profiler/RASS, at Stapleton International Airport. This technique can also be successfully applied to each wind profiler system within the Wind Profiler Demonstration Network (Schlatter and Zbar 1994). The two-channel microwave radiometer measurements used in this study are not available at the network sites, but Rocken et al. (1993) showed that the Global Positioning System (GPS) can be used to esti-

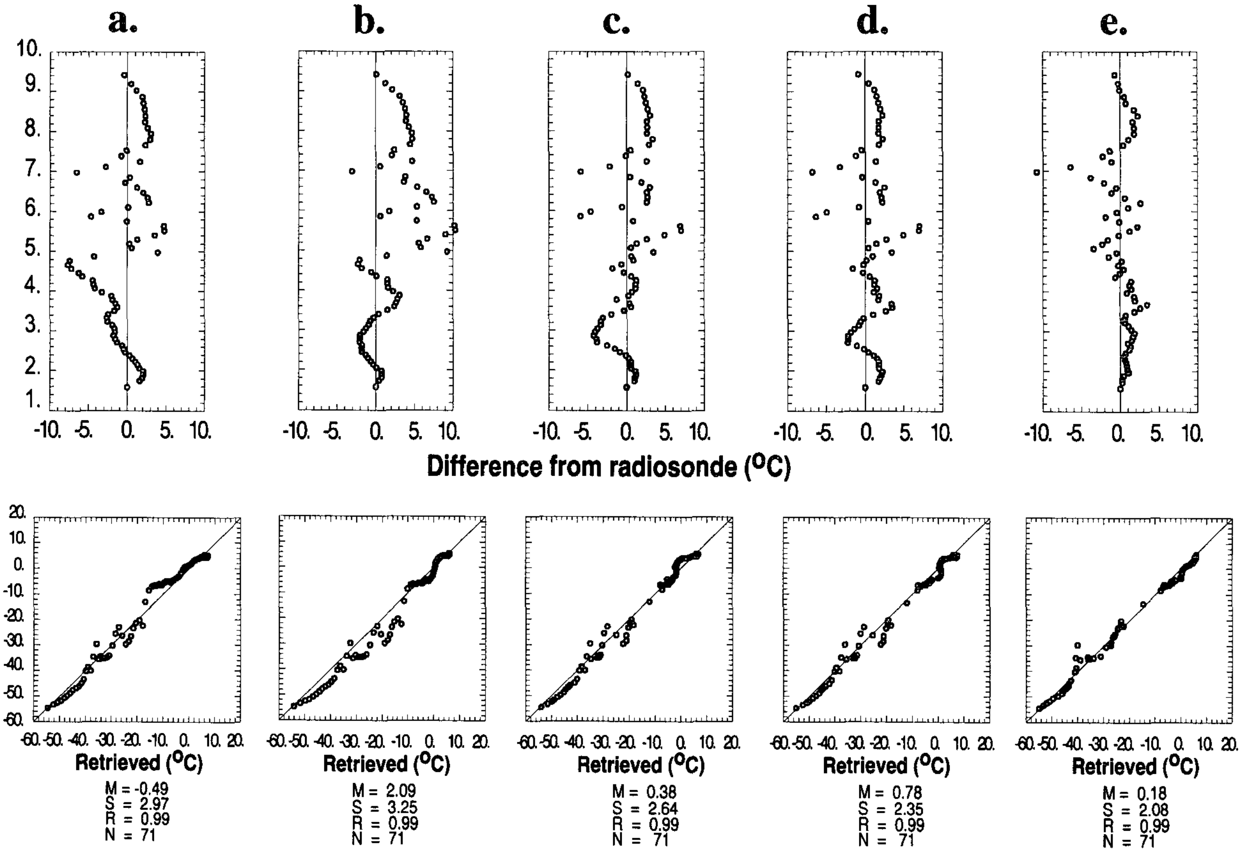

FIG. 2. The top row represents the height dependence of the dewpoint differences from the radiosonde (retrieved radiosonde) and the bottom row represents scattergrams of radiosonde vs retrieved dewpoint, for the cases in Figs. 1a,b,d,e,f. Mean M, standard deviation S, and correlation coefficient R, for each case are noted below the scattergrams.

mate integrated atmospheric precipitable water vapor with millimeter accuracy. Therefore, those estimates can replace radiometer water vapor measurements in the retrieval algorithm. Unfortunately, the GPS system does not provide measurements of the path-integrated liquid that were used to estimate cloud thickness of the lowest cloud but the new cloud profiling radars may provide even better answer for that. Commercial airliners routinely send ACARS reports with ever-increasing coverage, and lidar ceilometers will be routinely available as part of the Automated Surface Observing System.

This study investigated the possibility of including height-dependent moisture gradient information, available from wind profiler signals, in existing humidity retrieval algorithm. Encouraged by these results, ETL conducted an experiment in the humid, maritime air of southern California to test the technique further, using radar-retrieved humidity gradients, GPS, and ceilometer measurements. Analysis of this dataset is under way currently and it will provide a statistical estimate of how well the technique works in different meteorological situations.

Acknowledgments. The lead author would like to express her appreciation to Richard Lataitis for leading the humidity profiling study group, where she learned about the possibility of extracting moisture gradients from wind profiler radar/RASS measurements, and for carefully reading the manuscript. Tony Simon provided computer workstation and database support, and Dave Welsh assisted with converting part of a code from BASIC to Fortran. Anonymous reviewers influenced positively the outcome of this note. We thank them.

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