Ground- and Space-Based Humidity Profiling in a Cloudy Atmosphere with Strong Elevated Temperature Inversion

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Introduction

Stankov et al. (1993b) demonstrated that improved atmospheric profiles of temperature and humidity result when proper combinations of ground-based and space-based data from multiple platforms and sensors are used as a first guess for temperature and humidity in a physical retrieval algorithm. The platforms and sensors used included

- a radio acoustic sounding system (RASS)
- a 2-channel microwave radiometer
- an in situ commercial airliner Aerodynamic Research Incorporated Communication (ARINC) and Recording System (ACARS)
- standard surface meteorological instruments
- the Television and Infrared Observation Satellite (TIROS-N) Operational Vertical Sounder (TOVS).

The retrieval algorithm was provided by the International TOVS Processing Package (ITPP). In this ITPP method, all first-guess profiles are based on statistical regression analysis. Stankov et al. (1993a) also demonstrated that accurate profiles of humidity and liquid water density can be obtained during cloudy conditions by combining data from ground-based remote sensors only, in the iterative retrieval scheme, provided that the vertical cloud distribution is known. In this ground-based method, sensors included: RASS, K-band radar, 2-channel microwave radiometer, and standard surface meteorological instruments.

In this study, we show that in more complex meteorological situations, both methods described above can be used sequentially to obtain the humidity profile that represents the thermodynamic properties of the atmosphere. Figure 1 shows the 850-mb synoptic map for 12 UTC February 7. A cold front was approaching Platteville, Colorado, causing a 15°C, strong elevated inversion at 100 m above ground. The microwave radiometer showed 0.56 mm of liquid and 0.507 cm of vapor. This more complex type of meteorological situation was not encountered in either of the two previous studies.

Using only the ITPP method to retrieve the temperature and humidity profiles gives a good temperature profile; however, the retrieved humidity profile shows some serious problems. For instance, it does not show that the air inside the cloud layer is saturated. Thus, we use the ground-based method to retrieve a humidity profile and then use this retrieved humidity profile as a first guess in the ITPP method. The humidity profile obtained using this combined method is a significant improvement and represents the thermodynamic properties of the atmosphere very well.

Instrumentation and Technique

For this study, we used ground-based remote sensors and in situ instruments located at Platteville, Colorado. National Oceanic and Atmospheric Administration (NOAA) 404-MHz and 50-MHz wind profiler/RASS units (May et al. 1990) measured virtual temperature profiles to 300-mb and wind profiles to 50-mb levels once an hour. A 2-channel microwave radiometer measured brightness temperatures at 20.4 GHz and 31.65 GHz. From these measurements, the integrated liquid water and water vapor were computed at 2-min intervals using a simple statistical inversion

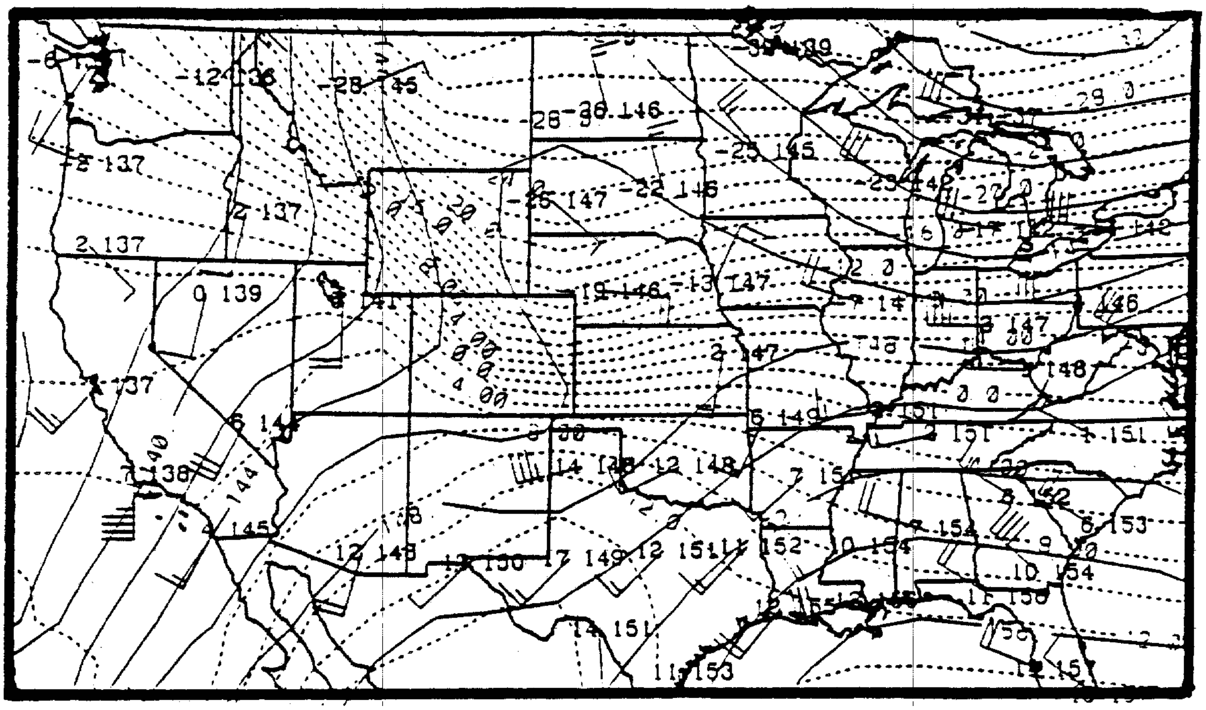

Figure 1. 800-mb synoptic map for February 7, 1994, at 12 UTC. Thin dashed lines are temperature lines, and thin solid lines are 850-mb heights.

technique (Hogg et al. 1983). Surface pressure, temperature, and dewpoint temperature were also obtained at 2-min intervals by NOAA's Environmental Technology Laboratory (ETL) with conventional ground-based instrumentation. These high frequency data were averaged for an hour and used with RASS data to construct the first-guess profiles.

For verification we used the National Center for Atmospheric Research (NCAR) Cross-chain Loran Atmospheric Sounding System (CLASS) radiosonde launches. A K-band (λ = 8 mm) Doppler radar with dual polarization and full scanning capabilities was used to determine cloud layer boundaries (cloud tops and bottoms). Its narrow beam (0.5°), fine range resolution (37.5 m), and high temporal resolution (1 sec) provide detailed measurements of cloud features (Martner and Kropfli 1993). University of Wyoming King Air N2UW in situ measurements of liquid water profiles (Stankov et al. 1993a) were used to construct the "composite" liquid water first guess profile.

Data for this study were collected on February 7, 1994, at 18 UTC as part of the Winter Icing and Storm Project (WISP) (Rassmussen et al. 1992) and the Ground- and Space-Based Profile Evaluation Project conducted by NOAA ETL/Forecast Systems Laboratory.

An iterative inversion scheme (Westwater and Strand 1974) was used to retrieve humidity and cloud liquid density profiles (see Figure 2a) from measured 2-channel microwave radiometer brightness temperatures (Tb). These two profiles and the RASS-based temperature first-guess profile were then used as the first-guess profiles in the ITPP method to obtain improved retrievals (Stankov et al. 1993b).

First-Guess Profile Construction

The ITPP Method

The first-guess temperature and humidity required by the ITPP were based on a regression analysis of a 15-yr long radiosonde dataset from Denver, Colorado (Westwater and Strand 1968). The coefficients were computed for the pressure levels required by the ITPP; the data vector consisted of surface temperature and humidity measurements, RASS virtual temperature measurements, ACARS, and 2-channel microwave radiometer measurements.

The Ground-Based Method

First-guess temperature was constructed from the surface temperature measurement, a RASS-measured virtual temperature profile, and a simple regression method (Schroeder and Westwater 1991) to extend the profile to the 0.5-mb level required by the iteration scheme.

Liquid water density was constrained to zero below cloud base and above cloud top which were determined by the K-band radar observations (Figure 2b). Inside the cloud layer, the liquid water density was assumed to vary according to the "composite" distribution based on 25 research ascents and descents through similar liquid cloud layers (Stankov et al. 1993a).

A first-guess water vapor density profile was also constructed based on the knowledge of cloud boundaries. Beneath the lowest cloud layer, the water vapor density was linearly interpolated from the surface value to the saturation value at the cloud base and was kept at the saturation (over water) throughout the lowest cloud (Figure 2b). The remaining water vapor was then calculated by subtracting the sub-cloud total vapor from total atmospheric vapor (measured by radiometer). Above cloud top, vapor was modeled to decay exponentially to the 0.5-mb level. If the K-band radar observed multiple layers, the humidity first-guess construction could be continued by exponentially decaying the remaining water vapor between the cloud layers and setting it to saturation (over ice) inside the cloud layers.

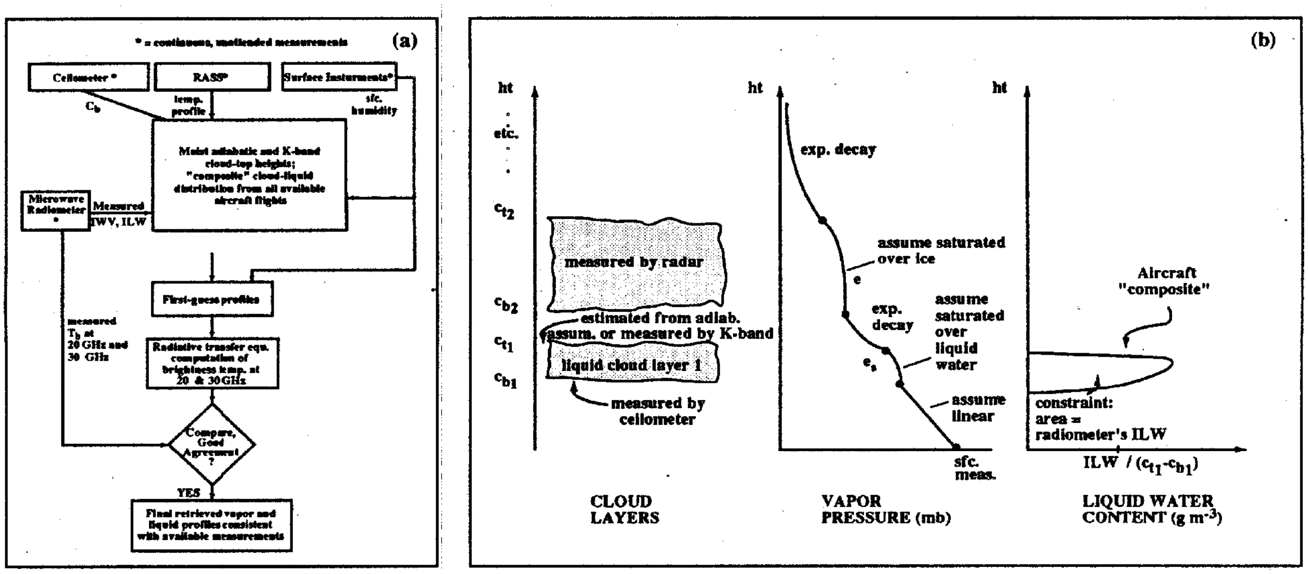

Figure 2. a) Flow diagram describing the first-guess construction of temperature, humidity, and liquid using the physical retrieval procedure. 2b) Schematic representation of the first-guess construction.

The Combined Method

The temperature first-guess profile remained the same as the one prepared for the ITPP method, and the retrieved humidity profile from the ground-based method became the first-guess humidity profile for the ITPP.

Results

On February 7, 1994, at 18 UTC, K-band radar detected only one cloud layer. Figure 3a shows a map of the Platteville area with all available satellite data marked by a "+" and the data chosen for this study marked as "•". Figures 3b and 3c show a skewT-logP diagram of the results obtained by using the first-guess profiles based on the ITPP method. Figure 3b shows the CLASS radiosonde and the retrieved temperature and dewpoint temperature to the 100-mb level. The rectangular box represents cloud-base and cloud-top heights determined by K-band radar (the horizontal extent of the box has no meaning here). Figure 3c shows the same results as Figure 3b but only to the 500-mb level, showing more detail in the temperature and dewpoint temperature profiles.

It is evident that the retrieved profile of dewpoint temperature lacks accuracy in the lowest 250 mb (with respect to radiosonde "ground truth"). The path integrated water vapor obtained from the CLASS sounding is 0.667 cm, while the path integrated water vapor from the retrieved profile is 0.260 cm. Radiometer observed path integrated water vapor was 0.507 cm, indicating a need for an improved humidity first guess. The RASS-based temperature profile agrees with the CLASS radiosonde temperature profile except near the ground. The first RASS gate is at 220 m AGL (800-mb level) so that linearly interpolating to the surface temperature does not show all the detail in the temperature structure of the atmospheric boundary layer.

Figure 4a shows a skewT-logP diagram of the CLASS radiosonde and the retrieved dewpoint temperature profile obtained by using the first-guess profiles based on ground-based method. Figure 4b shows the retrieved liquid water density profile based on the aircraft "composite." Figure 5 shows skewT-logP diagrams to the 50-mb level and to the 500-mb level of the dewpoint temperature and temperature profiles obtained with the combined method and the CLASS radiosonde profiles. For the retrieved profile of Figure 5, the path integrated water vapor is 0.530 cm, which is very close to the radiometer observed value of 0.507 cm.

Conclusions

This study documents a technique to improve retrieved humidity profiles in the presence of clouds, liquid water, and the presence of the elevated strong inversions, when cloud vertical distribution is known. K-band measurements of cloud distribution help construct the humidity profile, in combination with other remote sensor instruments which can operate continuously and unattended. However, the K-band radar measurements are expensive and not yet suitable for unattended operation.

In the absence of K-band measurements, a combination of cloud lidar ceilometer and microwave radiometer can provide an estimate of the vertical extent of the lowest cloud layer (Stankov et al. 1992). These two remote sensors are much cheaper and operate continuously and unattended. Knowledge about the higher layer clouds in this case can, perhaps, be provided by satellite observation. The possibility of using the satellite cloud-top measurements in situations of multiple cloud layers will be studied next.

The cloud-based algorithm could be incorporated into the ITPP algorithm and turned on whenever the lidar ceilometer detects clouds.

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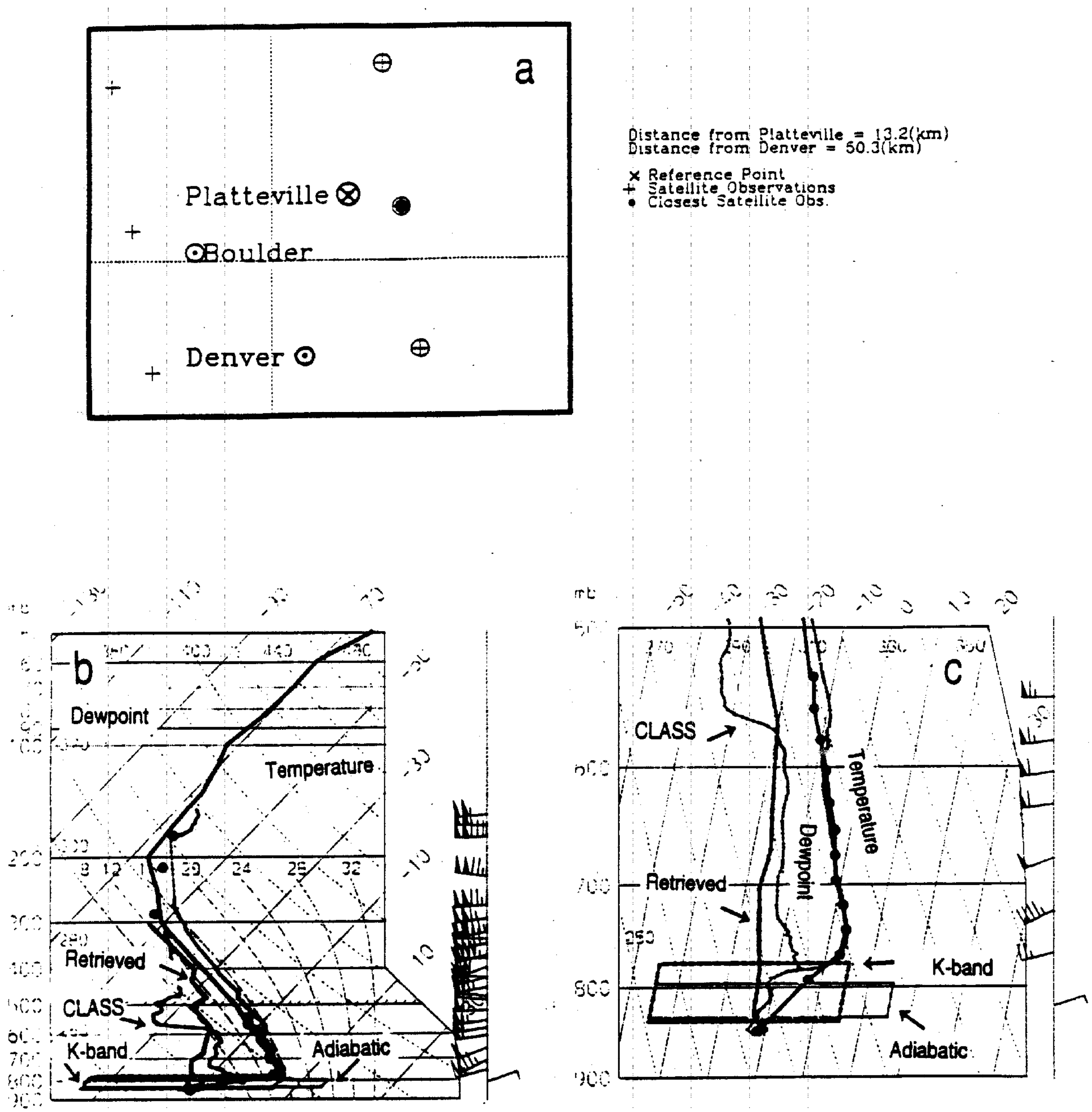

Figure 3. a) Map of available TIROS-11 data. b) SkewT-logP diagram of the CLASS radiosonde temperature and dewpoint temperature profiles and the retrieved temperature and dewpoint temperature profiles using the ITPP method only. c) Same as in 2b but only to 500-mb level.

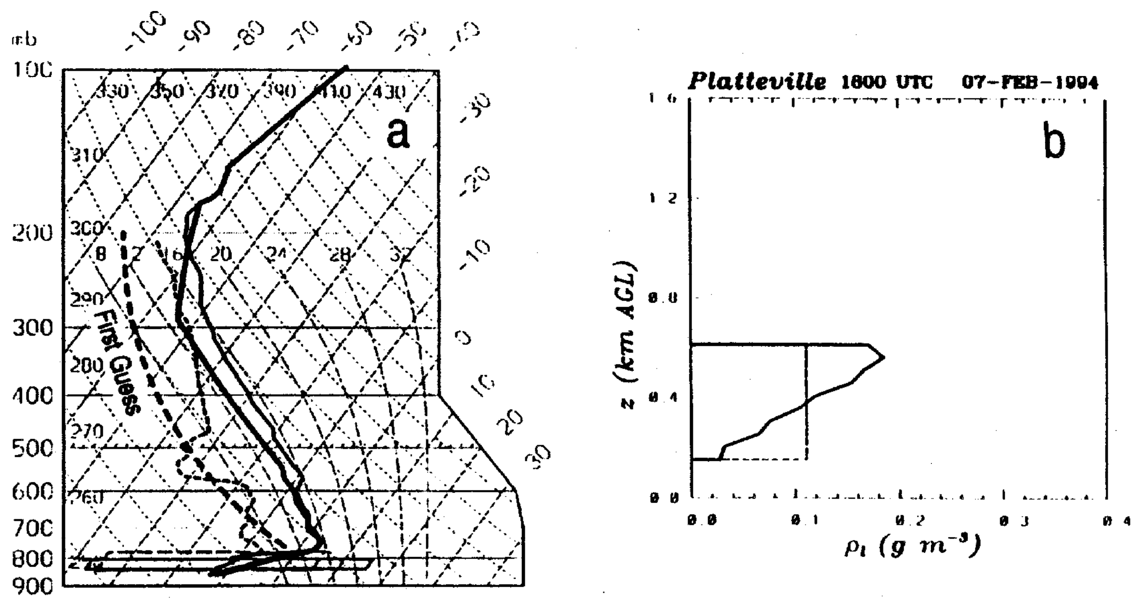

Figure 4. a) SkewT-logP diagram of the first-guess dewpoint temperature profile obtained from the K-band data and the iterative retrieval scheme, and the CLASS radiosonde profiles. b) Retrieved liquid water profile based on the "composite" from the aircraft measurements.

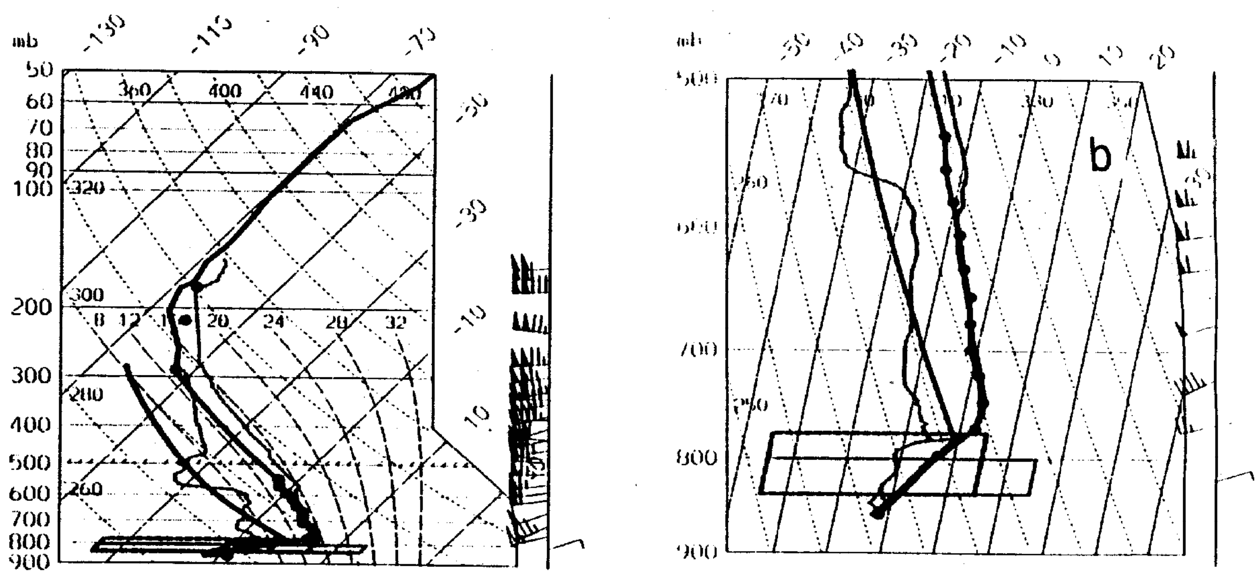

Figure 5. SkewT-logP diagram of improved dewpoint temperature profile obtained using combined method. The same retrieved temperature profile as in Figure 3b and the CLASS temperature and dewpoint temperature profiles. a) To the 50-mb level. b) To the 500-mb level.

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