REAL-TIME TEMPERATURE AND HUMIDITY PROFILES FROM GROUND- AND SPACE-BASED REMOTE SENSORS

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1. INTRODUCTION

Combining ground- and satellite-based remote sensor measurements provides temperature soundings that are more accurate than either system provides alone. Westwater and Grody (1980) and Westwater et al. (1984, 1985, 1989) used a six-channel microwave radiometer for the ground-based measurements; Schroeder et al. (1991) used a 915 MHz Radio Acoustic Sounding System (RASS) for the ground-based component and TIROS-N Operational Vertical Sounder (TOVS) for the space-based component. An inverse covariance weighting and another simple blending technique were used to combine the data for the RASS and TOVS combination. The resulting temperature profiles showed remarkable ability to detect sharp temperature inversions during extreme weather situations.

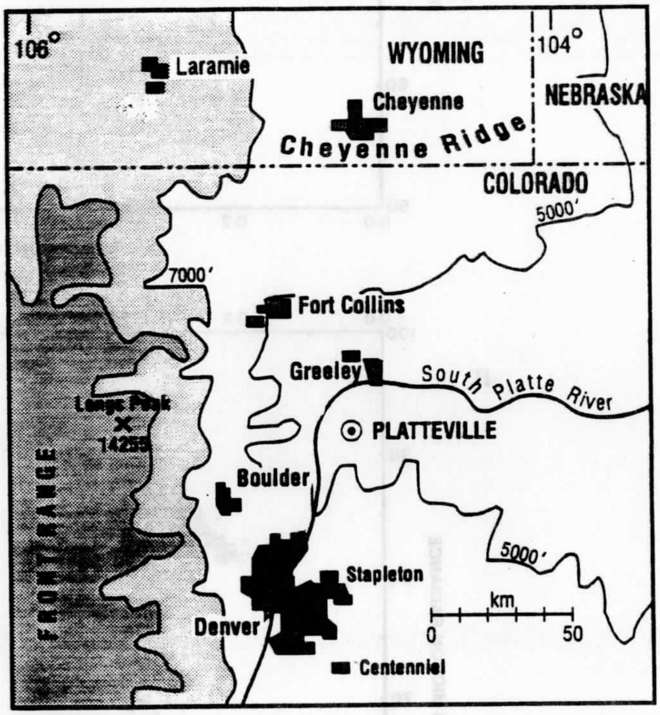

Fig. 1. Map of the WISP experimental area.

In this study, we incorporate data from RASS obtained with 405 and 50 MHz wind profiling radars and a two-frequency microwave radiometer, in situ Aircraft Communication and Recording System (ACARS) temperature data, and surface meteorological measurements. We insert the ground-based and ACARS retrievals directly into the International TOVS Processing Package (ITPP) by constructing a first guess field for temperature and humidity. For the situation when satellite data are not available, we also show that statistically retrieved temperature and humidity profiles based on RASS, two-channel microwave radiometer, ACARS, and surface data can be extrapolated to provide temperature time-height analysis to about 20 km.

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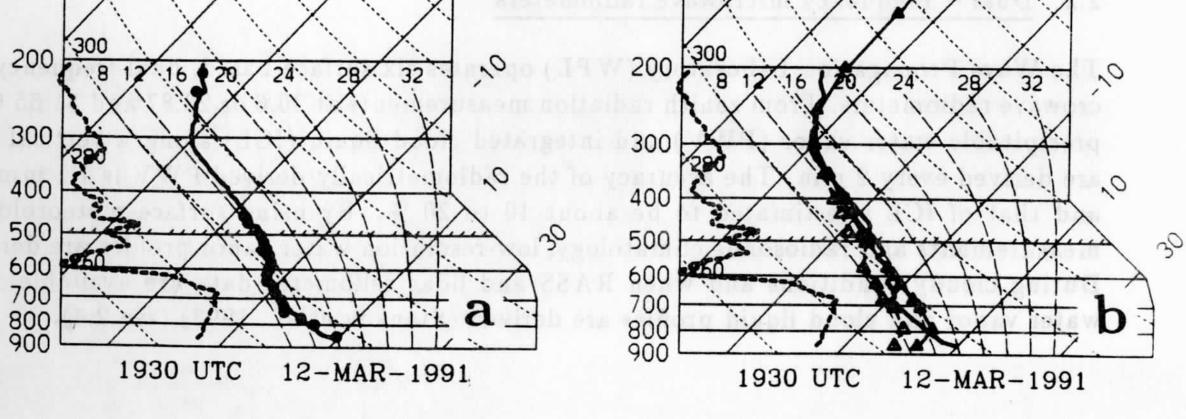
2. DESCRIPTION OF INSTRUMENTS

2.1 Radio Acoustis Sounding System

Wind profilers are Doppler radars that measure winds by measuring the Doppler shift of signals backscattered from refractive index perturbations at a scale of one-half the radar wavelength. These perturbations drift with the mean wind, and measuring their translational velocity provides a direct measure of the mean wind. The RASS combines acoustic sources with wind profilers to obtain measurements of the profile of virtual temperature (May et al., 1988). The profilers measure the speed of refractive index perturbations induced by vertically propagating acoustic waves (approximately matched with the radar's half-wavelength) as they ascend at the local speed of sound, which is directly related to the virtual temperature at each height.

Currently, wind profiler/RASS combinations operate at three electromagnetic frequencies: 915, 405, and 50 MHz. If corrections for vertical winds are introduced, all RASS systems measure virtual temperature with an rms accuracy of about 0.5 K. The height range of RASS is a function of the radar wavelength, acoustic and electromagnetic transmitter power, and the receiving antenna's area. Atmospheric limitations include acoustic attenuation, which is a strong function of frequency, turbulence, and horizontal wind, which advects the acoustic waves and causes the scattered electromagnetic waves to be focused away from the radar antenna. The heights reached 50 % of the time are 0.7, 3.2, and 5.5 km for the 915, 405, and 50 MHz systems, (Martner et al., 1993). Height resolution is about 100, 150, and 300 m. Minimum measurement height is about 150, 500, and 2000 m, respectively, for the three wavelengths. Temporal resolutions of 20 to 60 m are commonly available.



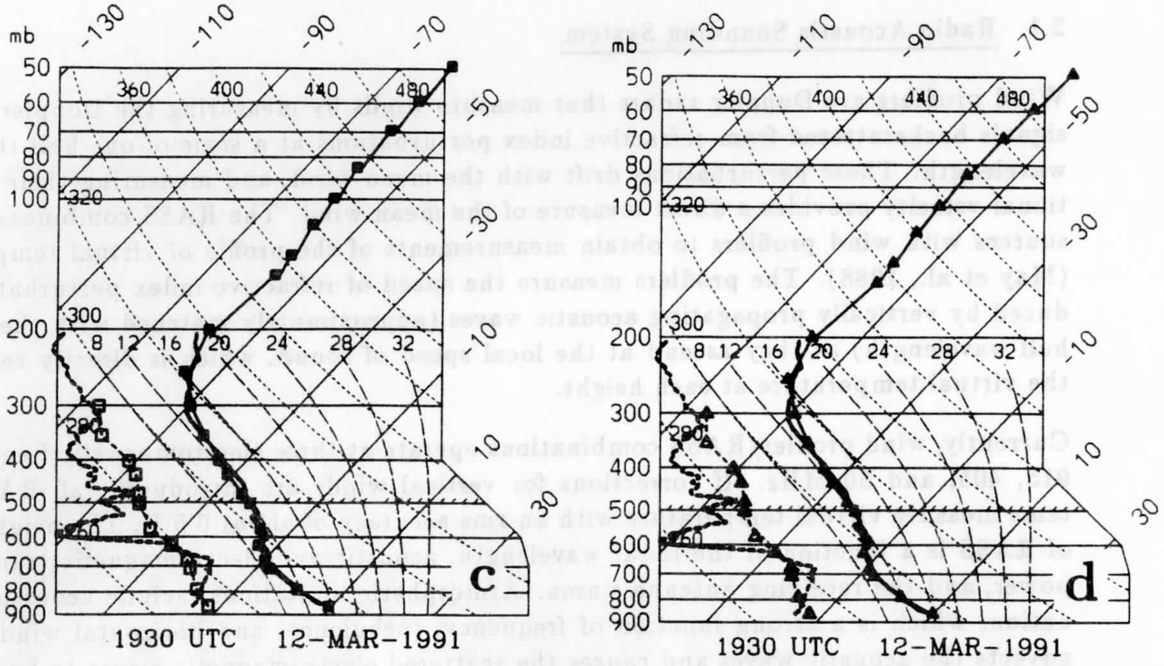


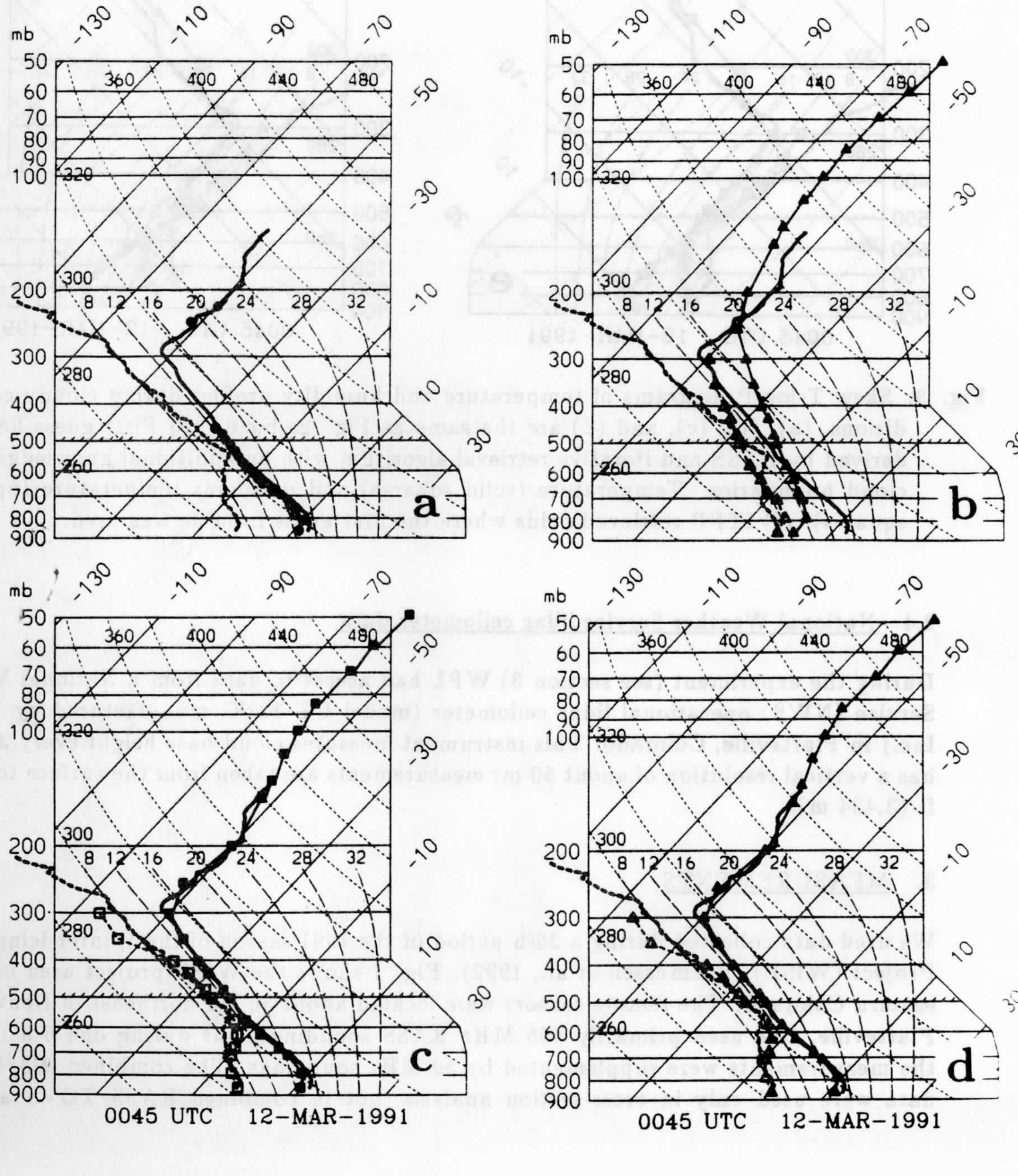
Fig. 2. Skew T-log P diagrams of temperature and humidity profiles during clear conditions obtained (a) by CLASS radiosonde (temperature = right solid line, dewpoint temperature = left dashed line), and by RASS, ACARS and surface temperature (filled circles); (b) ITPP retrieved temperature profile (solid triangles) and dewpoint temperature (open triangles); (c) regression derived first guess temperature (filled squares), dewpoint temperature (open squares);, (d) ITPP retrieved profiles using regression derived first guess temperature (filled triangles), dewpoint temperature (open triangles).

2.2 Dual – Frequency microwave radiometers

The Wave Propagation Laboratory (WPL) operates six surface-based, dual-frequency microwave radiometers. From zenith radiation measurements at 20.6 or 23.87 and 31.65 GHz, precipitable water vapor (PWV) and integrated cloud liquid (ICL) along a vertical path are derived every 2 min. The accuracy of the radiometrically-derived PWV is 1.1 mm rms and that of ICL is estimated to be about 10 to 20 %. By using surface meteorological measurements and radiosonde climatology, low-resolution water vapor profiles are derived. During cloudy conditions and when RASS and lidar ceilometer data are available, both water vapor and cloud liquid profiles are derived (Stankov et al., 1993) (see 2.4).

2.3 ACARS aircraft observations

The Forecast Systems Laboratory (FSL) is currently receiving flight level temperature and wind data from commercial carriers in real time (Benjamin et al., 1991). Depending on the carrier, the soundings san have a vertical resolution of 2000 ft (about 700 m) and originate every 7.5 min, but they may have an irregular distribution in space and time because of flight patterns and schedules. Temperature and wind data are available every 2000 ft from 31,000 to 43,000 ft (9.45 to 13.11 km) along major routes relatively frequently during travel hours.



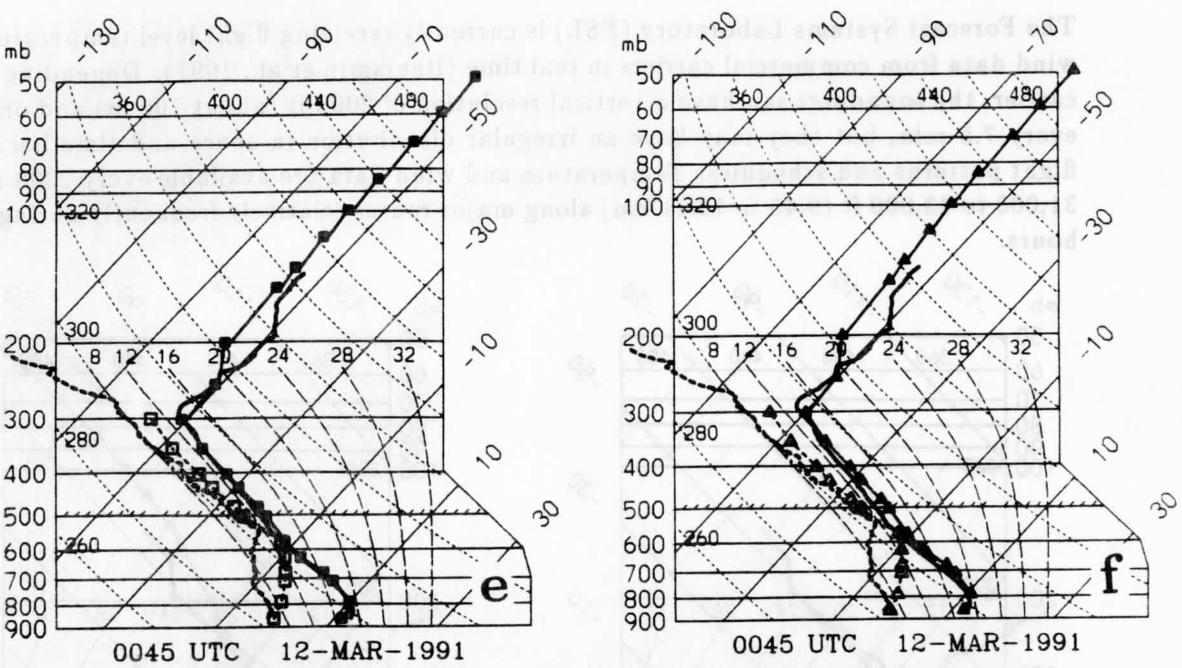


Fig. 3. Skew T-log P diagrams of temperature and humidity profiles during cloudy conditions, (a), (b), (c), and (d) are the same as Fig. 2a,b,c,d. (e) First guess fields derived by RASS and iterative retrieval algorithm with an additional knowledge of cloud boundaries. Temperature (solid squares) and dewpoint temperature (open squares). (f) ITPP retrieved fields where the first guess from 3e was used.

2.4 National Weather Service lidar ceilometer data

During the experiment (see section 3) WPL had access to data from a National Weather Service (NWS) operational lidar ceilometer (model CT 12 K, manufactured by Vaisala, Inc.) in Platteville, Colorado. This instrument measures cloud base height every 30 s and has a vertical resolution of about 50 m; measurements are taken from the surface to 12,000 ft (3,434 m).

3. MEASUREMENTS

We used data collected during a 26-h period of the 1991 season of the Winter Icing Storm Project (WISP) (Rasmussen et al., 1992). Fig. 1 shows the WISP project area in northeastern Colorado. The remote sensors were located about 50 km northeast of Denver near Platteville. We used primarily 405 MHz RASS soundings, but during one 6-h interval, the measurements were supplemented by 50 MHz soundings. The combined 405/50 MHz data were used only in cross-section analysis, not in combined RASS/TOVS analysis.

Verification soundings for temperature, humidity, and wind were obtained with special radiosonde launches near Platteville. Cross-chain Loran Atmospheric Sounding System (CLASS) (Lauritsen et al., 1987) radiosondes were launched 14 times during the 26-h period by the National Center for Atmospheric Research (NCAR). Conventional surface instruments from WPL measured surface temperature, dewpoint, and pressure every 2 min. During the experiment, the ceilometer measured cloud-base height every 0.5 min. Two polar-orbiting satellites, NOAA-10 and NOAA-11, provided TOVS measurements from six passes during the same period. Commercial aircraft provided numerous flight level wind and temperature measurements over the Platteville area.

4. FIRST GUESS CONSTRUCTION

We used two different methods for the first guess construction: a statistical inversion technique that applies to both clear and cloudy conditions, and an iterative retrieval technique that applies to cloudy conditions.

4.1 Statistical Retrieval

We use the statistical retrieval technique described by Strand and Westwater (1968) as applied to RASS by Schroeder et al. (1990). The technique is based on a priori knowledge of the site climatology as provided by a 15-yr-long radiosonde data set from Denver. Profile retrieval coefficients were prepared for the pressure levels required by the ITPP. A data vector was formed from RASS measurements of virtual temperature, ACARS data, two-channel microwave radiometer data, and surface temperature and humidity measurements. The retrieval produces a first guess temperature and humidity profile, which is then inserted into the ITPP. Our retrieval algorithms allow us to produce profiles for clear or cloudy conditions.

4.2 Iterative Retrieval

During cloudy conditions, we also constructed the first guess using the method developed by Stankov et al. (1993). This method uses combined remote sensor measurements in an iterative retrieval algorithm (based on the generalized Landweber Iteration method (Strand, 1974)) to obtain liquid water and water vapor profiles when the temperature profile is known from RASS. The cloud-base height from the lidar ceilometer, the path-integrated liquid water and water vapor from the two-channel microwave radiometer, and the cloud-top height from the TOVS data provide the humidity first guess for the ITPP. We also assume that the vapor is saturated over water in the lowest cloud layer and saturated over ice inside the higher level clouds to provide the humidity first guess for the ITPP. ITPP.

5. RESULTS

We considered two very different weather situations for the test our approach; one was clear, the other was cloudy. To eliminate the influence of the ITPP below the top of RASS measurements, we adjusted an ad hoc error factor provided by the ITPP to weight the channels that contribute to those levels, and we also adjusted the regularization parameters

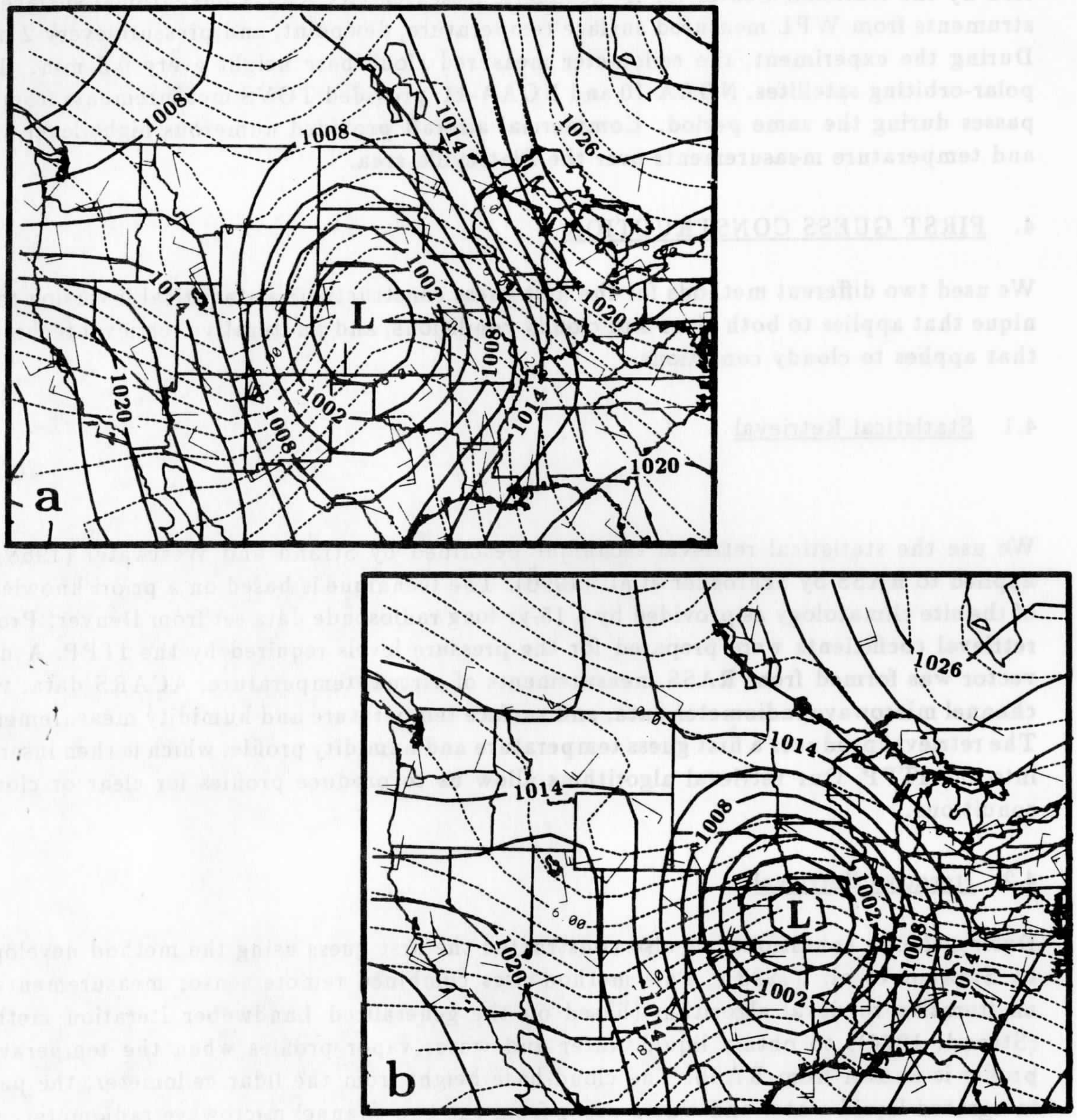


Fig. 4. Surface weather analysis for (a) 0045 UTC 12 March 1991 and (b) 1900 UTC 12 March 1991 (b). Dashed lines are temperature and solid lines are pressure.

that are provided by the ITPP. In addition, to get around the problem of the surface pressure not coinciding with the ITPP chosen pressure height, we arbitrarily set the surface pressure to the nearest pressure height. Since retrievals from the surface to the top of RASS are primarily gained from RASS, these assumptions have almost no effect on the final retrieval product.

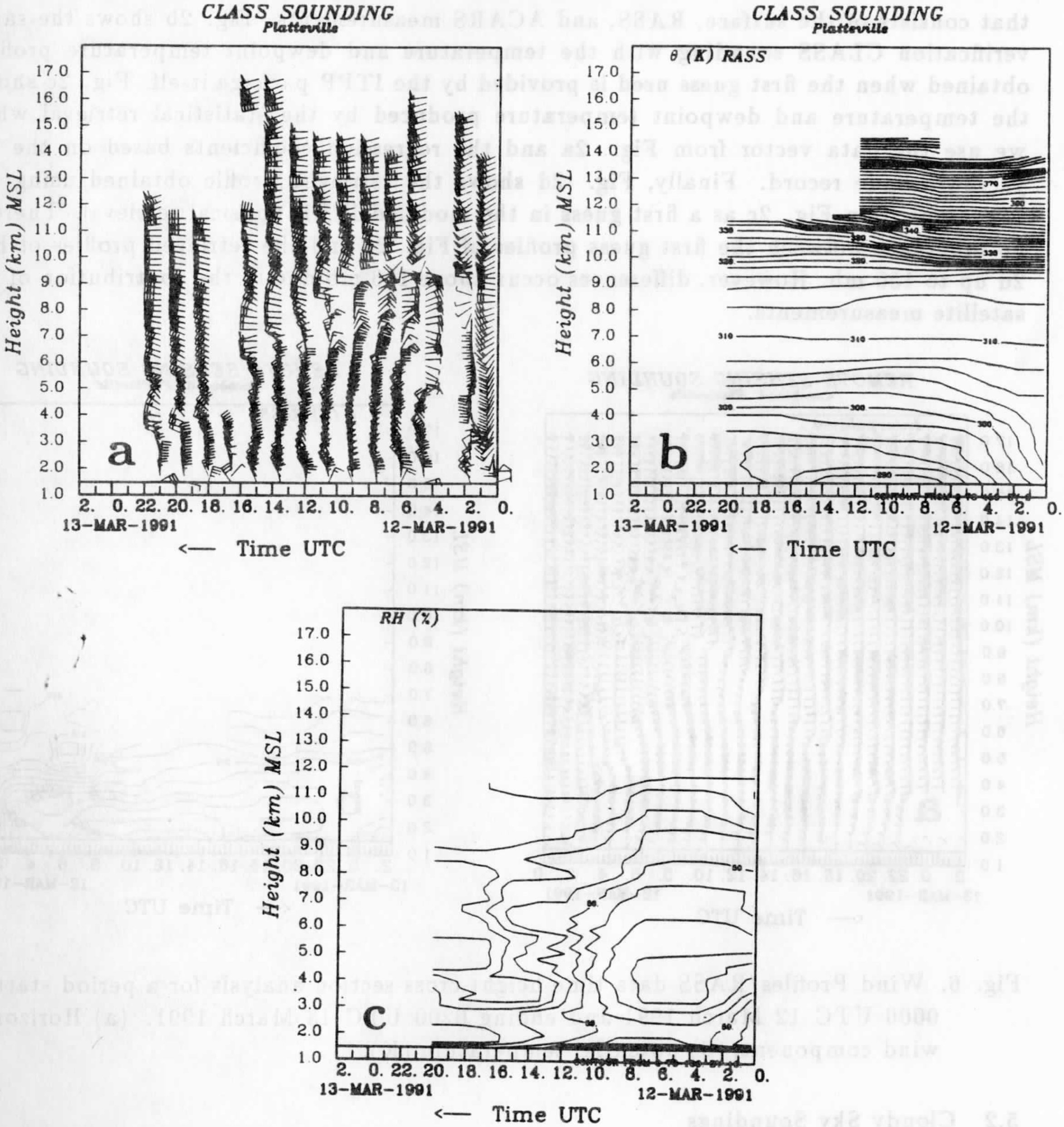


Fig. 5. CLASS radiosonde data time-height cross-section analysis for a period starting 0000 UTC 12 March 1991 and ending 0200 UTC 13 March 1991. (a) Horizontal wind component, (b) potential temperature (K), and (c) relative humidity.

5.1 Clear Sky Soundings

Fig. 2 shows a series of skew T-log P diagrams with different temperature and dewpoint temperature soundings. Fig. 2a shows a clear-air CLASS rawinsonde sounding of 12 March 1991 at 1930 UTC and the data vector used in the first-guess temperature construction that consists of the surface, RASS, and ACARS measurements. Fig. 2b shows the same verification CLASS sounding with the temperature and dewpoint temperature profiles obtained when the first guess used is provided by the ITPP package itself. Fig. 2c shows the temperature and dewpoint temperature produced by the statistical retrieval when we use the data vector from Fig. 2a and the regression coefficients based on the 15-yr rawinsonde record. Finally, Fig. 2d shows the retrieved profile obtained using the soundings from Fig. 2c as a first guess in the modified ITPP physical retrieval. There is no difference between the first guess profiles of Fig. 2c and the retrieved profiles of Fig. 2d up to 150 mb. However, differences occur above 150 mb due to the contribution of the satellite measurements.

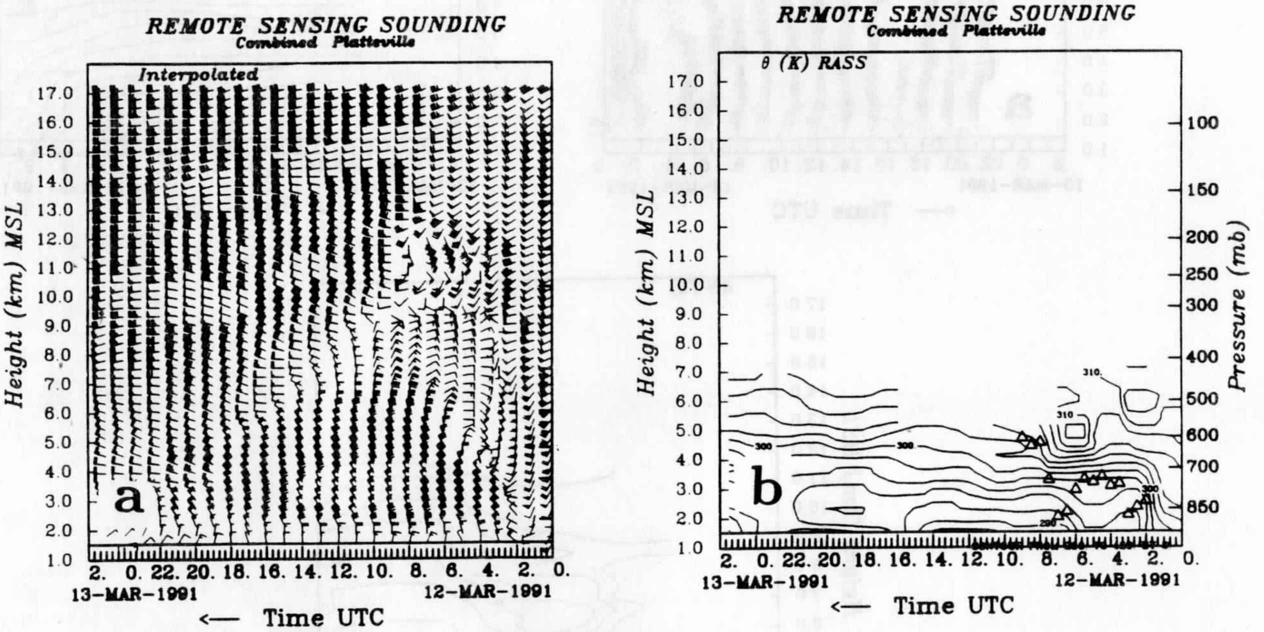


Fig. 6. Wind Profiles/RASS data time-height cross-section analysis for a period starting 0000 UTC 12 March 1991 and ending 0200 UTC 13 March 1991. (a) Horizontal wind component, (b) potential temperature (K).

5.2 Cloudy Sky Soundings

Figs. 3a, b, c, and d are analogous to Figs. 2a, b, c, and d, except that they show the 12 March 1991 0045 UTC sounding that was taken during cloudy conditions, and thus we used the appropriate regression coefficients. Again, the satellite contribution is noticeable

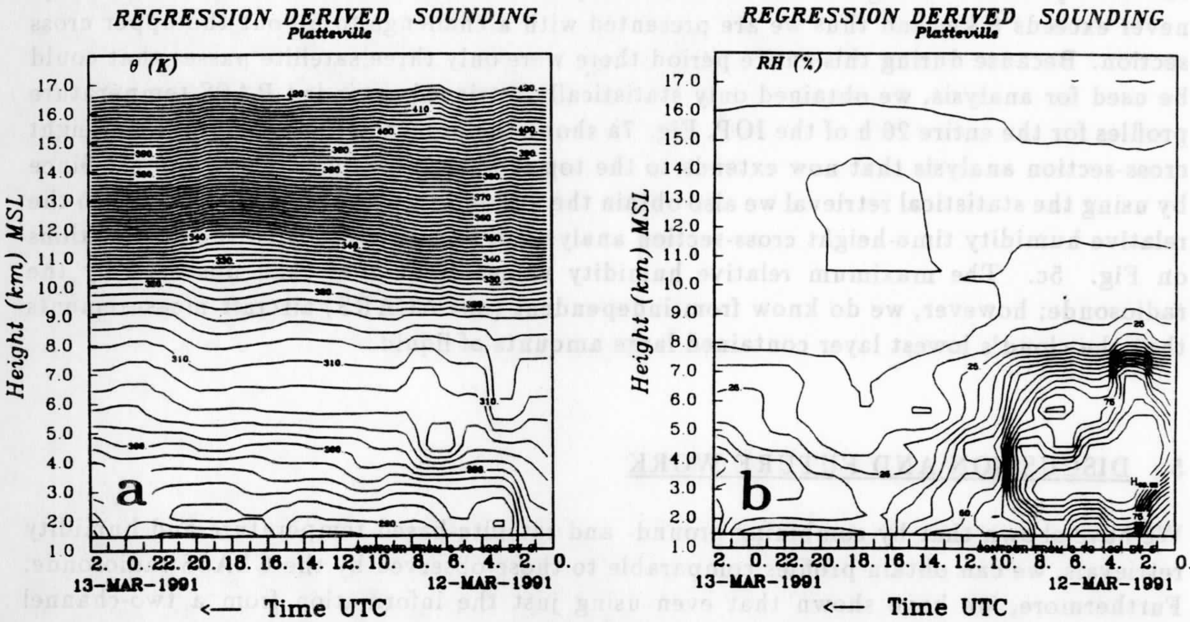


Fig. 7. Regression derived time-height cross-section analysis for a period starting 00:00 UTC 12 March 1991 and ending 02:00 UTC 13 March 1991 (a) potential temperature (K), (b) relative humidity.

only above 150 mb level, which is also where the satellite retrievals are most accurate. Fig. 3e shows the alternative first guess obtained by using the iterative retrieval and the additional knowledge of the cloud-base and cloud-top heights. Fig. 3f shows the retrieved temperature and dewpoint temperature after using the first guess from Fig. 3e in the modified ITPP code.

5.3 12 March 1991 Case

Figs. 4a and b show surface weather analysis at 0045 UTC and 1900 UTC 12 March 1991, i.e., at the beginning and the near the end of an intensive operating period (IOP) during WISP. A strong cold front passed through the Front Range from WNW to ESE between 0000 and 0300 UTC. The surface winds were gusting to 120 m s^{-1}, and a thunderstorm with lightning developed just behind the front. Fig. 4a shows a strong cyclogenesis at the surface just to the east of the Rockies, while the low pressure center of Fig. 4b has already moved to the Kansas-Missouri border. Fig. 5a, b, and c show the time-height cross-section analysis of the horizontal winds, potential temperature, and relative humidity as observed by the 14 CLASS radiosonde releases. The front passed through Platteville at 01:30 UTC as evidenced by the wind shift from southeasterly to northeasterly. The top of the thunderstorm is at 10 km MSL. The potential temperature shows a strong stable stratification at the top of the cold air and the relative humidity increased to 80% behind the front. Fig. 6a shows the time-height cross-section of the horizontal wind observed by the wind profiler and Fig. 6b shows the RASS potential temperature. The RASS coverage never exceeds 6 km and thus we are presented with a challenge to fill out the upper cross section. Because during this entire period there were only three satellite passes that could be used for analysis, we obtained only statistically retrieved extended RASS temperature profiles for the entire 26 h of the IOP. Fig. 7a shows the potential temperature time-height cross-section analysis that now extends to the top of the wind profiler observations. Since by using the statistical retrieval we also obtain the humidity profiles, we show in Fig. 7b the relative humidity time-height cross-section analysis to be compared with the observations on Fig. 5c. The maximum relative humidity values are higher than observed by the radiosonde; however, we do know from independent (not ACARS) aircraft measurements that the cloud's lowest layer contained large amounts of liquid.

5. DISCUSSION AND FUTURE WORK

We have shown that by combining ground- and satellite-based temperature and humidity retrievals, we can obtain profiles comparable to those observed by the CLASS radiosonde. Furthermore, we have shown that even using just the information from a two-channel microwave radiometer, ACARS, a 405 and a 50 MHz RASS, and surface observations, we can retrieve temperature and humidity profiles to the 100 mb level (comparable to the wind profiler height coverage) with high accuracy, good vertical resolution and good temporal resolution. In the future we will modify the ITPP so that we interpolate the radiative transfer equation to include the surface pressure level. After completing this, we will start obtaining temperature and humidity profiles in real time, using statistical retrieval only when no satellite data are available available, but incorporating each satellite pass into the analysis. In this way we hope to acquire statistics to evaluate the success of our method and to provide real-time profiles for evaluation by meteorologists.

There are currently three operating frequencies for RASS, and both the height resolution and the range of these systems differ substantially. Therefore, the accuracy of the retrievals obtained with each of these systems combined with TOVS should be evaluated. This is important because both the 915 and the 50 MHz systems will be used by the Department of Energy's Cloud and Radiation Test site (CART), the 405 MHz system will be used by NOAA's NWS, and the 915 MHz system may form a component of a WPL mobile facility.

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