Ground-Based Remote Sensing of Temperature Profiles by a Combination of Microwave Radiometry and Radar

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ABSTRACT

This paper describes the results of a three-week experiment in which ground-based microwave radiometric measurements were combined with VHF radar measurements of tropopause height to yield vertical temperature profiles. Several algorithms to derive tropopause height are presented and their results are compared with radiosondes. The best of the algorithms yields radar versus radiosonde rms differences of ~0.65 km. By the use of the combined radar–radiometric method, improvements were obtained in rms temperature accuracy of as much as 2.0 K rms over the pure radiometric technique.

1. Introduction

Research over the past several years shows that ground-based microwave radiometers can measure atmospheric temperature profiles from the surface to ~500 mb, under both clear and cloudy conditions (Yershov *et al.*, 1975; Decker *et al.*, 1978). Above 500 mb, retrievals are limited in accuracy because of exponentially decaying weighting functions. Recently, Westwater and Grody (1980) have shown theoretically that the addition of satellite radiance observations can substantially improve retrieval accuracy above 500 mb. In addition, they showed that measurements of tropopause height could further increase the accuracy of the combined radiometric systems, by as much as 1.0 K rms.

Using meter-length VHF radar, Gage and Green (1979) showed that it is possible to detect and to measure routinely the altitude of the tropopause. Our ground-based active–passive profiling system, as described by Hogg *et al.* (1980), contains a radar similar to that of Gage and Green and hence is also capable of tropopause monitoring.

Here, we present data obtained during a three week period in March 1980, in which radar measurements of tropopause height, ground-based microwave radiometric measurements, and radiosonde observations are available simultaneously. Our analysis of these data will 1) confirm that the radar can measure tropopause height and 2) demonstrate that radiometric retrieval accuracy can be significantly improved using the radar data.

2. The radiometric and radar equipment

The microwave radiometer and the VHF radar used in this study to jointly measure temperature profiles are parts of the NOAA Environmental Research Laboratories Profiler system designed to measure profiles of wind, temperature and moisture (Hogg *et al.*, 1980).

The six-channel microwave radiometer is colocated with the National Weather Service (NWS) radiosonde release facility at Stapleton International Airport, Denver, Colorado. The radiometer has channels at 20.6 and 31.65 GHz that are sensitive to water vapor and clouds, and four channels between 52 and 59 GHz in the oxygen absorption complex that sense atmospheric temperatures. All channels have equal antenna beamwidths of approximately 2.5° and observe radiation from the zenith. Adverse effects of precipitation are minimized by locating the antennas inside a building and pointing them horizontally through a low-loss window to a flat reflector aligned at 45° to the zenith. A cowling shields the window from rain.

Two-minute averages of the zenith radiation are recorded for further analysis. Although the Profiler operationally retrieves profiles every twenty minutes, in this paper we have used averages over one hour, which were chosen to correspond approximately with the time required for a radiosonde balloon to make a complete ascent.

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TABLE 1. Platteville radar system parameters.

Type	VHF, pulse-Doppler
Location	50 km north of Denver, CO
Antenna:	
type	Array of phased dipoles
area	10^4 m^2
beamwidth	~2° (two way)
Transmitter:	
frequency	49.92 MHz
peak power	~15 kW
pulse repetition frequency	625 Hz
pulse width	16 μs
range gate spacing	8 μs
Receiver:	
noise level	~3 dB
coherent integration	64 pulses

The VHF radar is located at the Platteville (Colorado) Radar Facility, located ~50 km north of Denver, and is operated jointly by the NOAA/Aeronomy Laboratory and the NOAA/Wave Propagation Laboratory. Although the primary purpose of the radar is to measure horizontal winds, during the month of March 1981 the radar was operated in the vertical sounding mode. Pertinent system parameters of this radar are listed in Table 1.

Power spectra were averaged for one minute before further processing. The noise level was then estimated and subtracted, following the method of Hildebrand and Sekhon (1974). The power density of the adjusted spectra was then integrated for a return power value. The range-gate spacing was set at 1.2 km, i.e., at one-half of the pulse width.

3. Radar identification of tropopause heights

The analysis of Gage and Green (1979), using the Sunset, Colorado radar showed that VHF radar systems are capable of routinely monitoring tropopause heights. Their subjective height determination was based on an examination of 1) backscattered power, which increased above the tropopause, 2) spectral width, which was smaller above the tropopause, and 3) anisotropy (enhancement of the backscattered power in echoes obtained at vertical incidence relative to that obtained at oblique incidence), which is greater above the tropopause. Here, we discuss and compare two objective algorithms for tropopause height determination.

a. Algorithms

The first class of algorithms developed for the Profiler system applies time series statistical tests to the reflectivity profiles recorded by the radar system. The identification of the tropopause is then derived by application of various threshold criteria as described below.

The Profiler operationally retrieves temperature profiles every 20 minutes; hence, the basic analysis interval for the radar also was chosen to be 20 minutes. Intensity records of return power were converted into a reflectivity (cross-section per unit volume) data array of time series records. In the time domain, each point represented a 1-min average, and in the vertical spatial domain, each point represented a 1.2 km range-gate sample. The range cells varied in height from 3.4 to 25.0 km. From the reflectivity array, two statistical quantities were calculated. The first of these quantities, the temporal variance $V(h_j)$ at height h_j, is given by

$$V(h_j) = (N_t - 1)^{-1} \sum_{i=1}^{N_t} [R(t_i, h_j) - \bar{R}(h_j)]^2, \quad (1)$$

where

$$\bar{R}(h_j) = N_t^{-1} \sum_{i=1}^{N_t} R(t_i, h_j). \quad (2)$$

In (1) and (2), $R(t_i, h_j)$ is the radar reflectivity at the height cell centered at h_j at the time t_i, and N_t is the number of time samples in the analysis interval. The second quantity we use is a scaled correlation function

$$C(t_i, h_j) = \sum_{k=i}^{i+3} [R(t_k, h_j)/\sigma(t_k)][R(t_{k+1}, h_j)/\sigma(t_{k+1})], \quad (3)$$

where

$$\sigma^2(t_k) = \frac{1}{N_R - 1} \sum_{i=1}^{N_R} [R(t_k, h_i) - \bar{R}(t_k)]^2, \quad (4)$$

$$\bar{R}(t_k) = \frac{1}{N_R} \sum_{i=1}^{N_R} R(t_k, h_i). \quad (5)$$

In (3), (4) and (5), N_R is the number of range cells and, by trial and error, we arrived at the 3-min time interval over which the covariances at 1-min lag were added. Because of the slow data rate of the radar (~1 Hz) relative to the rapidly changing (1–10 s) structural features of the turbulent medium (Röttger and Vincent, 1978), and because of some features of data processing, different records represent different circumstances. Hence, we "normalized" the cross-correlation function by dividing $R(t_k, h_j)$ by the average standard deviation $\sigma(t_k)$ of the range cells.

From the quantities in (1)–(5), we determined three different tests for tropopause height: the first was based on a straightforward examination of the average reflectivity profile. We chose the tropopause height h_{trop} as the first high-altitude range cell for which the average reflectivity (2) exceeded 10 dB. Call this the R method. The second test (the V method) determined h_{trop} as the first high-altitude range cell

TABLE 2. Comparison of various methods of tropopause height determination.

Method	Sample size	Radar average (km above sea level)	Radiosonde average (km above sea level)	Radar standard deviation (km)	Radiosonde standard deviation (km)	rms radar versus radiosonde (km)
R	32	11.04	10.86	1.06	1.04	0.72
V	30	11.37	10.86	1.04	1.02	0.85
C	32	11.52	10.93	1.08	1.15	0.94
RC	33	11.10	10.94	1.20	1.13	0.68
RV	32	11.04	10.86	1.06	1.04	0.72
CV	33	11.33	10.94	1.14	1.13	0.75
GG	30	11.21	11.03	1.00	1.11	0.65

for which the variance (1) exceeded 9 dB. Finally, the correlation (C) method determined h_{trop} from a conditional test involving both the peak in the variance profile and a predetermined threshold of the correlation function (3). After comparing each of these h_{trop} determinations with the ones obtained from NWS radiosondes, we determined that each of the three methods, on the average, overestimated h_{trop} (see Table 2). As a simple method of reducing this overestimation, we examined the use of the minimum of each of the three possible pairs (RC, RV, CV) as estimators. Of the statistical methods, the RC method gave the smallest rms error (see Section 3b).

The second algorithm (GG) used in the tropopause height determination was the objective method of Gage and Green (1982a). Here, the measured backscattered power profile is compared with the power profile calculated assuming a 2 K km^{-1} lapse rate. The height at which the two curves cross is an estimate of the tropopause. The use of this method requires a precisely calibrated radar, which the Platteville radar was not. Lack of calibration was circumvented here by matching, at tropopause altitudes, a single, measured reflectivity profile with a radiosonde-determined profile.

b. *Results*

During the last three weeks of March 1981, the Platteville radar was operated in the vertical sounding mode, and for much of this time, 20 min segments of data were available for analysis. We compared these measurements with the twice-a-day NWS radiosonde soundings at Stapleton Airport, Denver, Colorado, approximately 50 km to the south. Ideally, one could compare the radar sounding with that of the radiosonde when the balloon was in the vicinity of the tropopause. However, because of instances in which threshold criteria were not met, occasional gaps occurred in each of the radar determinations of tropopause height. To increase our data base for the comparison of both radar and radiometer data with radiosondes, we included as many radar measurements as were available from a 2-h interval centered about the radiosonde release time. Thus, we included from one to six measurements in each radar tropopause height determination. During the 33 measurement periods in which we were able to compare data, the radar measurement of tropopause height changed at most two resolution cells (on one occasion) during any 2-h analysis interval.

Fig. 1 shows the comparison of radar and radiosonde determination of h_{trop}. The results of two radar algorithms (RC and GG) generally agree well with the radiosonde; rms differences are ~0.7 km (see Table 2). In the three cases for which the radar tropopause differed by more than one radar resolution element from the radiosonde, there were levels on the temperature profile slightly failing to satisfy the conventional criteria for tropopause height; in two cases, the region in which the lapse rate fell below 2 K km^{-1} did not extend 2 km above the first critical level; in the third, the measured lapse rate was 2.07 K km^{-1}. On Fig. 1 these special cases, which occurred on day 70 1600 MST, day 71 0400 MST and on day 72 1600 MST, are labeled as pseudo-tropopause levels. Gage and Green (1979) also observed similar cases in which the radar responded to levels slightly failing to meet the conventional tropopause criteria.

4. Combined radar–radiometric temperature retrievals

a. *Retrieval algorithms*

We reconstructed temperature profiles from the radiometric data and from the combined radiometric–radar data by using linear statistical estimation (Westwater and Strand, 1968). Our method of generating *a priori* ensembles to represent clear and cloudy meteorological and radiometric data, from which retrieval coefficients are calculated, is described by Decker *et al.* (1978). For the pure radiometric retrievals, we derived coefficients for use in March, from six years of NWS radiosonde soundings (1972–77) taken during February, March and April at Denver, Colorado. These coefficients [$c_i(h)$, $i = 0, 1, 2, \ldots, 9$] are then combined with a nine-component data vector (d_i, $i = 1, 2, \ldots, 9$) to yield the temperature estimate $\hat{T}(h)$ at height h

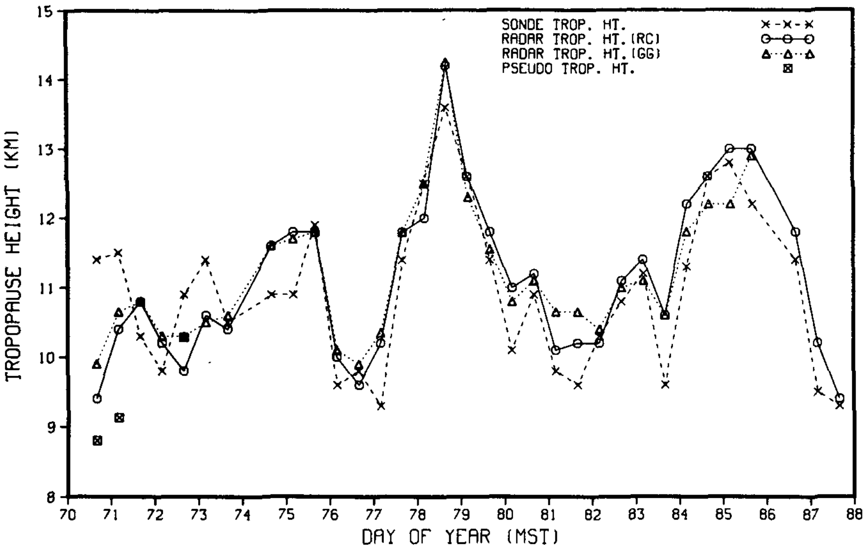

FIG. 1. Radar versus radiosonde measurements of tropopause height. RC refers to the reflectivity–correlation method and GG refers to the Gage-Green method (see text for details).

$$\hat{T}(h) = c_0(h) + \sum_{i=1}^{9} c_i(h)d_i. \qquad (6)$$

The data vector consisted of brightness temperatures at 52.85, 53.85, 55.45 and 58.8 GHz, optical depths (derived from brightness temperatures at 20.6 and 31.65 GHz), and surface observations of pressure, temperature and relative humidity.

The retrieval method of Westwater and Grody (1980) was used to combine the radar measurement of tropopause height h_T, with the radiometric measurements, and is described below. Initially, a large collection of profiles is decomposed into subsets whose members contain tropopause coordinates P_{trop} within a certain pressure interval Δ_{trop}. For example, a typical subset might contain profiles whose tropopause pressure is between 200 and 240 mb. For each of these subsets, statistical retrieval coefficients are calculated. If we have a radar measurement of h_{trop}, we first convert it to a pressure P_{trop} using the hydrostatic equation and the unconstrained retrieval. Then, using P_{trop} as a reference level, we use coefficients that were calculated from the ensemble of profiles whose tropopause pressure differed at most $\Delta_{\mathrm{trop}}/2$ from P_{trop}. For the work performed here, we choose Δ_{trop} to be 40 mb, a value consistent with the 1.2 km sampling interval of the Platteville radar. The original ensemble, from which the restricted subsets were selected, contained all NWS radiosonde soundings at Denver during January–July (1972–77). The sample sizes of the tropopause classes ranged from a minimum of 178 to a maximum of 1327 profiles.

b. Results

For the 18 day period in which the Platteville radar was operating, we succeeded in obtaining 21 triplets of radar, radiometric and radiosonde data. The missing data intervals were caused, for the most part, by computer failures in the radiometric system. Although the sample size was small, it was deemed sufficiently large to demonstrate the potential of the technique, although, clearly, a much more extensive data base is required to thoroughly evaluate the accuracy of the method.

Typical results are shown in Fig. 2, in which both radiometric and combined radar–radiometric temperature retrievals are compared with the NWS radiosonde sounding. Note that, in addition to the substantial improvement of the combined retrievals in the vicinity of the tropopause, some improvement in retrieval accuracy is also achieved in the lower atmosphere. Such nonlocal improvement in accuracy due to the imposition of local constraints occurs frequently when statistical retrieval methods are used.

It was mentioned in Section 3 that three cases occurred in which the radar tropopause measurement differed substantially from that of the radiosonde. In one of these cases, radiometric data also were available; the corresponding retrieval using the RC method is shown in Fig. 3a. For this case, the RC determination was 1.1 km below the radiosonde tropopause. Note that both the pure radiometric and the combined retrieval are accurate below ~9.8 km, but that they are degraded above this altitude. This level is near the height at which the radar measured the change in temperature gradient that almost satisfied the tropopause criteria (see Section 3). If the radiosonde tropopause measurement is inserted into the retrieval algorithm, the combined retrieval shown in Fig. 3b is obtained. It is apparent that considerable error in this case was introduced by the mis-identification of the tropopause. We mention that for this time (day 72, 1600 MST) the GG tropopause deter-

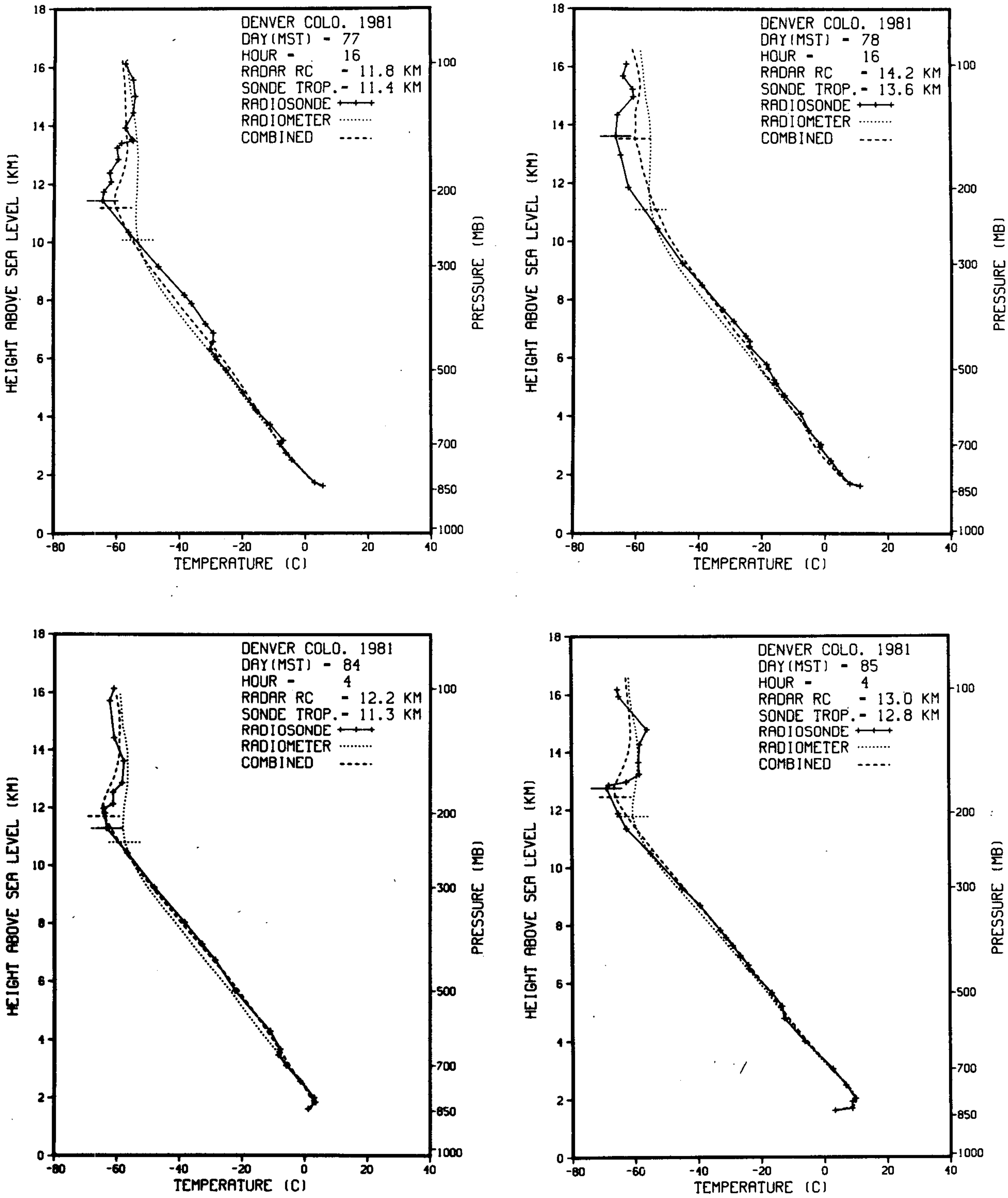

FIG. 2. Typical comparisons of temperature profiles, for four different days retrieved from radiometric and from combined radar-radiometric techniques with NWS radiosondes. Tropopause heights, as determined from the NWS definition, are indicated by horizontal lines on the appropriate profiles.

mination was 10.3 km, ~0.6 km below the radiosonde tropopause. The corresponding temperature retrieval (not shown) was almost identical to the pure radiometric one.

The statistical evaluation of our results is shown in Fig. 4. Here, we show the rms differences of the combined radar-radiometric retrieval (using the RC method) versus radiosonde, and the pure radiometric

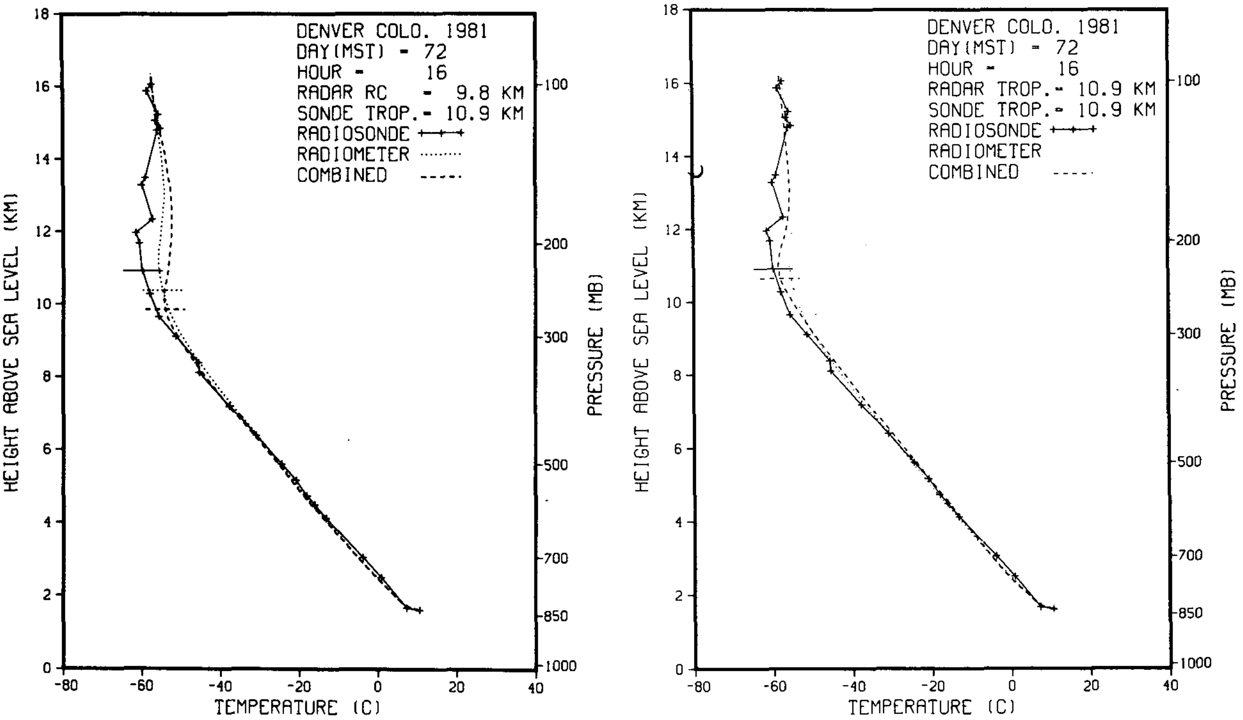

FIG. 3. Examples of temperature retrieval when (a) tropopause measurement is 1.5 km in error, and (b) tropopause height is known exactly.

retrieval versus the radiosonde. As a baseline value, we also show the combined case, when the radiosonde-measured tropopause is used as an exact measurement (with 40-mb resolution). The near coincidence of the combined retrievals using both the measured and the exact tropopause height indicates that the assumed 40-mb resolution was broad enough to minimize the effect of measurement errors, but was narrow enough to allow considerable improvement in accuracy. Note that in the region from 500 to 100 mb, a substantial improvement in accuracy is achieved; at some levels it is as much as 2°C rms. This amount of improvement is somewhat larger than the theoretical error estimates of Westwater and Grody (1980). Accuracy statistics were also computed using the GG height determination. As might be expected, the rms error profile was very close to that of the RC method shown in Fig. 4.

We also estimated the information content of each part of the combined system by comparing the rms retrieval errors of each component with the rms differences about the *a priori* climatological mean. In Fig. 5 we show the rms difference in temperatures between the radiosondes and 1) the *a priori* mean profile, 2) the *a priori* mean profile conditional on the radar measurement of tropopause height, 3) profiles retrieved from the radiometric data only, and 4) the combined radar–radiometric retrievals using the RC algorithm. The figure shows that use of the tropopause height alone as a predictor results in improved retrieval accuracies at all altitudes above 700 mb and the improvement is as much as 2 K in the tropopause region. The interaction of the radiometric and the tropopause height information results in a retrieval accuracy improvement over that of each separate system from approximately 600 to 200 mb. Above 200 mb, retrieval accuracy is almost entirely from the radar information. Finally, the combined system yields an accuracy that is a substantial improvement over climatology at every level we evaluated.

5. Discussion

The experimental results presented in Section 4, show that ground-based radiometric temperature retrievals are substantially improved by radar measurements of tropopause height. These results confirm earlier theoretical predictions by Westwater and Grody (1980) that these height measurements can improve retrieval accuracy over a broad vertical region not necessarily confined to the immediate vicinity of the tropopause.

In one case in which both radar and radiometric data were available, the radar was sensitive to sharp changes in the temperature gradient that came close to satisfying, but did not completely satisfy, the definition of tropopause height. In this situation, the inferred height was 1.1 km less than the "true" tropopause and, as a consequence, the combined radar–

radiometric retrieval was less accurate than that of the radiometer alone. However, as shown in Fig. 4, with the relatively modest 40 mb radar resolution, the overall effect of height misidentification was not large.

The combined radar–radiometric technique might be improved in several ways. One promising idea was suggested by Gage and Green (1982b). They presented a technique for directly determining the temperature gradient above the tropopause from radar reflectivity measurements. This technique, coupled with radiometric measurements, could potentially yield a high-resolution profile retrieval. It is also expected that the addition of satellite soundings would substantially improve upper altitude results. The experimental evaluation of the combined satellite–ground-based techniques is now under way.

It is not at all unreasonable to expect that the radar resolution could be improved by a factor of 2 to 4. The result of this improvement on retrieval accuracy has not been evaluated, but some improvement would be expected.

Construction of a UHF radar is now nearing completion at Stapleton Airport, Denver, Colorado, as a component of the Profiler system (Hogg *et al.*, 1980). The UHF radar, with its 100-m resolution, will form the low-altitude complement of the high-altitude, coarser-resolution radar still operating at Platteville, Colorado. In particular, the UHF radar should be able to identify significant features of the temperature profile below 500 mb, such as the heights of nocturnal and elevated thermal inversions. As suggested by Westwater (1978), knowledge of these heights can significantly improve low-altitude profile retrievals, a technique that was illustrated here in the case of tropopause heights. Thus, it seems promising that a combined ground-based radar-radiometric system can accurately determine temperature profiles from the surface to perhaps 100 mb.

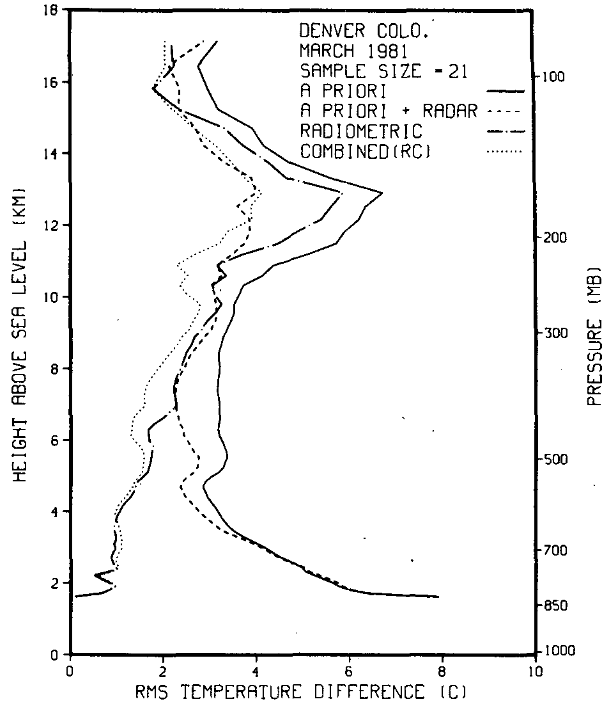

FIG. 5. rms comparisons of radiosonde temperatures with profiles inferred from: (a) *a priori* climatology, (b) *a priori* climatology plus radar measurements of tropopause height using the RC algorithm, (c) the ground-based radiometer, and (d) the radiometer and radar combined.

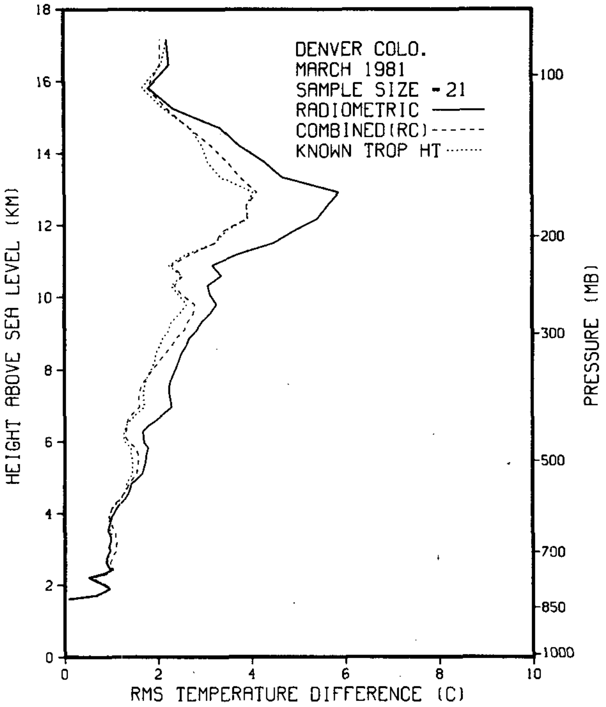

FIG. 4. rms comparisons of radiosonde temperatures with profiles inferred from a radiometer, a combined radar–radiometer, and a radiometer with exactly known tropopause height.

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REFERENCES

Decker, M. T., E. R. Westwater and F. O. Guiraud, 1978: Experimental evaluation of ground-based microwave radiometric sensing of atmospheric temperature and water vapor profiles. *J. Appl. Meteor.*, **17**, 1788–1795.

Gage, K. S., and J. L. Green, 1979: Tropopause detection by partial specular reflection with very-high-frequency radar. *Science*, **203**, 1238–1239.

——, and ——, 1982a: An objective method for the determination of tropopause height from VHF radar observations. *J. Appl. Meteor.*, **21**, 1150–1151.

——, and ——, 1982b: A technique for determining the temperature profile from VHF radar observations. *J. Appl. Meteor.*, **21,** 1146–1149.

Hildebrand, P. H., and R. S. Sekhon, 1974: Objective determination of the noise level in Doppler spectra. *J. Appl. Meteor.*, **13,** 808–811.

Hogg, D. C., C. G. Little, M. T. Decker, F. O. Guiraud, R. G. Strauch and E. R. Westwater, 1980: Design of a ground-based remote sensing system using radio wavelengths to profile lower atmospheric winds, temperature and humidity. *Remote Sensing of Oceans and Atmospheres*, A. Deepak, Ed., Academic Press, 313–364.

Röttger, J., and R. A. Vincent, 1978: VHF radar studies of tropospheric velocities and irregularities using spaced antenna techniques. *Geophys. Res. Lett.*, **5,** 917–920.

Westwater, E. R., 1978: Improved determination of vertical temperature profiles of the atmosphere by a combination of radiometric and active ground-based remote sensors. *Preprints Fourth Symp. on Meteorological Observation and Instrumentation*, Denver, Amer. Meteor. Soc., 153–157.

——, and O. N. Strand, 1968: Statistical information content of radiation measurements used in indirect sensing. *J. Atmos. Sci.*, **25,** 750–758.

——, and N. C. Grody, 1980: Combined surface- and satellite-based microwave temperature profile retrieval. *J. Appl. Meteor.*, **19,** 1438–1444.

Yershov, A. T., Yu. V. Lebskiy, A. P. Naumov and V. M. Plechkov, 1975: Determination of the vertical temperature profile from ground-based measurements of the atmospheric radiation at $\lambda = 5$ mm. *Izv. Acad. Sci. USSR, Atmos. Ocean. Phys.*, **11,** 1220–1229.