Determination of Atmospheric Temperature Profiles from a Statistical Combination of Ground-Based Profiler and Operational NOAA 6/7 Satellite Retrievals

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ABSTRACT

Radiometric soundings from the Wave Propagation Laboratory's ground-based Profiler, the NOAA 6/7 satellites, and the combination of the two, were compared in their ability to derive temperature and moisture profiles. Radiosonde data for the period December 1981–December 1982, taken by the National Weather Service at Stapleton International Airport, Denver, Colorado, were used as "ground-truth" for the comparison; in all, 460 soundings were analyzed. The set of soundings contained 216 clear, 173 partly cloudy and 71 cloudy cases. Comparisons show that Profiler retrievals were more accurate than those of the satellite in the lowest 500 mb of the atmosphere, with the converse being true above that level. The combined temperature retrievals were more accurate, in the rms sense, than either of the separate retrievals at every level from the surface to 10 mb. Below 50 mb, the maximum rms difference of the combined system from radiosondes was 2.7 K; below 300 mb, it was 2.0 K. Geopotential heights and pressure thicknesses were also derived from the combined system with an accuracy approaching that of a radiosonde.

1. Introduction

In developing operational systems to sound the atmosphere, it is difficult to design a single system operating from a given platform that will satisfy all user requirements. To satisfy requirements of synoptic observation, for example, radiometric soundings of temperature profiles from orbiting satellites yield excellent horizontal coverage and modest vertical resolution, but at asynoptic times and with a degrading accuracy both during cloudy conditions and near the earth's surface (Phillips *et al.*, 1979). Conversely, a ground-based observing system, such as the radiometric Profiler (Hogg *et al.*, 1983), can provide measurements continuously in time, and with good vertical resolution near the surface, but with an accuracy that is poor above 500 mb, and with no horizontal coverage at all. To eliminate some of the difficulties of a single-platform observing system, Little (1982) suggested placing a network of profilers at carefully selected locations across the United States, and interpolating observations between grid points with satellite data, such as those from VAS (Smith *et al.*, 1981) or from TIROS-N (Phillips *et al.*, 1979). To evaluate such a plan, data are needed to determine the single station accuracy that can be achieved by a combined satellite-Profiler system. Estimates of this accuracy for a purely microwave system were made by Westwater and Grody (1980).

We present here an analysis of the temperature and moisture retrieval accuracy achieved at Denver during 1982 by each of three systems: 1) the ground-based Profiler, 2) the NOAA 6/7 satellites, and 3) the combination of 1) and 2). Because Denver is close to the Rocky Mountains and has an average surface pressure of ~835 mb, its meteorology represents a severe challenge to satellite observing systems, and because of a wide variety of temperature profiles, is also a challenge for the Profiler. Nevertheless, we present accuracies of some observables inferred by the combined system, notably pressure heights, that compare favorably with those measured by a radiosonde.

2. Operational temperature and moisture retrievals for NOAA 6/7 satellites

Most of the steps that are required to convert measurements of radiance from satellite instruments to profiles of temperature and moisture are described in detail in other documents (Smith *et al.*, 1979; Phillips *et al.*). Measurements are obtained from the three instruments that constitute the TOVS (TIROS-N Operational Vertical Sounder) system. The main tropospheric instrument is the 20 channel HIRS, which consists of seven temperature sounding channels in the 15 μm region, five more temperature sounding channels in the 4.3 μm region, one ozone channel at 9.7 μm, three window channels at 11.1, 4.0, and 3.7 μm, three water vapor channels at 8.3, 7.3, and 6.7 μm, and one visible channel. This instrument is supplemented in the stratosphere with the Stratospheric Sounding Unit (SSU), a three channel instrument that uses a pressure modulation technique to measure the upper atmosphere. The HIRS is also supplemented by a Microwave Sounding Unit (MSU) to help eliminate the effects of clouds and to provide a limited sounding capability in overcast regions. The MSU is a four channel instrument consisting of a window channel and three atmospheric channels. An excellent summary of the instruments is given in Table 1 of Smith *et al.*, and Schwalb (1978) gives a complete description of the unit.

When the data are received, locations based on the satellite orbit are assigned and the data are calibrated. Adjustments are subsequently made for the change in radiance with angle, the water vapor attenuation in the window channel, and surface emittance and diffraction effects in the microwave. Smith *et al.* describe the flow of data through the programs, and Phillips *et al.* provide additional information.

These straightforward processing procedures are followed by complex data processing algorithms which are required for soundings under cloudy conditions. Because radiation in the infrared region does not penetrate clouds, the radiation in a cloudy area is not representative of the region below the clouds. Therefore, the program first attempts to determine which areas are clear by using various tests such as those based on known clear-air statistical relationships between channels. If cloud-free areas are not found, an attempt is made to extract clear radiances from partly cloudy values. In this process, the fact that microwave radiances are relatively unaffected by most clouds is used. If clear infrared radiances cannot be extracted, an attempt is made to produce a retrieval using only the microwave radiances. Finally, no retrievals are made if the tests for good retrievals fail. A detailed description of the entire procedure is given by McMillin and Dean (1982). Once cloud-free radiances are obtained, they are converted to brightness temperatures from which temperature profiles are determined by using the eigenvector regression described by Smith and Woolf (1976). Regression coefficients for the latitude zone containing Denver are updated weekly using colocated radiosonde data uniformly distributed over the past two weeks. Coefficients are then usesd for the following week resulting in an average time lag of about 1½ weeks.

3. Profiler temperature and moisture retrievals

The Profiler is a prototype ground-based remote sensing system composed of: a six channel microwave radiometer; surface instruments to measure pressure *P*, temperature *T*, relative humidity *RH*, wind, and rain rate; a wind-profiling Doppler radar operating in the VHF (50 MHz); another wind-profiling radar operating at UHF frequencies (915 MHz); a data system, including a host computer that provides an accessible data base and auto-dial equipment. This system and its initial results are extensively described by Hogg *et al.* We briefly describe here the radiometric portion of the Profiler and the details of its processing that are relevant to the satellite and radiosonde comparison.

The Profiler, located at Stapleton International Airport in Denver is less than 100 m from the National Weather Service (NWS) radiosonde launch site. The Profiler's six-channel radiometer has two channels operating at 20.6 and 31.65 GHz and four channels between 50 and 60 GHz. The two lower channels are used to derive precipitable water and cloud liquid and also provide corrections for these variables to the 50–60 GHz temperature channels. Data from the six channels, supplemented with surface measurements of *P*, *T*, and *RH*, are converted to profiles of temperature and humidity by means of a linear statistical inversion procedure (Strand and Westwater, 1968). The method differs from that used to process the operational NOAA 6/7 soundings (see Sec. 2); it uses *a priori* calculations of brightness temperatures and estimated instrumental noise levels to produce profile retrieval coefficients. Different coefficients are used for each month which were derived from six years of Denver radiosonde data (1972–77).

Although 2 min samples of profile retrievals are derived and archived, we use 20 min averages for comparison with the satellite and radiosonde data. For the satellite comparison we use the 20 min period centered at the time of satellite overflight; for the sonde comparison, we use the average starting at the time of radiosonde release.

The data processing for the Profiler eliminates strong cloud and rain effects by rejecting data for which the 31 GHz brightness temperature exceeds 100 K. This threshold was exceeded for 3 of the 460 cases we analyze in Sec. 4–6. In these three cases, we replaced the deleted data with those from another 20 min period within ±1 h of radiosonde launch time. For all other data, no additional processing was necessary.

4. Comparison of Profiler and NOAA 6/7 operational retrievals with radiosondes

To form our data base to compare Profiler and satellite remote soundings, we obtained operational NOAA 6/7 temperature and moisture retrievals near the Denver area. These soundings were restricted to be within ±3 h from 0000 or 1200 GMT and to fall within an area −0.5 to +1.0°N and 0.0 to +2.0°E of the joint NWS—Profiler site at 39°46′N, 104°53′W. The area included the plains east and north of Denver and excluded all of the Rocky Mountains. The set of 460 soundings that we were able to compare contained 216 clear, 173 partly cloudy and 71 cloudy satellite retrievals.

The NOAA operational retrievals of temperature and moisture at 40 fixed standard pressure levels are integrated above some reference pressure level P_r to derive geopotential heights. Although satellites do not measure surface pressure P_s directly, the range of values of P_s is known approximately from surface topography, and hence P_r is chosen to be less than P_s. Some of our retrieval comparisons require geopotential heights above sea level. To convert the satellite retrievals to these coordinates, we used the radiosonde measurement of P_s, the value of P_r, and a simple interpolation algorithm to achieve this transformation.

Because of the continuity in time of the Profiler, we could compare its soundings with the radiosonde both

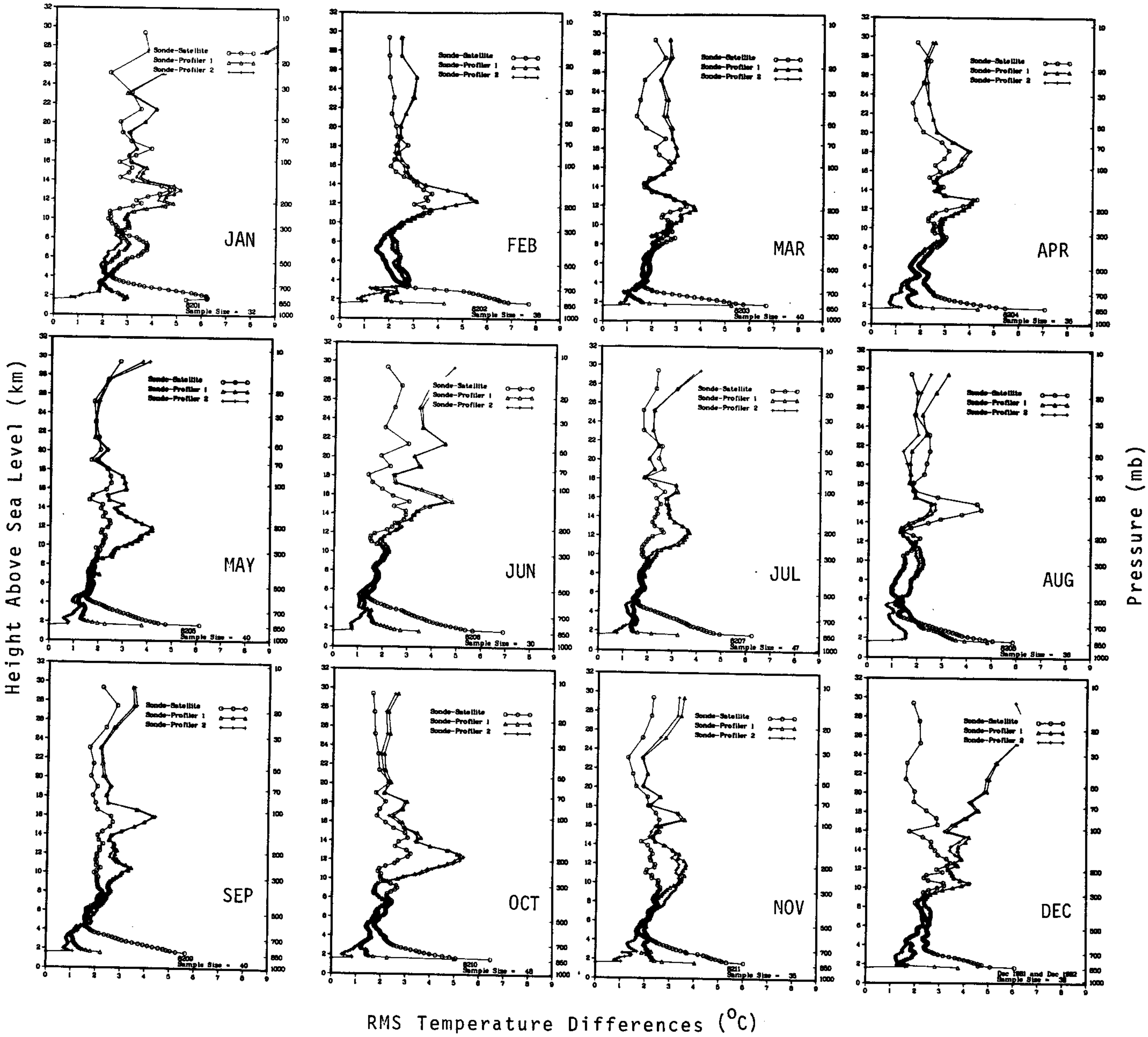

FIG. 1. Monthly statistics of rms temperature differences between National Weather Service radiosondes at Denver and operational NOAA 6/7 satellites retrievals (circles), Profiler retrievals, evaluated at time of satellite overflight (triangles), and Profiler retrievals, evaluated at time of radiosonde release (crosses).

at the radiosonde release time and at the time of the satellite overflight. In Fig. 1, we show the monthly rms statistics of 1) radiosonde–satellite, 2) radiosonde–Profiler (evaluated at satellite time), and 3) radiosonde–Profiler (evaluated at radiosonde time). We note immediately that due to the time differences there are substantial differences in Profiler comparison curves 2) and 3) from the surface to 700 mb and at times noticeable differences from the surface to about 500 mb. Thus, by implication, a considerable portion of the satellite–radiosonde differences in the lowest 150 mb above the surface is due to time differences. We also note that in general, below 500 mb the Profiler is more accurate than the satellite and that the converse is true above this level. The rms differences for the entire data set are shown in Fig. 2. In all further comparisons, we will use only the Profiler data at the radiosonde time.

As discussed in Section 2, the NOAA 6/7 satellites operational retrievals are based on regression techniques. These retrieval coefficients are derived from a collection of radiosonde–satellite pairs gathered globally over a given latitude band. However, soundings over an area of high elevation such as Denver are subject to an error in the lower levels. This error occurs because most of the matches of radiosondes and satellite data that are used to generate regression coefficients are obtained over lower elevations and the radiances are representative of a typical lapse rate between 1000 and 850 mb. Over Denver, the radiances represent a surface that is equivalent to a constant temperature layer between 1000 and 850 mb whose temperature is the 850 mb surface temperature. The retrieval cannot change enough from the expected case so it makes the retrieval at 1000 mb (which really is not made) too warm and the retrieval near 850 mb too cold to compensate. The net result is a cold bias at 850 mb which decreases with height. A nonuniform distribution of temporal differences between satellite overflights and radiosonde releases also contributes to the (apparent) bias. Conversely, since the Profiler retrieval coefficients were constructed from local climatological data, bias effects, at least at lower altitudes, should be minimized. Evidence of these qualitative considerations is shown in Figs. 3 and 4, which show the mean and rms differences in temperature between the radiosonde and the satellite retrievals, and between the radiosonde and the Profiler retrievals, respectively. The satellite retrievals below ~700 mb always exhibit a cold bias with a magnitude typically around 3°C. Above this altitude, except for two or three minor exceptions, the satellite retrieval bias is confined to ±1°C. On the other hand, the bias in Profiler retrievals is generally between ±1°C up to about 200 mb, but above this altitude the bias and the retrieval error increase substantially. Above ~200 mb, the Profiler retrievals are very much influenced by climatology, and hence, if there is a dramatic change from the climatological average, the Profiler retrievals will not reflect it. For the three months in which large stratospheric biases did appear in the retrievals (December, January and June), the monthly averages deviated significantly from the *a priori* means. We also show the yearly composite mean and rms temperature statistics in Fig. 5.

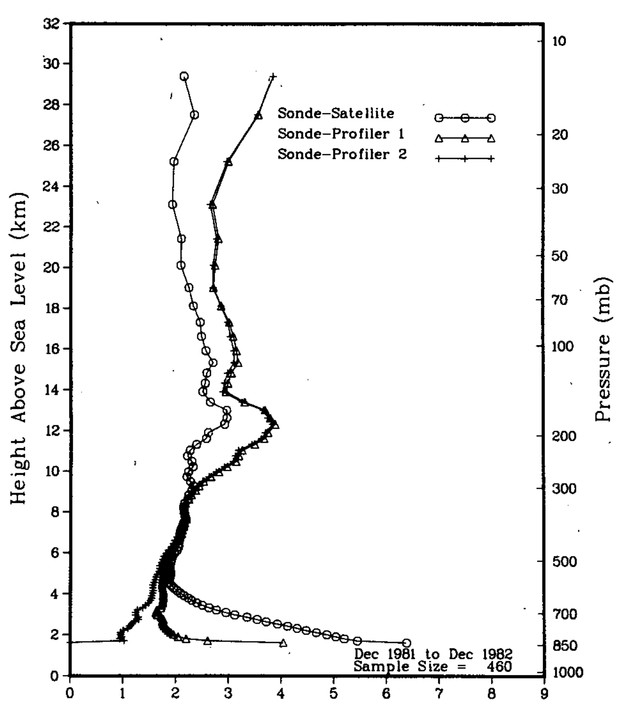

FIG. 2. Composite statistics of rms temperature differences between radiosondes and NOAA 6/7 satellites and Profiler temperature retrievals. Same notation as Fig. 1.

We performed similar comparisons of Profiler and satellite retrievals of water vapor, but for brevity, will only show the yearly composite statistics for this parameter (see Fig. 6). Since satellite operational retrievals of vapor are not given for the so-called "cloudy" retrieval case the original sample size was reduced from 460 to 389. The Profiler vapor retrievals are about a factor of 2 better in the rms sense, than those of the satellite. This occurs because the Profiler has 1) the advantage of surface meteorological measurements, and 2) water channels that are viewing cold space and are not affected by changing surface conditions. Not shown in the figure are small biases that appeared in the monthly Profiler water vapor statistics. These biases seem to be due to our inability to calculate water vapor absorption exactly at 20.6 and 31.65 GHz (Hogg *et al.*, 1983).

5. Method of combining satellite and Profiler retrievals

We have observed that the ground-based Profiler temperature retrievals approximate the radiosonde

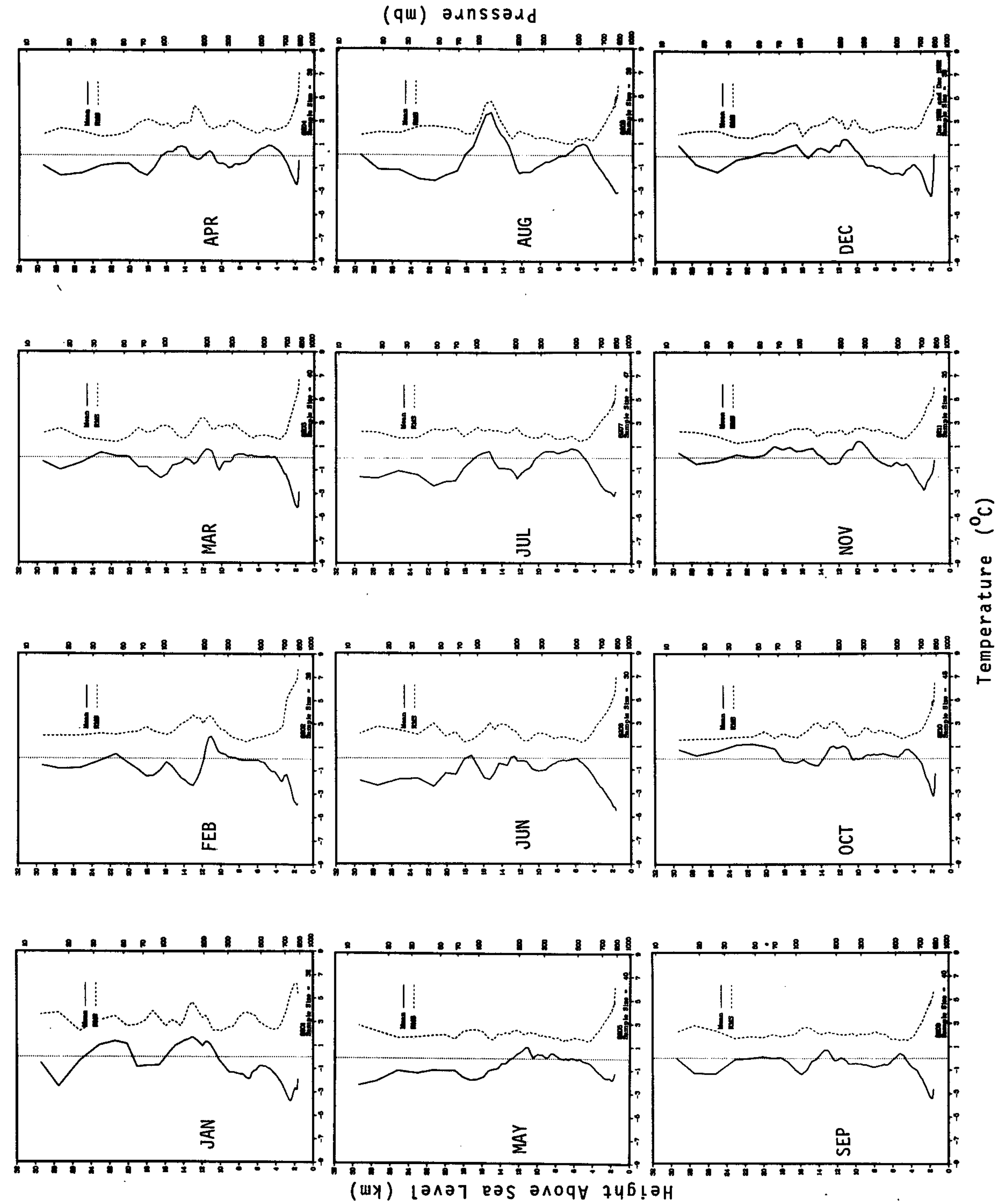

FIG. 3. Monthly statistics of mean and rms differences with radiosondes of NOAA 6/7 satellites operational temperature retrievals over Denver.

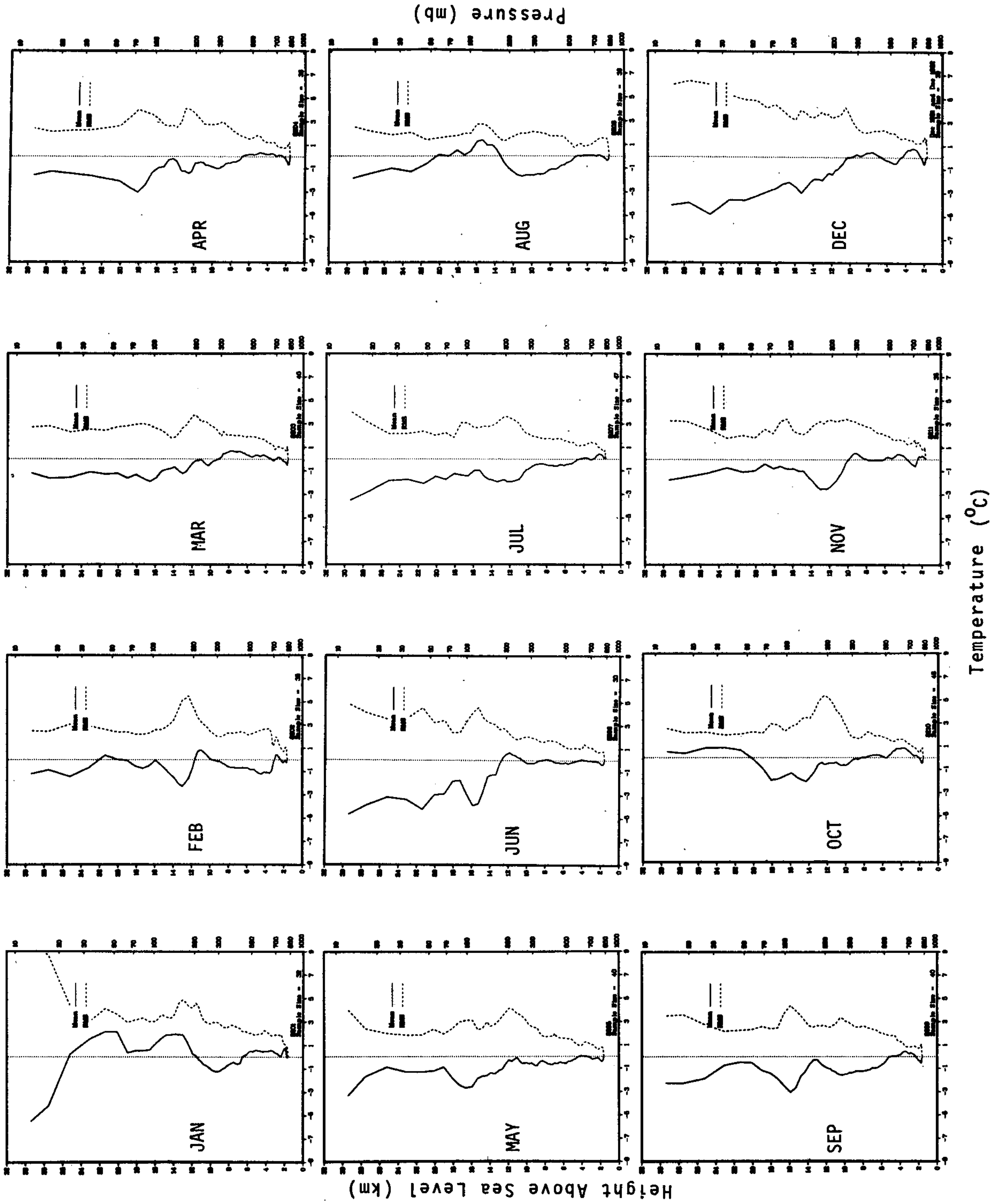

FIG. 4. Monthly statistics of mean and rms differences with radiosondes of Profiler temperature retrievals at Denver.

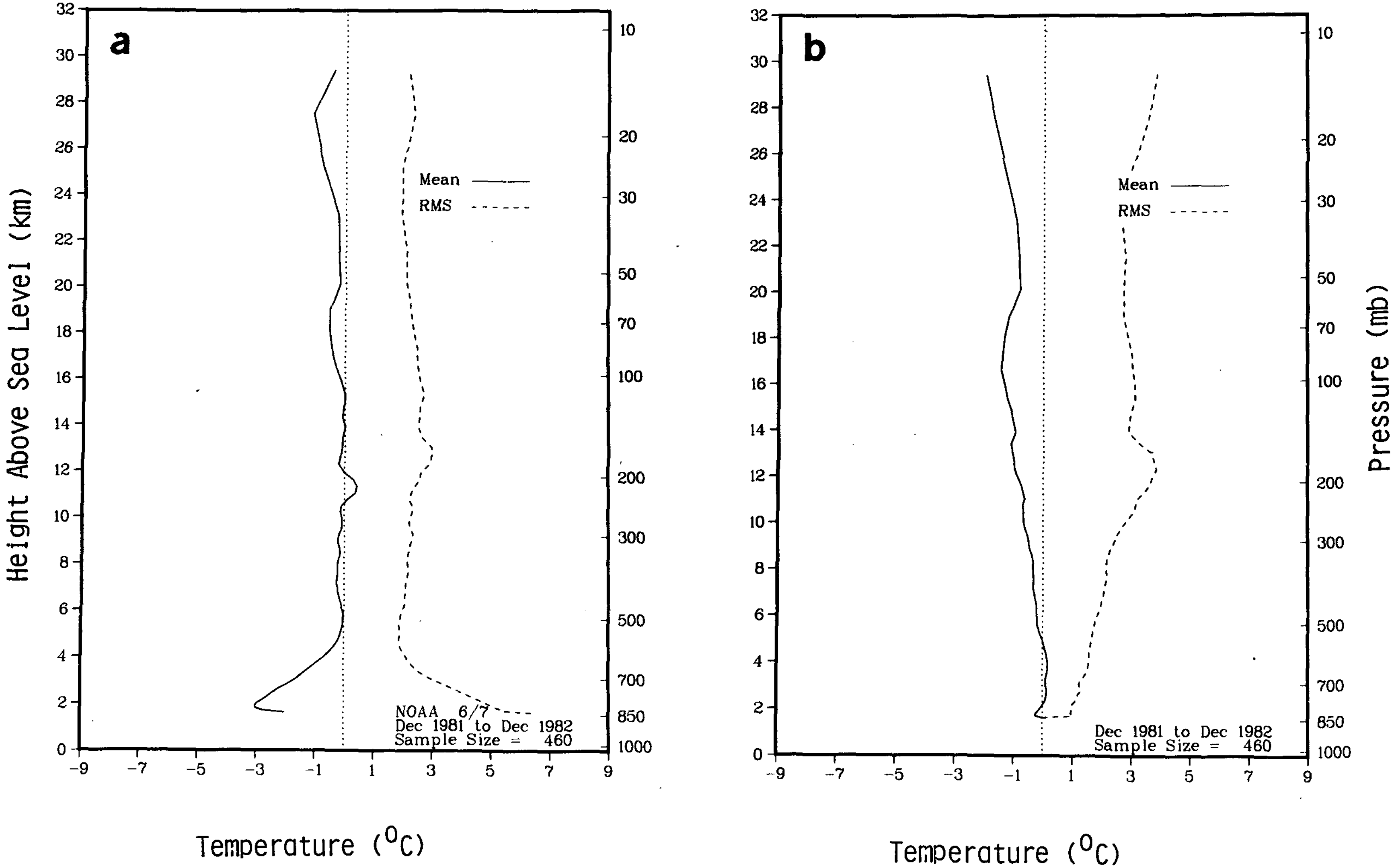

FIG. 5. Composite statistics of mean and rms differences with radiosondes of (a) NOAA 6/7 satellites operational temperature retrievals and (b) Profiler temperature retrievals at Denver.

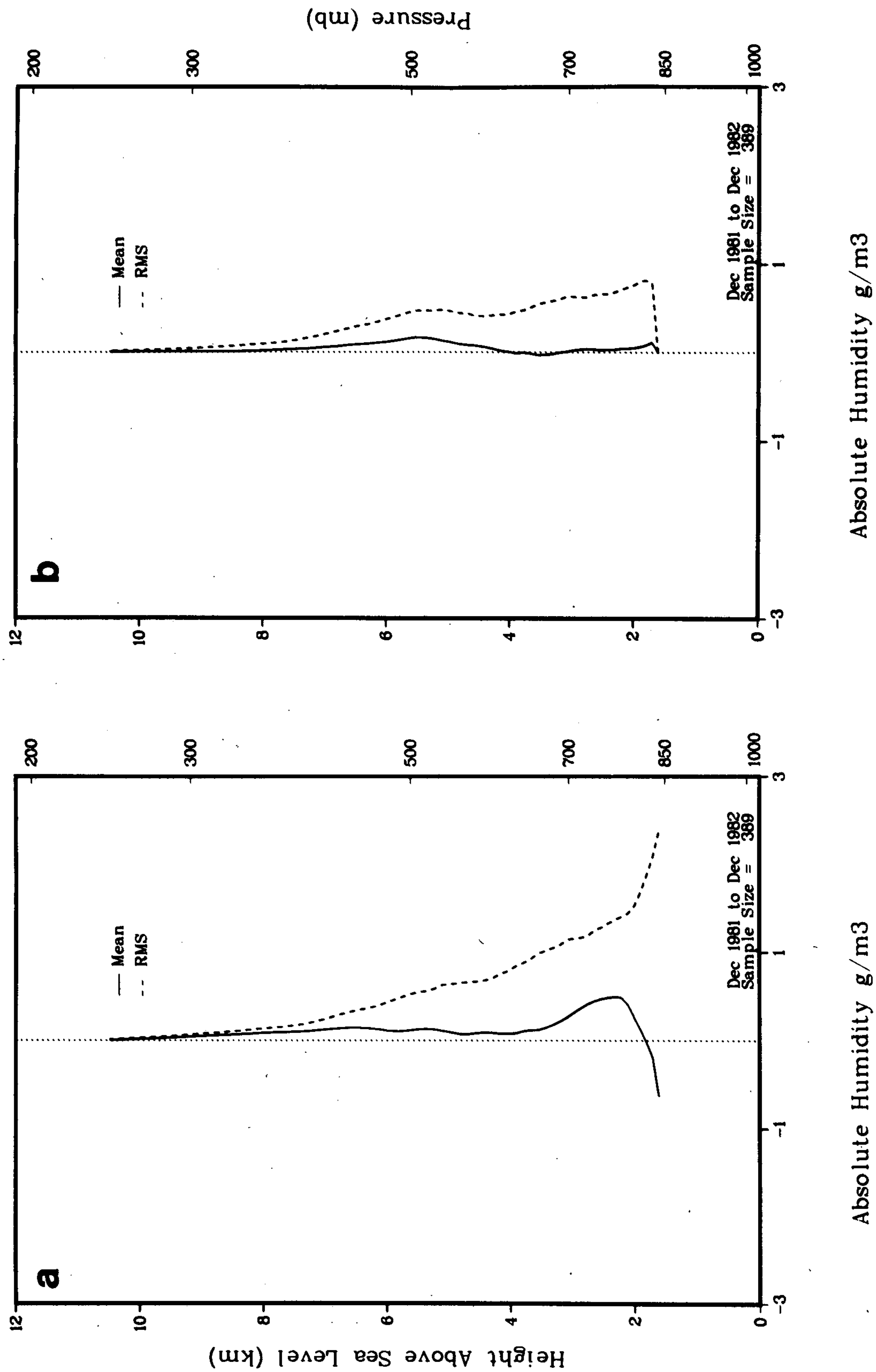

FIG. 6. Composite statistics of mean and rms differences with radiosondes of (a) NOAA 6/7 satellites operational humidity retrievals, and (b) Profiler humidity retrievals at Denver.

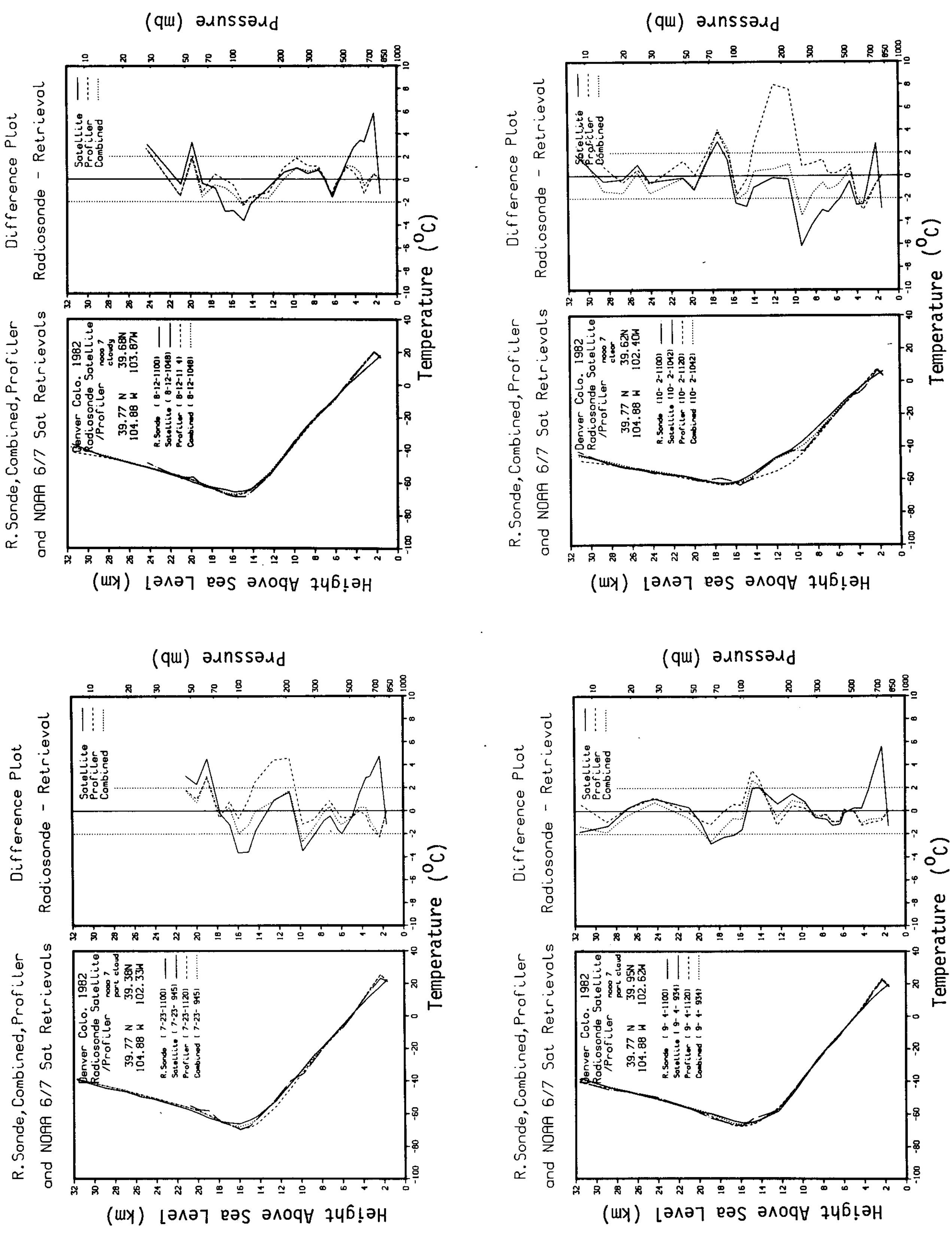

FIG. 7. Four typical temperature retrieval comparisons at Denver with radiosonde and temperature difference plot of NOAA 6/7 satellites operational retrievals, Profiler retrievals, and combined satellite-Profiler retrievals.

temperature soundings much more closely than the satellite retrievals in the lower troposphere, while the opposite is true in the stratosphere. It is reasonable, therefore, to assume that the ground-based and satellite retrievals can be systematically combined to obtain a better approximation throughout the atmosphere.

Let the vectors $\mathbf{t}_p$ and $\mathbf{t}_s$ be the ground-based and satellite retrievals of the temperature profile, respectively. Then we derived a composite retrieval $\mathbf{t}$ by inverse covariance weighting of the separate retrievals (Rodgers, 1976) to yield

$$\mathbf{t} = (\mathbf{S}_p^{-1} + \mathbf{S}_s^{-1})^{-1}(\mathbf{S}_p^{-1}\mathbf{t}_p + \mathbf{S}_s^{-1}\mathbf{t}_s), \tag{1}$$

where $\mathbf{S}_x$ is the unbiased error covariance matrix of $\mathbf{t}_x$, $\mathbf{S}_x^{-1}$ its matrix inverse, and x either p or s. We assumed $\mathbf{S}_p$ and $\mathbf{S}_s$ to be positive definite and performed numerical studies to confirm this assumption. Since both the data from which the retrievals were generated and the retrieval methods were independent, statistical independence of $\mathbf{t}_p$ and $\mathbf{t}_s$ is assumed in Eq. (1).

a. Sample selection

To evaluate the inverse covariance weighting method of combining profiles, two independent samples are required: one sample to compute the error covariances for each of the ground-based and satellite retrievals and the other to compare the combined profiles with the satellite and ground-based retrievals. The latter sample consists of a set of triads of remotely-inferred profiles and a "ground-truth" radiosonde profile. Both samples must be large enough to yield meaningful statistics. Of course, when we have two independent samples, we can use each of them for error covariances and for combined profile evaluation, giving us two independent checks of the method.

Our total data set of 460 cases (each case consisting of corresponding profiles from the three measurement sources—radiosonde, Profiler, and satellite) was divided into two samples by assigning a uniform random deviate, r ($0 < r < 1$) to each case. Cases having $r < 1/2$ were assigned to sample one; those having $r \geq 1/2$ were assigned to sample two. The two samples were checked for distribution of date and time to be certain that we had not introduced seasonal or diurnal biases by dividing the sample. As expected, the sample sizes were nearly equal—233 cases and 227 cases.

The computation of the error covariances and the statistical comparison of retrieved and radiosonde profiles require all temperature profiles to be evaluated at fixed values of the independent variable (i.e., pressure or height). Satellite retrievals are initially derived at 40 constant pressure levels (including the mandatory radiosonde levels) from 1000 mb to 0.1 mb. These levels are subsequently processed to derive layer averaged temperatures which form a standard operational product. The 26 intermediate levels, from 780 mb (the first level above the surface at Denver) to 10 mb (near the top of the ground-based retrievals), provide a suitable basis for profile representation. The ground-based retrievals and the radiosonde soundings are interpolated to these 26 levels and are constrained to the same surface values of temperature and pressure. The interpolation tends to obscure some of the detailed vertical structure of the radiosonde profiles, but still provides a good basis for combining and comparing profiles, particularly at mandatory levels.

b. Error (difference) covariances

We will use the term error to refer to the differences between the retrieved profiles and the radiosonde profiles; thus we neglect time and space differences and treat the radiosonde as correct. However, since radiosonde flights frequently terminate below 10 mb, we were faced with the problem of estimating a 26 × 26 covariance matrix from profiles not always containing 26 elements. For missing levels, we interpolated from time-neighboring radiosondes according to the following strategy: let t_0 be the time for the radiosonde containing an incomplete set of levels and $t \pm 12$ and $t \pm 24$ be the times of neighboring releases ±12 and ±24 h, respectively, from t_0. If either of the soundings at $t + 12$ or $t - 12$ has complete levels, then the missing levels from the sounding at t_0 are filled with those of the complete sounding. If both nearest neighbors are

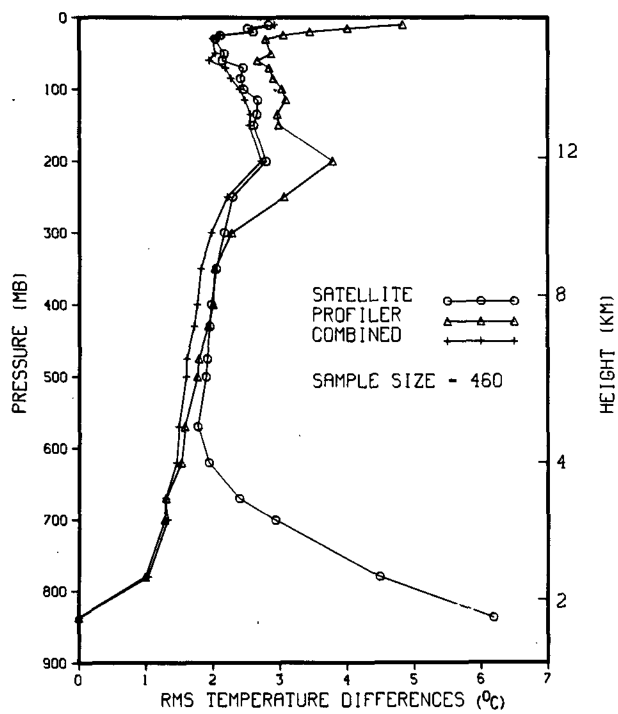

FIG. 8. Rms temperature differences of radiosonde from systems as in Fig. 7.

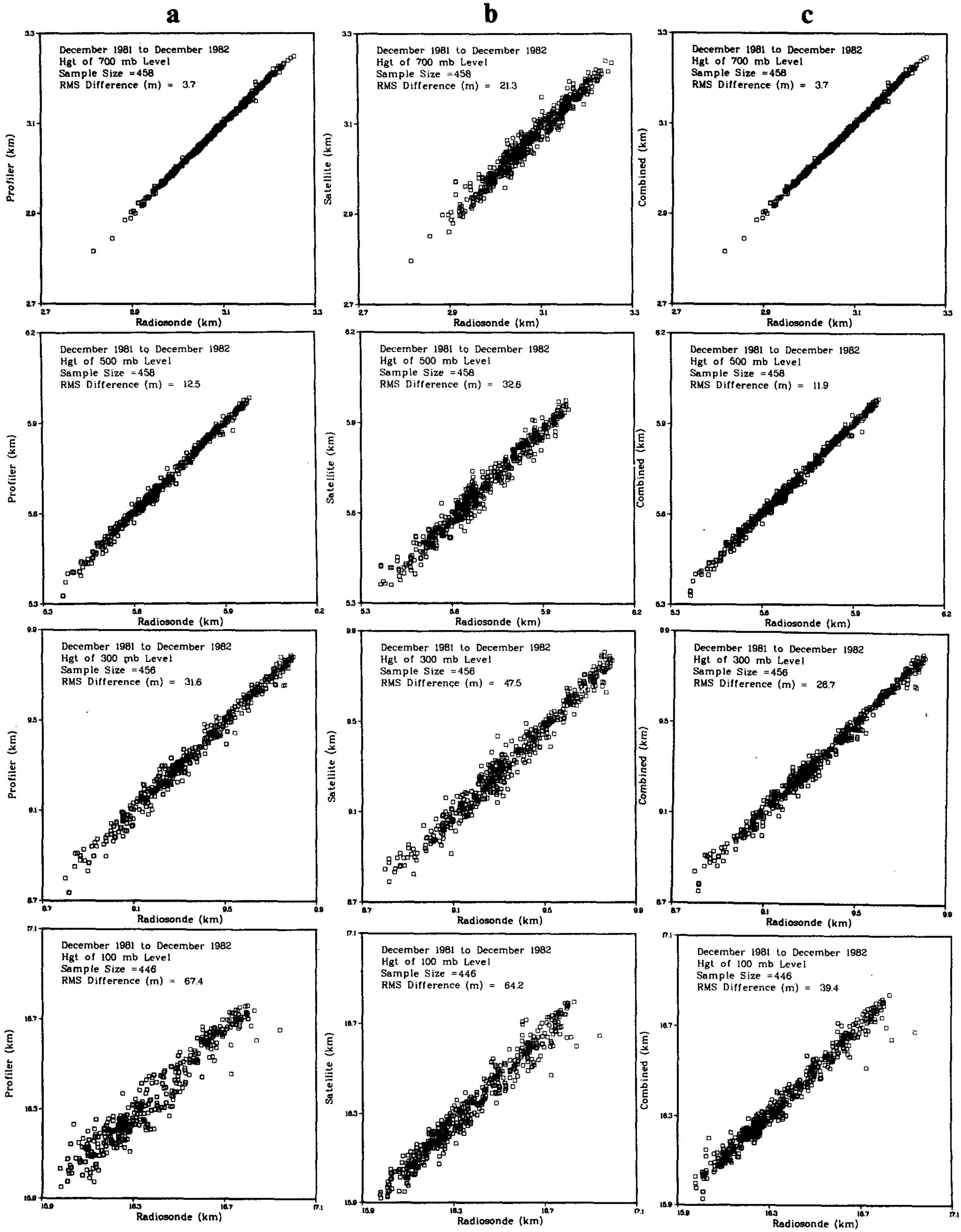

FIG. 9. Scatter plots of geopotential heights at 700, 500, 300, and 100 mb as measured by NWS radiosondes at Denver and heights determined from (a) Profiler retrievals, (b) NOAA 6/7 satellites retrievals, and (c) combined satellite-Profiler retrievals.

complete, the missing levels are filled in with the average of the two complete ones. If both $t + 12$ or $t - 12$ are incomplete, the same procedure is repeated for $t \pm 24$. Finally if none of the soundings at $t \pm 12$ or $t \pm 24$ are complete, the sounding at t_0 was dropped from the ensemble that was used to estimate covariances. However, the ensemble used to compare retrievals with radiosondes contains no estimated radiosonde levels, and hence all rms difference comparisons are based on sample sizes that vary with altitude. As discussed in Section 4, significant biases were noted in certain portions of the atmosphere for both types of retrievals. After removing the biases, we computed the error covariance in the usual way:

$$s_{ij} = (\sum_{k=1}^{N} \epsilon_{ik}\epsilon_{jk})/(N - 1), \tag{2}$$

where s_{ij} are the elements of error covariance matrix $\mathbf{S}$, ϵ_{ik} and ϵ_{jk} the unbiased errors at the ith and jth level respectively, and N the total sample size.

Four error covariance matrices $\mathbf{S}_{p1}$ and $\mathbf{S}_{p2}$, $\mathbf{S}_{s1}$, and $\mathbf{S}_{s2}$ (where the second subscript labels the sample) were computed and used to generate the following combined profiles:

$$\left.\begin{aligned} \mathbf{t}_{1k} &= (\mathbf{S}_{p2}^{-1} + \mathbf{S}_{s2}^{-1})^{-1}(\mathbf{S}_{p2}^{-1}\mathbf{t}_{p1k} + \mathbf{S}_{s2}^{-1}\mathbf{t}_{s1k}) \\ \mathbf{t}_{2k} &= (\mathbf{S}_{p1}^{-1} + \mathbf{S}_{s1}^{-1})^{-1}(\mathbf{S}_{p1}^{-1}\mathbf{t}_{p2k} + \mathbf{S}_{s1}^{-1}\mathbf{t}_{s2k}) \end{aligned}\right\}, \tag{3}$$

where k is the individual case number, and $\mathbf{t}_{pnk}$ and $\mathbf{t}_{snk}$ the unbiased ground-based Profiler and satellite retrieval profiles from sample n. The combined profiles are constrained to the same surface values as those from the radiosonde and ground-based Profiler. The combined profiles were also computed from the biased retrieval profiles and only slight degradation was observed. We can explain this by noting that the only significant biases in ground-based retrievals are in the stratosphere where the error variances are also large; likewise in the satellite retrievals the most significant biases and larger error variances occur in the troposphere, so that the biased data receive very little weight in the combined estimate. However, only the combined profiles derived from unbiased retrievals were used for the individual case studies and to determine error statistics for each sample.

Stability is a common problem associated with inverting matrices with large number of elements. We numerically analyzed each of the matrices entering into the profile composition equations and found condition numbers (ratio of maximum to minimum eigenvalues) to be less than 300. Thus stability was not a problem here.

6. Results

The purpose of the method of profile combination discussed in Section 5 is, generally speaking, to derive profiles that have Profiler quality in the lower atmosphere and the satellite quality at upper levels. In addition, because of statistical error reduction using redundant data, we expect some improvement at all levels. As we show in this section, these goals are obtained, and with the result that some, but not all, inferred parameters have accuracies comparable with the accuracy of the radiosonde.

Typical retrieval results are shown in Fig. 7, in which we compare with the radiosonde the temperature profile retrievals of the Profiler, the satellite, and the combined Profiler–satellite. Note on the difference plot comparisons that both of the individual systems yield differences that exceed, at some level in the atmosphere, the ±2°C region shown on the plots. As indicated, these excursions beyond ±2°C are very much reduced in the combined retrievals.

The improvement in accuracy achieved by the combined system is also achieved in a statistical sense as can be seen in Fig. 8. We note that, as expected, Profiler accuracy is better in the lower atmosphere and the satellite is better in the upper atmosphere, with the accuracy crossover point occurring at about 400 mb. Also, from 500 to 300 mb, the accuracy of the two systems is almost the same. The combined system ex-

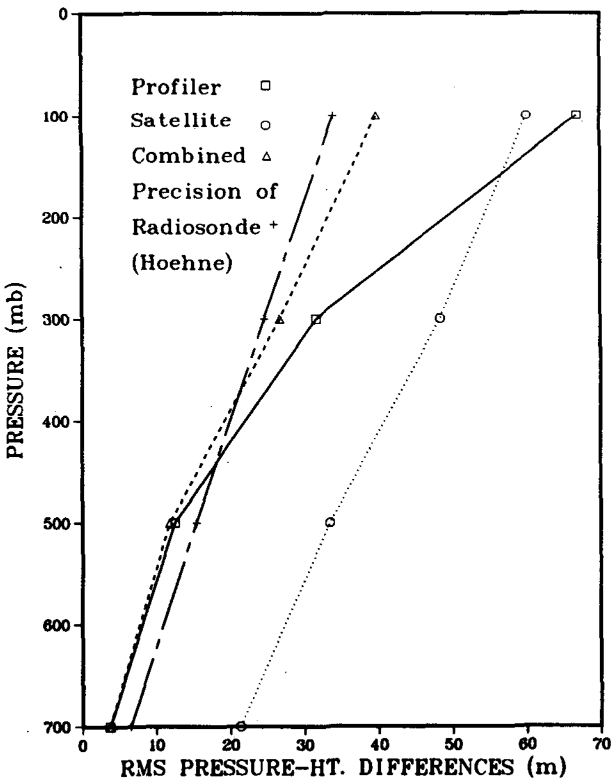

FIG. 10. Comparison of rms differences in geopotential height between radiosonde and Profiler, NOAA 6/7 satellites, and combined retrievals. For comparison Hoehne's (1980) values of the functional precision of radiosondes (adjusted to Denver average surface pressure of 835 mb) are plotted.

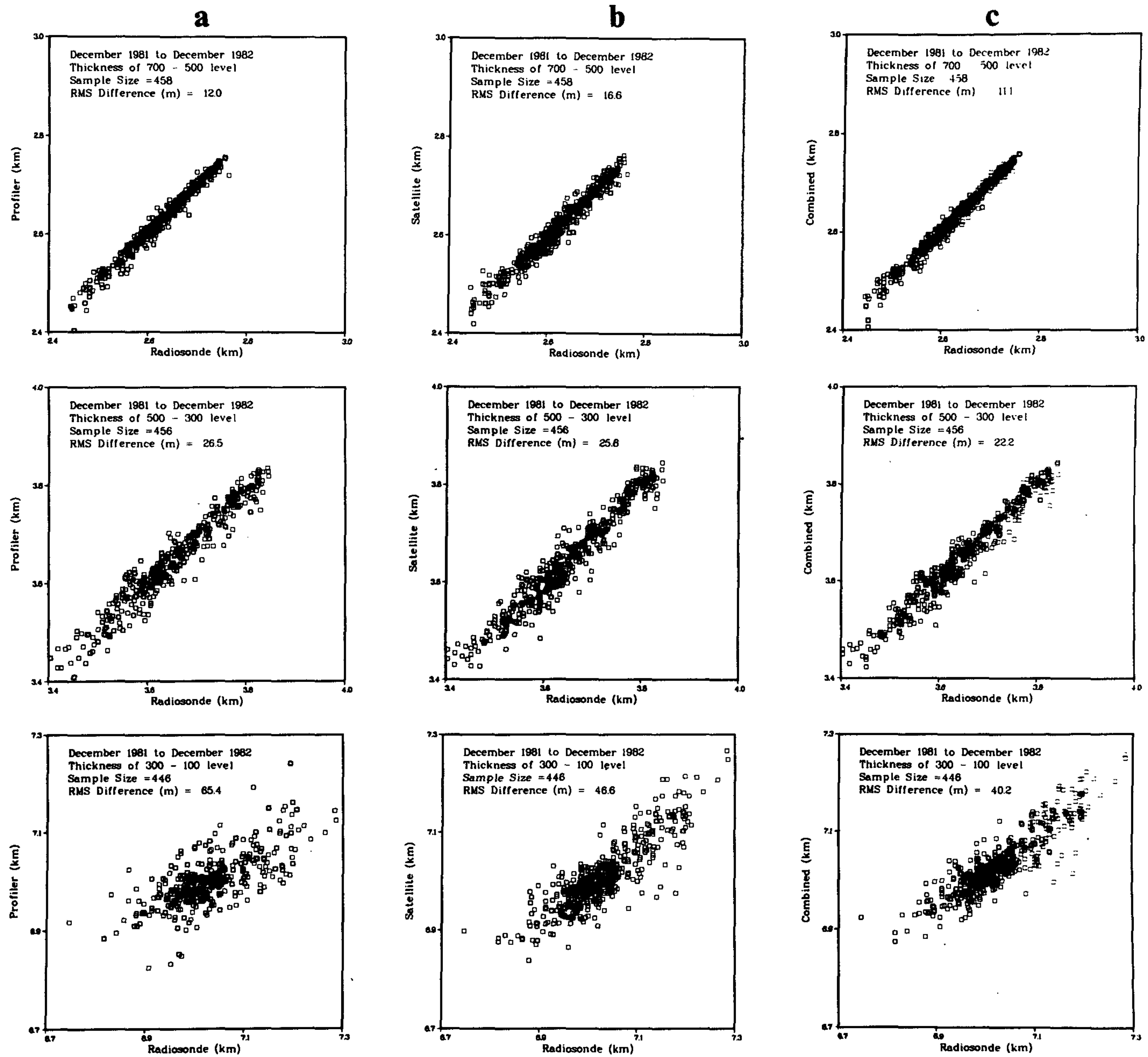

FIG. 11. Scatter plots of thickness of the pressure layers 700–500, 500–300, and 300–100 mb, as measured by radiosondes at Denver and determined from (a) Profiler, (b) NOAA 6/7 satellites, and (c) combined satellite-Profiler retrievals.

hibits an accuracy everywhere better than the best of the two individual systems, with a maximum rms error of 2.7 K below 50 mb. Below 300 mb, all rms errors of the composite system are less than 2.0 K. Hoehne (1980) estimates the functional precision of the radiosonde to be 0.84 K (at fixed height levels) and 0.61 K at fixed pressure levels.

The results of Fig. 8 should be compared with theoretical predictions (for microwave satellite data only) of Westwater and Grody. Their Fig. 3, showing predicted rms temperature retrieval accuracies for the Denver climatology, is in close agreement with the experimental results given here. We are now evaluating the experimentally determined accuracy of the Profiler and the MSU (alone) for the 460 profile data samples that we have assembled.

We also derived geopotential heights from the retrievals of the three systems. For each system, the radiosonde measurement of surface pressure was used (instead of the Profiler surface measurement) so that comparisons of pressure-height differences with the radiosonde reflect only differences in temperature and moisture profiles. Finally, pressure heights for the combined system were derived by first combining the temperature profiles and then using the Profiler-determined moisture profile to derive the parameters needed to integrate the hydrostatic equation. The results for geopotential heights at 700, 500, 300 and 100 mb are shown in Fig. 9, in which we show scatter plots of each of the systems compared with the radiosonde. The ability of the Profiler to sound the atmosphere accurately below 500 mb is clearly evident as is the additional information added by the satellite above this level. We note that, at all levels, the height accuracy of the combined system is better than or equal to either of its two components, and that a significant improvement is obtained at 300 and 100 mb. We show in Fig. 10 the rms values of pressure-height differences for the three systems and for the four pressure levels that we evaluated. For comparison, we also show the estimated functional precision of the current NWS radiosonde, as given by Hoehne (1980). In this figure, we converted the Hoehne values to those appropriate to Denver (surface pressure = 835 mb). Note that the accuracy of the combined Profiler-satellite system is approaching that of the radiosonde in terms of pressure heights.

Comparisons of layer thicknesses for the layers 700–500, 500–300, and 300–100 mb are shown in Fig. 11. Here the improvement using the combined system is not as great as in the case of pressure heights, but in every level there is some improvement over the better of the two systems operating alone. We also note that the satellite thickness retrievals are more accurate than those of the Profiler for the upper two intervals (500–300 and 300–100 mb), but for height only, the 100 mb level is more accurately retrieved. This occurs because height errors tend to accumulate from the surface to the particular point, whereas thickness errors are limited by the interval in question. Thus, a poor retrieval of a 100 mb height could, and for a satellite frequently does, arise from a poor retrieval in the first 300 mb of the atmosphere.

7. Summary and conclusions

The results shown here indicate that the remote sensing capability of ground-based radiometers can be effectively extended to pressures above heights of 500 mb by use of the NOAA 6/7 operational temperature retrievals. Conversely, satellite retrievals below heights of 500 mb can be greatly improved by use of the ground-based sensors. The ability of the total system (NOAA 6/7 satellites plus Profiler) to infer pressure-heights and thicknesses approaches that of the radiosonde.

Other improvements not evaluated here are being added to the remote sensing system. Most notable of these is the ability of the Profilers VHF radar to measure tropopause height. As shown by the experimental work of Westwater *et al.* (1983), the addition of tropopause height information can dramatically improve sounding accuracies near the tropopause.

In addition to sounding data from orbiting satellites, similar data from the VAS sounder on its geostationary platform could be effectively combined with Profiler soundings. Preliminary results on this possible combination have been reported by Menzel *et al.* (1983). To evaluate this combination further, a data set of VAS, Profiler, and radiosonde soundings as large as the one reported here should be analyzed.

The inverse covariance weighting method we used here to combine retrievals from the separate systems was easy to implement and produced high quality retrievals, and is a very effective way of combining data from independent sources. Another method is to use a data vector composed of both Profiler and satellite brightness temperatures, and a retrieval could be produced by applying either a statistical or a deterministic operator to this data vector. Further work should develop and evaluate such techniques to see if significant improvement over our method can be achieved.

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