Combined Surface- and Satellite-Based Microwave Temperature Profile Retrieval

E. R. WESTWATER

NOAA/ERL/Wave Propagation Laboratory, Boulder, CO 80303

N. C. GRODY

National Environmental Satellite Service, NOAA, Suitland, MD 20233

ABSTRACT

Remote sensing of vertical temperature profiles by combined satellite- and surface-based microwave radiometers is evaluated. For both clear and cloudy conditions, realistic simulations of retrieval accuracy for three climatologies with highly variable temperature structure suggest that rms retrieval accuracies from 1.0 to 2.0 K can be obtained from the surface to 300 mb using the combined passive measurements. When the height of the tropopause, as measured by ground-based radars, is used in a retrieval algorithm, simulations show that retrievals are improved over a broad altitude range, and that retrieval accuracies better than ~2 K rms from the surface to 100 mb can be achieved.

1. Introduction

Recent developments in ground-based remote sensing of temperature (Decker *et al.*, 1978), humidity (Guiraud *et al.*, 1979) and wind (Chadwick *et al.*, 1976; Gage and Balsley, 1978) may have a substantial impact on weather observation and forecasting. By combining a six-channel microwave radiometer and a microwave radar into a single system, it is possible to monitor continuously these three atmospheric variables mentioned above (Hogg *et al.*, 1980). In this paper we investigate the ability of this total surface-based system to measure vertical temperature profiles and the degree to which these profiles can be improved by using satellite soundings.

Both theoretical predictions (Westwater *et al.*, 1976)[1] and experimental results (Decker *et al.*, 1978) have demonstrated the ability of a five-channel microwave radiometer (frequencies ~22, 31, 53, 54 and 56 GHz), operating from a surface platform in a zenith viewing mode, to recover vertical temperature structure under nonprecipitating conditions. The 50 GHz channels, on the side of the O_2 absorption band, are used to sound temperature while the lower frequency channels provide corrections for water vapor and cloud liquid. Experiments described by Decker *et al.* (1978) used the Nimbus 6 SCAMS radiometer (Grody and Pellegrino, 1977) in an up-

ward-viewing mode to achieve accuracies from the surface to about 600 mb of ~1.0–2.0 K rms. These accuracies may be further improved if thermal inversion heights, which can be measured by active sounders, are inserted into profile retrieval algorithms (Hogg *et al.*, 1980). The accuracy to which inversion heights can be measured by microwave radar, acoustic sounding (SODAR) and lidar was the subject of a recent experimental investigation (Kaimal *et al.*, 1980).[2] The accuracies obtained with the active sounders, generally better than 100 m, are sufficient to improve lower altitude retrievals, especially those of elevated subsidence inversions. However, because of the exponential height decay of temperature weighting functions for surface-based measurements, retrievals above 600 mb are gradually degraded.

The SCAMS radiometer on the Nimbus 6 satellite has demonstrated the ability to recover temperature structure of the middle and upper troposphere with rms accuracies better than 3 K rms (Grody and Pellegrino, 1977). Especially important is its ability to perform in the presence of clouds. Because of uncertainties in surface emission and broad weighting functions, retrievals below 700 mb frequently show errors >3 K rms. However, this region is precisely where the surface-based sound-

---

[1] Westwater, E. R., M. T. Decker and F. O. Guiraud, 1976: Feasibility of atmospheric temperature sensing from ocean data buoys by microwave radiometry. NOAA Tech. Rep. ERL 375-WPL 48, 32 pp. [NTIS 262-421].

[2] Kaimal, J. C., N. L. Abshire, R. B. Chadwick, M. T. Decker, W. H. Hooke, R. A. Kropfli, W. D. Neff, F. Pasqualucci and P. H. Hildebrand: Convective boundary layer thickness estimated by *in-situ* and remote probes. *Preprints 19th Conf. Radar Meteorology*, Miami, Fl., Amer. Meteor. Soc., 633–636.

ings are the most accurate. If surface-based and satellite soundings are combined, the composite temperature sounding should be improved.

2. Choice of frequencies

The scanning microwave spectrometer (SCAMS) aboard the Nimbus 6 satellite contains three temperature sounding channels in the oxygen band (52.85, 53.85, 55.45 GHz) and two water channels (22.235 and 31.65). Since the satellite's launch in 1975, much experience has been gained in using this system to sound temperature and moisture under nearly all weather conditions. The SCAMS instrument has also been extensively used in the ground-based mode (Decker et al., 1978). Here, as well as in the satellite application, the performance of the sounder is well understood, and accuracies in temperature retrieval are close to those predicted by theory. To improve profile determination above 300 mb and in the first 100 mb above the surface, we added to the SCAMS channels, in our simulations, a 58.8 GHz channel from both satellite and surface platforms. This channel was used on the Nimbus 5 satellite.

Information content of soundings is related to the shape and magnitude of the temperature weighting functions, which are defined as the negative of the derivative of the transmission with respect to distance. Normalized ground- and satellite-based weighting functions for zenith- and nadir-viewing radiometers are shown in Fig. 1. Note that the Gaussian-like satellite weighting functions peak at increasing height as the frequency approaches the center of the oxygen band at 60 GHz. In contrast,
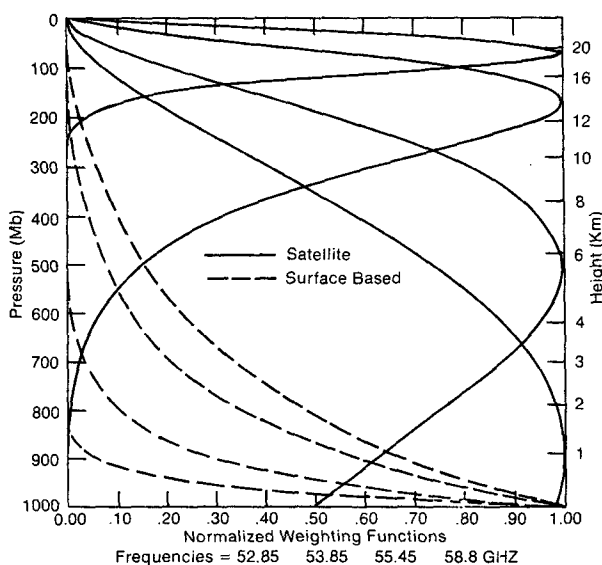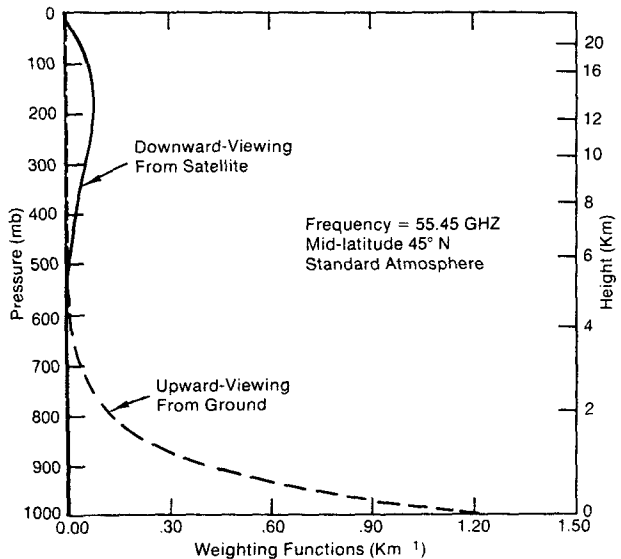

FIG. 2. Weighting functions for surface-based and satellite-based microwave temperature profiling.

the exponential-like ground-based weighting functions become more opaque to the upper atmosphere as the frequency approaches the band center. The 3 dB widths for the surface-based weighting functions range from 25 to 200 mb, while the width of the satellite functions range from 100 to ~800 mb. It is apparent that the surface-based weighting functions provide the greatest vertical resolution for pressures greater than roughly 700 mb, while the satellite weighting functions offer the best resolution above this level. To indicate the differing degrees of response of the two systems to temperature perturbations, in Fig. 2 we show unnormalized weighting functions at 55.45 GHz. From these curves we calculate that the response of the surface-based channel to a 1 K temperature perturbation of 1 km extent near the surface is ~0.45 K; the same perturbation placed at ~150 mb, the maximum of the satellite function, gives a brightness temperature change of 0.1 K, nearly a factor of five less.

Surface-based remote sensing observations are easily supplemented with surface meteorological observations. Here, we assume surface temperature, pressure and humidity to be available. The surface temperature is a useful constraint on the profile shape, particularly in the boundary layer; the surface humidity measurement improves temperature profile retrievals by reducing effects of moisture; and the pressure measurement is used to correct the transmission of the most transparent oxygen channel (52.85 GHz).

In the following sections then, we evaluate the temperature sounding capability of the combined surface- and satellite-based microwave systems consisting of four uplooking and four downlooking

FIG. 1. Weighting functions, normalized to unit maxima, for surface-based and satellite-based microwave temperature profiling.
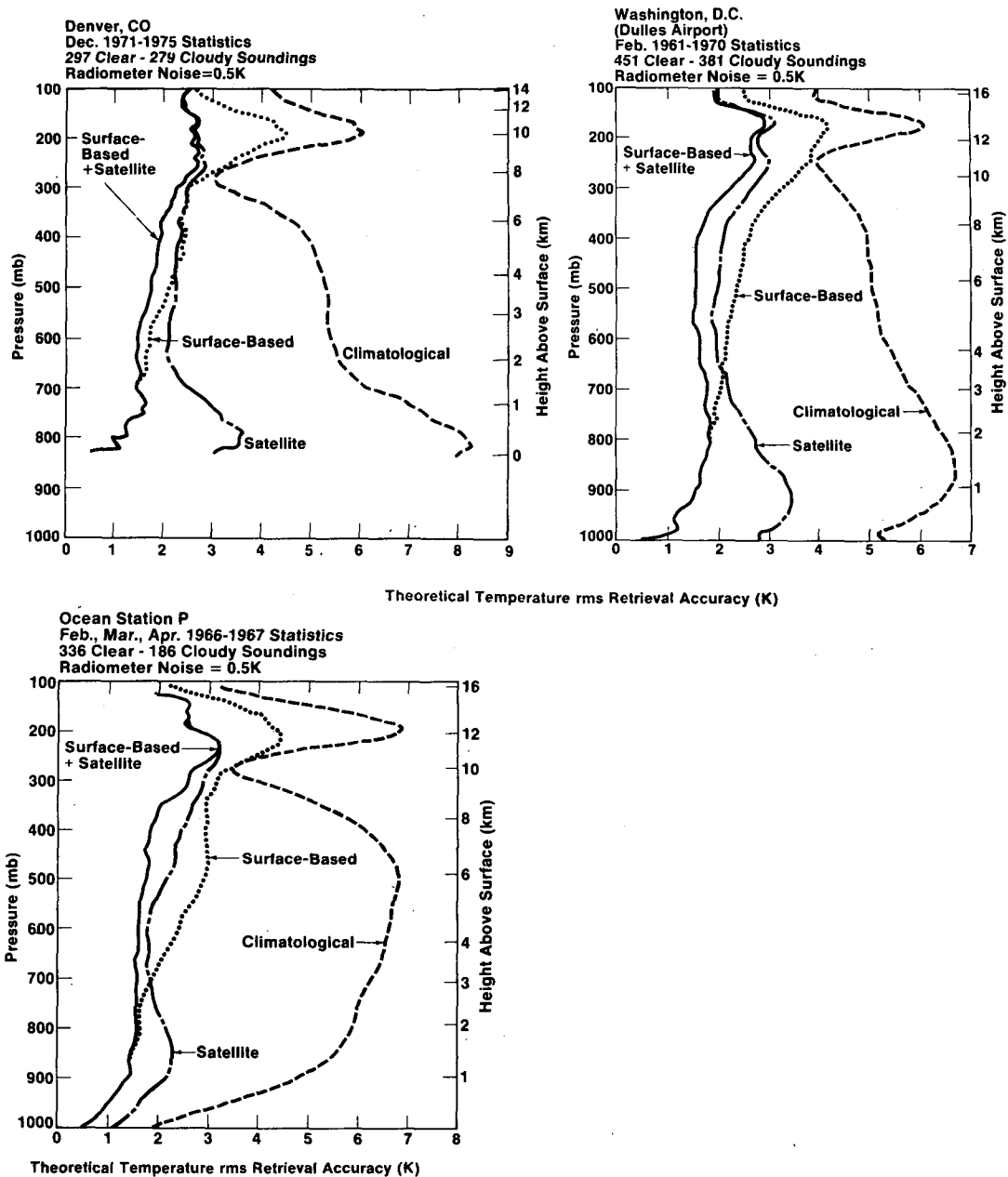
FIG. 3. Computer-simulated estimates of temperature profile retrieval accuracy using dependent sample linear regression analysis.

temperature channels, two uplooking and two down-looking moisture channels, and three surface meteorological observations.

3. Accuracy simulations of combined radiometric systems

To estimate the improvement in accuracy that composite satellite- and surface-based soundings would yield, simulated retrievals were performed for three climatologies with highly variable temperature structure: Denver, Colorado, December; Washing-ton, DC, February; and Ocean Station P in the Gulf of Alaska, February–April. Their rms climato-logical temperature variation as a function of alti-tude is shown in Fig. 3.

Denver, December, was chosen because of the high frequency of occurrence of 1) intense, low-altitude ground-based thermal inversions and 2) elevated (subsidence) inversions which occur almost to the tropopause. Since precipitable water vapor is quite low in December, little interference with temperature retrieval is expected from this variable. At Dulles Airport at Washington, DC, February,

surface variation is not as extreme as in Denver, but upper altitude variation exceeds 5 K rms from the surface to ~400 mb. Moisture variation is about twice that of Denver. The ocean climatology of Ocean Station P (Gulf of Alaska), February–April is also highly variable. For this location, surface temperature variation is <2 K rms, but the upper altitude variation from 900 to 400 mb exceeds 6 K rms. The moisture variation is similar to that of Dulles in February.

The temperature profile retrieval simulations were carried out as follows. For each profile in the three ensembles, brightness temperatures at the relevant frequencies were calculated using standard absorption (Liebe, 1969; Rosenkranz, 1975) and radiative transfer models (Meeks and Lilley, 1963). Clouds were included by using the model described by Decker et al., 1978. Gaussian measurement noise with standard deviation of 0.5 K was added to each brightness temperature. This choice of noise level is consistent with contemporary radiometric sensitivities. For example, using a 1 s integration time, a radiometer constructed by Guiraud et al. (1979) has an rms sensitivity of 0.1 K, while the SCAMS radiometers have an rms sensitivity of 0.5 K. In addition, Gaussian noise with standard deviations of 0.5 K, 1.0 mb and 5% was added to surface temperature, pressure and relative humidity. These errors in surface meteorological measurements are somewhat larger than typical requirements of class A weather stations (accuracies within ±0.56 K in temperature, ±0.3 mb in pressure, and over the temperature range of +30°C to −23°C, ±1.11 K in dewpoint temperature). Although we have chosen conservative measurement error estimates, the predicted accuracies which follow would be degraded by larger noise levels. For the downward-viewing satellite observations, variable surface emissivities of $0.9 + 0.1u$ and $0.5 + 0.1u$ were assumed for land and ocean surfaces (u is a random number uniformly distributed between 0 and 1). Profiles were recovered from the brightness temperatures using linear statistical inversion (dependent samples). The results are shown in Fig. 3.

Although the three climatologies shown in Fig. 3 are substantially different, the retrieval results show some close similarities. In the first 200 mb above the surface, satellite observations add little, if any, information to the ground-based system. Above roughly 700 mb, where the accuracy of the surface-based system is decreasing, the inclusion of the downward-viewing observations offers a substantial improvement. For all three climatologies, the predicted accuracy of the combined system is ~1.5–2.0 from the surface to ~300 mb. Above this, temperature variations associated with the tropopause are much harder to recover.

It was indicated in Section 2 that addition of conventional surface meteorological observations to ground-based radiometric observations improves profile accuracy. To investigate this same concept for satellite observations, we ran simulations for the three climatologies used above to compare various combinations of observations. As shown in Fig. 4, except in the first 10–20 mb, below 700 mb there was only a small difference in retrieval accuracy between satellite and satellite plus surface. As is evident from the figure the information leading to the improvement in retrieval accuracy below ~600 mb comes from the ground-based radiometer. In the region from 600 to 300 mb, the surface meteorological observations do add a modest amount of information to the satellite-based temperature retrievals. A correlation analysis showed that the improvement was due to the pressure observation, and was not due, as might be expected, to the surface temperature observation.

4. Inclusion of tropopause height in temperature retrievals

Using meter-wavelength, VHF radar, Gage and Green (1979) have shown that it is possible to detect and measure routinely the altitude of the tropopause. Using a 1 km range gate, the rms difference between radar and radiosonde measurements of tropopause height was 0.71 km. During the three month period of the observations, the tropopause height varied over a range of 7 km. Our ground-based active-passive profiling system, as described by Hogg et al. (1980), will contain a radar similar to that of Gage and Green (1979), and hence also will be capable of tropopause monitoring.

It was shown by Thompson and Wolski (1977) that satellite-based temperature retrievals are adversely affected by an improperly located tropopause in the first guess field. It is apparent, therefore, that measurements of tropopause height should improve the accuracy of the combined ground- and satellite-based retrievals. The following procedure was found to best utilize such height information to improve retrieval accuracy.

Our algorithm to combine an (imperfectly) measured tropopause height with radiance observations to derive a profile is a variation of statistical inversion. An ensemble of radiosonde profiles is decomposed into subsets, each of which contains only profiles whose tropopause height is within a specified height interval. The minimum width of this interval would correspond to the radar range gate. Inversion coefficients are then constructed for each of these mutually exclusive and exhaustive sub-ensembles by the usual technique of linear statistical inversion.

The improvement in retrieval accuracy achieved by stratifying retrieval coefficients according to tropopause height was estimated by computer simulations for each of the three climatologies

Denver, CO
Dec. 1971-1975 Statistics
297 Clear - 279 Cloudy Soundings
Radiometer Noise=0.5K

Washington, D.C.
(Dulles Airport)
Feb. 1961-1970 Statistics
451 Clear - 381 Cloudy Soundings
Radiometer Noise=0.5K

Theoretical rms Temperature Retrieval Accuracy (K)

Ocean Station P
Feb., Mar., Apr. 1966-1967 Statistics
336 Clear - 186 Cloudy Soundings
Radiometer Noise=0.5K

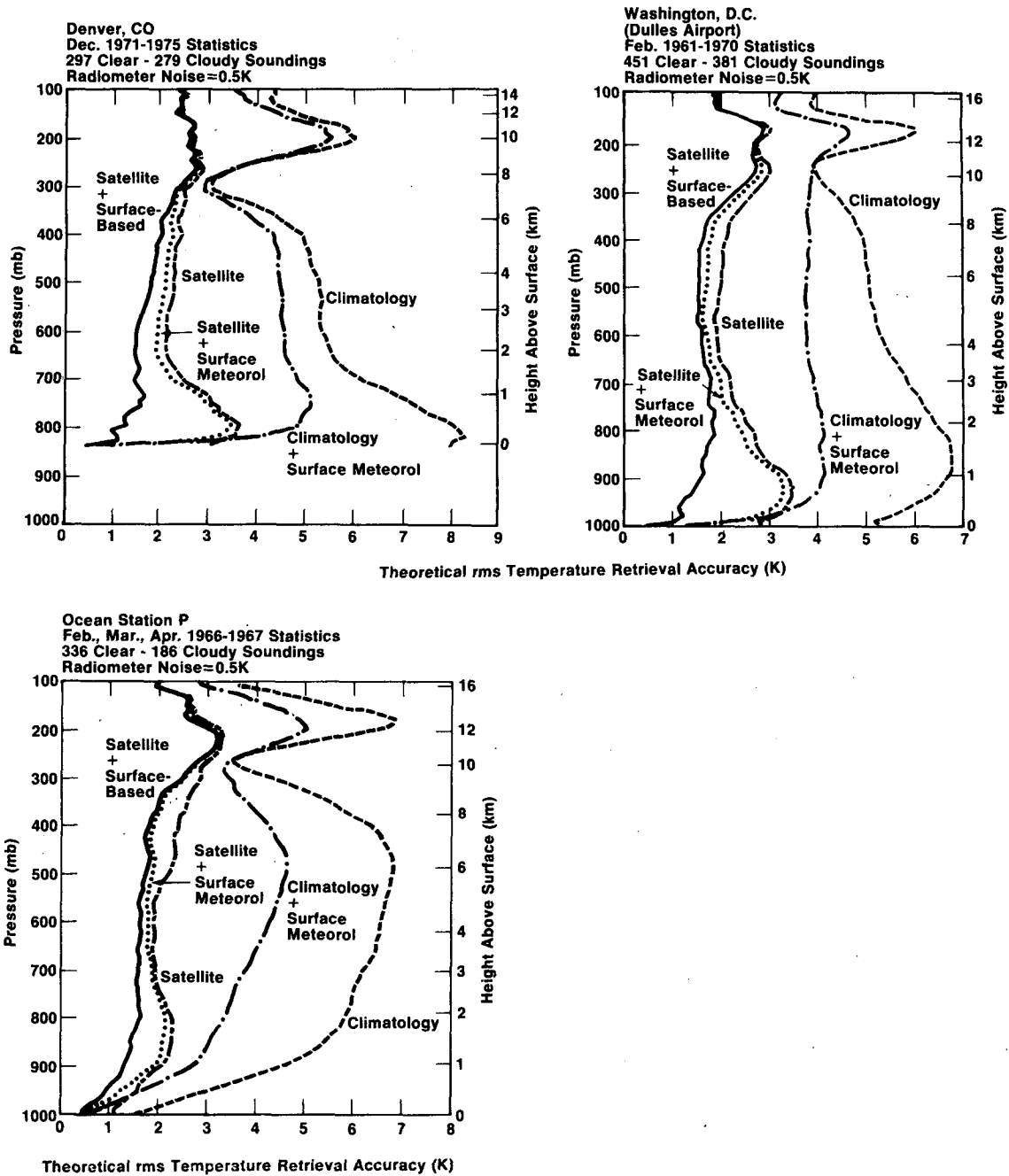Theoretical rms Temperature Retrieval Accuracy (K)

FIG. 4. Temperature retrieval accuracy for selected combinations of measurement ordinates.

discussed in Section 3. The height resolution assumed was 30 mb, roughly equivalent to 1 km in the region of the tropopause. The results, shown in Fig. 5, indicate that near the tropopause (100–300 mb) improvements in retrieval accuracy of ~1 K rms are achieved. In addition, due mainly to correlation that exists between temperature fluctuations at even widely separated height intervals, retrieval results are improved in the entire region of sounding. With the tropopause information, the predicted rms error from the surface to 100 mb is <2.2 K. In contrast to these results, obtained by data stratification, when the tropopause height was used as a component of a data vector in the usual form of statistical inversion, the temperature variance was not reduced substantially.

5. Concluding remarks

Our simulations have indicated that the accuracy of ground-based microwave temperature retrievals
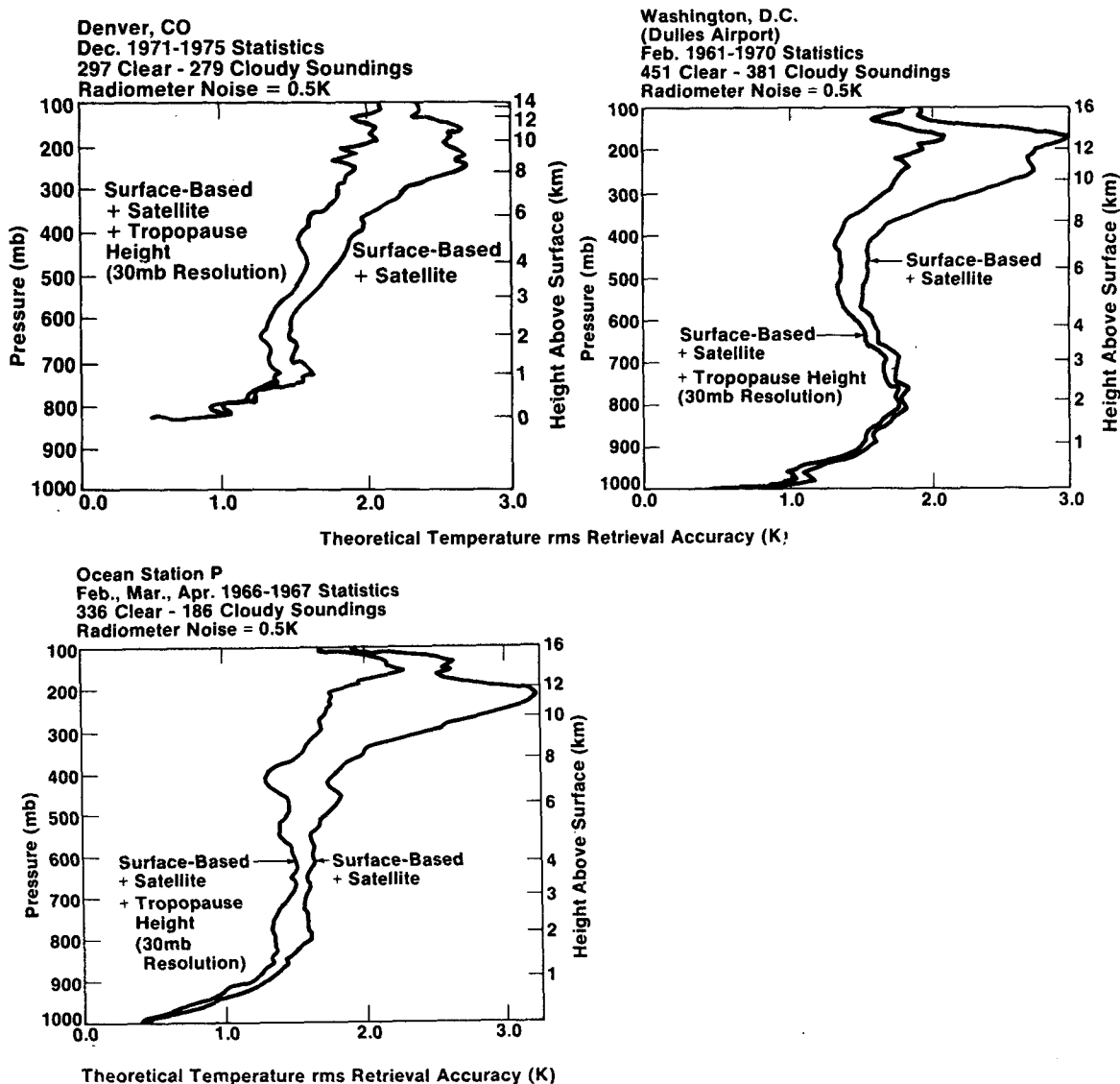
FIG. 5. Temperature-retrieval accuracy with and without knowledge of tropopause height;
same conditions as in Fig. 3.

can be considerably improved in the middle to upper troposphere by supplementary use of satellite microwave observations. Ground-based radar measurements of tropopause height further increase sounding accuracy by about 1 K rms in the 300–100 mb region. To experimentally verify these theoretical results, we can use satellite microwave soundings that are currently available (Phillips *et al.*, 1979), and the ground-based radar and radiometers (Hogg *et al.*, 1980) that will be available in the fall of 1980.

As was discussed in Section 3, surface meteorological observations also can be used in the satellite retrievals. For the three climatologies studied in this paper, these surface observations did little to improve lower atmospheric sounding accuracy.

At Denver, we will compare satellite retrievals with and without the use of surface observations to see if these predictions are true on a seasonal basis.

The largest uncertainty in evaluating the utility of a combined system is the difficulty in amalgamating two sets of data which represent widely different spatial scales. With satellite footprints of the order of tens of kilometers and the near pencil beam of the ground-based system, difficulties in interpretation may arise. The degree to which such difficulties can be reduced by data processing techniques awaits experimental evaluation.

REFERENCES

Chadwick, R. B., K. P. Moran, R. G. Strauch, G. E. Morrison and W. C. Campbell, 1976: Microwave radar wind measurements in the clear air. *Radio Sci.*, **11**, 795–802.

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 B. B. Balsley, 1978: Doppler radar probing of the clear atmosphere. *Bull. Amer. Meteor. Soc.*, **59**, 1074–1100.

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

Grody, N., and P. P. Pellegrino, 1977: Synoptic-scale studies using the Nimbus 6 scanning microwave spectrometer. *J. Appl. Meteor.*, **16**, 816–826.

Guiraud, F. O., J. Howard and D. C. Hogg, 1979: A dual-channel microwave radiometer for measurement of precipitable water vapor and liquid. *IEEE Trans. Geosci. Electron.*, **GE-17**, 129–136.

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.

Liebe, H. J., 1969: Calculated tropospheric dispersion and absorption due to the 22-GHz water vapor line. *IEEE Trans. Antennas Propag.*, **AP-17**, 621–627.

Meeks, M. L., and A. E. Lilley, 1963: The microwave spectrum of oxygen in the earth's atmosphere. *J. Geophys. Res.*, **68**, 1683–1703.

Phillips, N., L. McMillin, A. Gruber and D. Wark, 1979: An evaluation of early operational temperature soundings from TIROS-N. *Bull. Amer. Meteor. Soc.*, **60**, 1188–1197.

Rosenkranz, P. W., 1975: Shape of the 5-mm oxygen band in the atmosphere. *IEEE Trans. Antennas Propag.*, **AP-23**, 498–506.

Thompson, O. E., and R. J. Wolski, 1977: Nonlinear functions of satellite-measured spectral radiance as estimators of tropopause height. *J. Appl. Meteor.*, **16**, 281–289.