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CAPABILITIES OF OPERATIONAL INFRARED SOUNDING SYSTEMS FROM SATELLITE ALTITUDE

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ABSTRACT

Operational soundings have been produced from Vertical Temperature Profile Radiometers (VTPR) since October 1972. In September 1973, a description of the processing system (McMillin et al.) was published. Changes to the processing system are described. A new series of operational sounding instruments is being built for launch in 1978. Capabilities of this system are compared to the present VTPR. In the past, radiances have been used to duplicate radiosonde information. Approaches not based on producing radiosonde profiles are being incorporated into operational procedures.

1. INTRODUCTION

Given a temperature profile and cloud distribution, it is relatively easy to integrate the radiative transfer equation to obtain radiances. However, to obtain profiles of temperature and humidity from radiance measurements, the more difficult inverse problem must be solved. There are two main problem areas: the retrieval of temperature profiles from clear radiances and the derivation or selection of clear radiances from measurements which are contaminated by clouds.

The retrieval of temperature is based on radiometric measurements at several wavelengths in an absorbing region for a gas with a uniform mixing ratio in the atmosphere. Radiation at each wavelength is characteristic of an average temperature over a relatively thick layer of the atmosphere. Two basic approaches to the problem have been tried. Presently, approaches which rely on the physics of the problem are limited in accuracy by uncertainties in the knowledge of atmospheric transmittance parameters upon which the approaches depend. However, these approaches offer the hope of greater accuracy in addition to being capable of producing soundings from a stand-alone system that does not rely on measurements from other instruments such as radiosondes. Ongoing studies are directed toward better laboratory measurements of the spectroscopic parameters to improve the models used to calculate atmospheric transmittance. While physical models are being improved, current systems use statistical information in the form of regression of radiosonde temperature profiles as a function of satellite measurements that are reasonably simultaneous in time and coincident in space.

In the past, most of the sounding effort has been directed toward the retrieval problem. Recent papers by Fleming (1977) and Rodgers (1976) describe the relationships between the numerous and seemingly diverse solutions which have appeared. However, the errors in clear radiances are the major limiting factor in achieving better accuracy. Early approaches concentrated on finding holes or areas that were completely cloud free. There was a problem of some residual cloudiness contaminating the measurements, but the major limitation of the method was a lack of soundings in the meteorological interesting areas. Current methods are based on the adjacent field-of-view approach originally proposed by Smith in Fritz et al. 1972 and Smith et al. 1970. This method is based on the assumption that clouds in adjacent spots are at the same level, a condition that does not hold over significant areas of the globe. Most procedures which use this method employ a screen to reject questionable values. Although this method is not limited to cloud-free spots, it is limited to areas that are partly clear and have a uniform cloud height. While more soundings are produced with this system, it still fails to produce soundings in many areas of meteorological interest.

2. THE PRESENT METHOD

Production of operational temperature soundings from satellites began shortly after the launch of the first pair of Vertical Temperature Profile Radiometers (VTPR's) on NOAA 2 in October 1972. To provide continuous coverage as various satellite components failed due to aging, NOAA 2 was followed by NOAA 3, NOAA 4, and NOAA 5. Each of these satellites carried two instruments for redundancy. Table 1 shows the periods that various satellites were used. After an initial failure, one of the instruments on NOAA 2 recovered and was used until it failed a second time in October 1974.

On April 5, 1974, NOAA 3 was rotated in orbit so that space was viewed through the normal earth position. This exercise revealed a scan-position dependent bias in the data as well as a difference between earth and space ports. Both were caused by stray radiation from parts of the instrument reaching the detector. Baffles were added to later instruments carried on NOAA 4 and NOAA 5 to correct the problem.

The initial VTPR processing system has been described in McMillin et al. 1973. Since 1973, several of the procedures used to calibrate the data, eliminate cloud effects, and produce temperature retrievals have changed. Changes to the calibration algorithm have been minor. Instruments on NOAA 5 and later satellites measure the patch temperature every scan instead of the secondary optics temperature.

Both the clear radiance procedure and retrieval algorithm have changed extensively from methods described in McMillin et al. The clear radiance procedure is still based on the assumption that if cloud amount is the only parameter that changes between two adjacent fields-of-view, then radiances for any channel are a linear function of cloud amount. If a clear radiance value is known for any channel, then the cloud amount can be determined and clear radiances for other channels can be derived from the linear relationship between radiance and cloud amount as suggested by Smith. In the VTPR system, window radiances for two spots are compared to determine if values differ enough (>1 mW/cm^{2}sr cm^{-1}) to define a line and an estimated clear value for the window channel is calculated from a sea surface temperature analysis and the NMC forecast air temperatures. Then the ratio of the radiance difference between the two measured values to the difference between one of the values and the calculated clear value is obtained from

$$r = \frac{I_1(\nu_i) - I_2(\nu_i)}{I_{clr}(\nu_i) - I_1(\nu_i)} \quad (1)$$

where r is the ratio,

$I_1(\nu_i)$ is the radiance at wavenumber ν_i for spot 1,

$I_2(\nu_i)$ is the radiance at wavenumber ν_i for spot 2, and

$I_{clr}(\nu_i)$ is the calculated clear radiance at wavenumber ν_i.

Knowing r, values of $I_{clr}(\nu_i)$ are obtained for the remaining channels.

In early versions of the processing system, the resulting clear radiance estimates were combined in a histogram and a single value was obtained. That has been changed to an approach based on screening the values to provide a distribution that is symmetric, and then averaging the result. Three separate tests are involved. Each VTPR scan spot not on the edge of a scan is surrounded by eight scan spots which touch it on a corner or a side. For a given spot, pairs are formed with four of the adjacent spots; the remaining four pairs will result with one of the adjacent points as the center. Each of these four pairs has one point, the center point, in common. In the first test, derived radiances for each of the 49 groups of four pairs of adjacent points are compared and a variance calculated. Values are obtained for each of the 49 possible groups for which two or more pairs pass the 1 mW(m^2 sr cm^{-2}) test and are over water. For each channel, the lowest group variance is determined, an increment is added to the lowest value, and all points with group variances less than the limit are accepted. Finally acceptable values from the various channels are compared and only those acceptable for all channels are kept.

If cloud amount is the only variable that changes, then derived clear radiances should be constant. In other words, the value $I_{clr}(\nu_i)$ should not depend on the value of r. When mixed cloud levels are present, values of $I_{clr}(\nu_i)$ resulting from low values of $I_1(\nu_i)$ and $I_2(\nu_i)$ are likely to contain high clouds and thus mixed cloud levels as found in towering cumulus. As a result, values of $I_{clr}(\nu_i)$ are frequently in error and result in radiances that are too high. not just noisy. Each of the 196 potential values of $I_{clr}(\nu_i)$ is derived from radiances at two spots. The highest window channel radiance of the pair is selected and the median of these values is determined. An average value of $I_{clr}(\nu_i)$ for channel 6, the lowest peaking carbon dioxide channel is determined for all pairs where the window channel exceeds the median and a similar average is determined for values less than the median value. Averages are required to agree to within ± 0.5 mW/(m^2 sr cm^{-1}) or the half of the sample with window radiances less than the median is rejected and the process is repeated on the remaining points. The process is iterated until the test is passed or until the sample is reduced to fewer than ten points. In the latter case no sounding is produced.

Finally, a limit is placed on the variance of the total sample. Significant meteorological gradients can exist across the area represented by a single VTPR retrieval. These gradients result in a relatively large variance for the sample. In cloudy areas, radiances which pass the previous tests are clustered in the clearer spots. Thus a small sample usually comes from one geographical location within the total area covered by one sounding, and the expected variance is less because the meteorologically induced variance is less over the shorter distance. If the calculated variance for an array is less than 0.07 times the number of points, a sounding is produced. This particular test has no effect on the larger samples found in good areas but does eliminate questionable soundings when only a few points are included in the average.

Figure 1 is a plot of the number of rejections from all tests as a function of time. As a result of these tests, about 20 percent of the possible soundings over water are rejected as being too cloud contaminated to produce reliable radiances.

The VTPR temperature retrieval method has also been modified. Temperature retrievals are now determined from a regression of temperature as a function of radiance as described in Werbowetzki 1975. Stepwise regression is used because radiances in the various channels are correlated to the extent that numerical difficulties are experienced when all channels are used as predictors. Separate regression coefficients are produced for different categories of temperature profiles because the relationship between radiance and temperature is nonlinear over large changes in temperature. Three categories are determined from the radiance measurements. For pressures between and including 100 and 1000 mb, the window channel radiance is used to select categories. For pressure levels above the 100 mb level in height, VTPR channel 2 is used to select categories. The dividing points between categories are 95 and 111 mW/(m^2 sr cm^{-1}) for the window channel and 44 and 48 mW/(m^2 sr cm^{-1}) for channel 2.

In the discussion of the clear radiance and the retrieval methods, values of limits for various tests have been given. These values are the ones that provided the best results when they were determined. It should be noted that these limits are subject to re-evaluation and tuning. It is unlikely that any algorithms will be changed before the launch of TIROS-N in 1978.

3. COMPARISON OF PRESENT AND PLANNED OPERATIONAL SOUNDING INSTRUMENTS

VTPR is an eight-channel instrument consisting of one channel measuring radiances in the atmospheric window at 833 cm^{-1}, one channel in the water vapor absorption region at 535 cm^{-1} and six channels in the 15 μm CO_2 band: one at 668.5 cm^{-1} responding to atmospheric temperatures between 1 and 70 mb, one at 677.5 cm^{-1} responding to temperatures between 10 and 150 mb, one at 695.0 cm^{-1} responding to temperatures between 30 and 300 mb, one at 708.0 cm^{-1} responding to temperatures between 150 and 700 mb, one at 725.0 cm^{-1} responding to temperatures between 250 and 1000 mb, and one at 747.0 cm^{-1} responding to temperatures below the 400 mb pressure level.

TIROS-N will carry three separate instruments, a Stratospheric Sounding Unit (SSU), a Microwave Sounding Unit (MSU), and an infrared sounding unit designated as High Resolution Infrared Radiation Sounding version two (HIRS/2). The HIRS/2 serves as the basic sounding instrument but is supplemented by the SSU which can measure higher levels in the atmosphere and the MSU which can produce radiances in cloudy areas.

The HIRS/2 has seven channels in the 15 μm CO_2 band. These channels peak at 668.5, 680.0, 690.0, 703.0, 716.0, 733.0, and 749.0 cm^{-1}, respectively, and are used to infer temperature profiles. Additional channels centered at 2190.0, 2210.0, 2240.0, 2270.0, and 2360.0 cm^{-1} in the 4.3 μm CO_2 band are used to increase the accuracy of the temperature retrievals in the lower atmosphere. Measurements in the atmospheric windows at 900.0, 2514.0, and 2700.0 cm^{-1} are used to determine the boundary temperature. Water vapor is obtained from three channels peaking at 1225.0, 1345.0, and 1488.0 cm^{-1} in the 6.3 μm water vapor absorption band and ozone is obtained from a channel peaking at 1030 μm in the 9.6 μm ozone band. Low level clouds are detected by a visible channel at 14,500 cm^{-1}.

The SSU obtains measurements in the 15 μm CO_2 band and provides temperature information for levels above those sensed by HIRS/2. The SSU is a Pressure Modulated Radiometer (PMR) and is a successor to the Selective Chopper Radiometer (SCR) flown on Nimbus 5 and Nimbus 6 (Smith et al. 1974). Measurements of stratospheric temperatures at three levels are obtained with this instrument. Since all channels sense the stratosphere to some extent, information about this region serves as a correction to channels which respond to temperatures in the troposphere.

The MSU has three channels which peak in the oxygen absorption band (53.74 GHz, 54.96 GHz, and 57.95 GHz) plus a "window" channel at 50.3 GHz. Microwaves are virtually unaffected by clouds, but do suffer some attenuation in precipitating areas. In contrast, infrared measurements are affected by any clouds in the field-of-view. With the MSU, it will be possible to obtain soundings with limited vertical resolution in cloudy areas where it is not possible with infrared measurements.

4. OUTLOOK

Satellite soundings have been produced from infrared radiances which are affected by clouds. Techniques to handle clouds either work poorly or do not produce soundings over cloudy areas, yet these are the areas most likely to affect the forecast. Future satellite systems will use microwave measurements to sense in cloudy areas that are now being missed. They will also blend soundings with other information. For example, satellite winds derived from satellite observed cloud motions complement soundings in that wind information can be derived from cloudy areas whereas soundings are more easily obtained in clear areas. New methods are being developed to extract the information available in radiances in forms other than temperature soundings. An example is the derivation of winds from the measured radiances (Horn et al. 1976).

One approach that is currently receiving attention is that of using radiances themselves as an analysis. The radiance value for a particular channel represents an average temperature weighted over a rather broad layer of the atmosphere as determined by the transmittance. If clear radiances are available, a meteorologist can extract much of the same information from an analysis of radiances that he would be able to obtain from a thickness chart. The National Environmental Satellite Service (NESS) is currently providing information about the strength and location of the jet stream based on a manual analysis radiance from VTPR channel 3 as well as information available from other sources. Use of a man in the procedure allows detection of errors when outputs from some of the many sources of information are in conflict. Because of the many forms that information can take (cloud patterns, radiance fields, satellites, winds, etc.), a man is able to detect and correct problems in a manner that is difficult to conceive of automating on a computer. A similar procedure is being utilized to produce moisture fields from a variety of inputs including VTPR radiance data for the moisture channel. Radiances at microwave frequencies, which are relatively unaffected by clouds, are capable of determining the structure of cloud-covered areas such as the hurricane shown in figure 2 (Grody, 1977).

Accuracy is an important indicator of satellite performance. However, two factors need to be considered when looking at accuracies of satellite soundings. First, the most common source of ground truth is radiosondes which measure point values rather than the vertically and horizontally averaged values sensed by satellites. Radiosondes are also subject to errors. Second, with satellite systems, it is possible to trade accuracy for coverage. Since the meteorologically active areas cover a relatively small portion of the globe, errors in these important areas tend to get overwhelmed by areas where soundings can easily be produced but where the soundings do not provide any information about developing systems. This problem is compounded when satellite systems delete a portion of the soundings. There is no real alternative, but one must remember that producing more accurate soundings may not increase the information if the coverage is inadequate.

The first attempt at determining the accuracy of satellite soundings resulted in the collection of a set of radiosonde - VTPR match ups for March 1973. The RMS error for this data set is shown in figure 3 along with the RMS error of the initial profile used in the retrieval system at that time. Since that time, accuracies have generally improved except for the period that is required after the launch of a new satellite to collect a sample large enough to produce stable regression coefficients. The increased capabilities of future instruments with more channels and other improvements should result in increases in accuracy after the launch of TIROS-N.

Satellite sounding systems provide the only means of obtaining anything more than spot checks of features above levels usually sensed by radiosondes (14 mb). Present sounders are limited to sensing temperature in this region, but future systems will provide information on ozone, and the possibility of sensing other minor gases is being studied. Since clouds have a minimal effect on channels used to sense these regions, their effects are easily removed by cloud correction techniques and some channels require no correction. Because there has been a lack of comprehensive data for these regions, dynamics of this region and interaction between the troposphere and stratosphere are not well known. The daily global coverage provided by satellites will provide a means of proving or disproving the various theories which exist. With the increasing concern about climate and climate changes, satellite measurements at these altitudes will continue to be a valuable source of information.

5. SUMMARY

Initial attempts at using satellite radiances resulted in the production of temperature profiles similar to those produced by radiosondes. While increases in accuracy have been made and additional increases are expected to result from increased instrument capabilities, it has been recognized that the production of level temperatures is not consistent with the average temperature that is represented by the radiances and that other methods of extracting the information make better use of the broad coverage and horizontal consistency which characterize satellite radiances in the cloud-free regions of the atmosphere. Use of satellite radiances to derive parameters such as thickness values, winds, ozone, or water vapor is expected to increase.

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TABLE I. OPERATING PERIODS OF NOAA SATELLITES

NOAA 2	26 October 1972---------------17 March 1974
NOAA 3	17 March 1974-----------------1 July 1974
NOAA 2	1 July 1974-------------------15 October 1974
NOAA 3	15 October 1974---------------17 December 1974
NOAA 4	17 December 1974--------------14 September 1976
NOAA 5	14 September 1976-------------Present

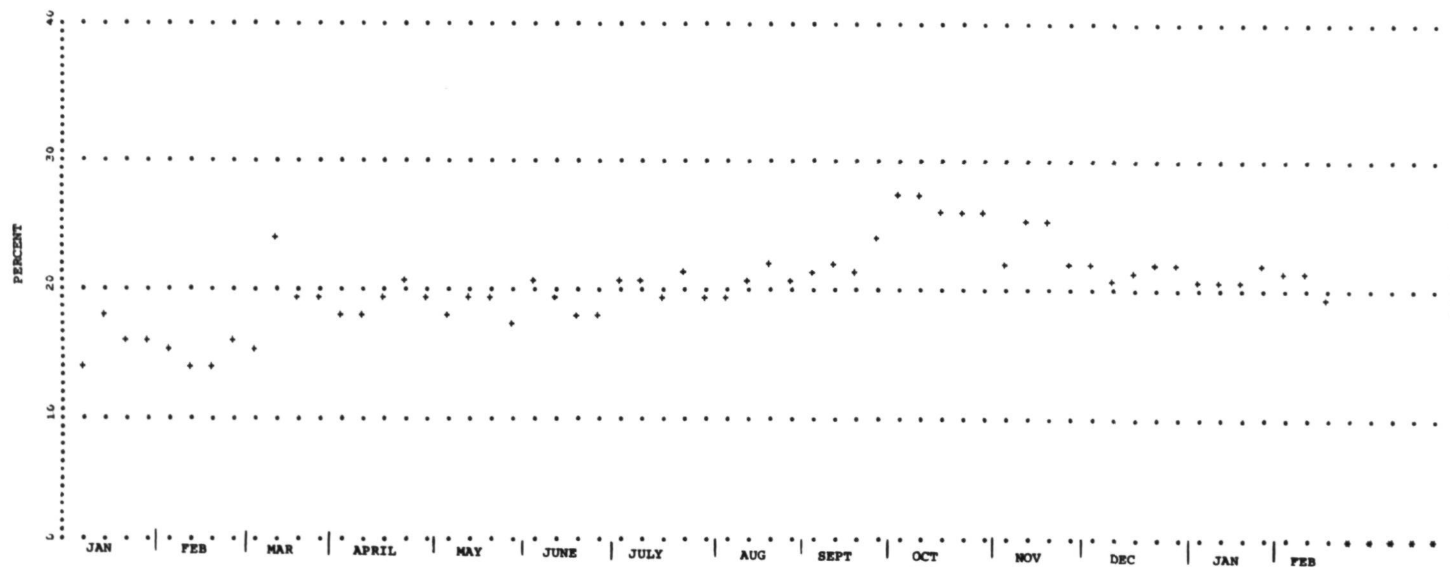
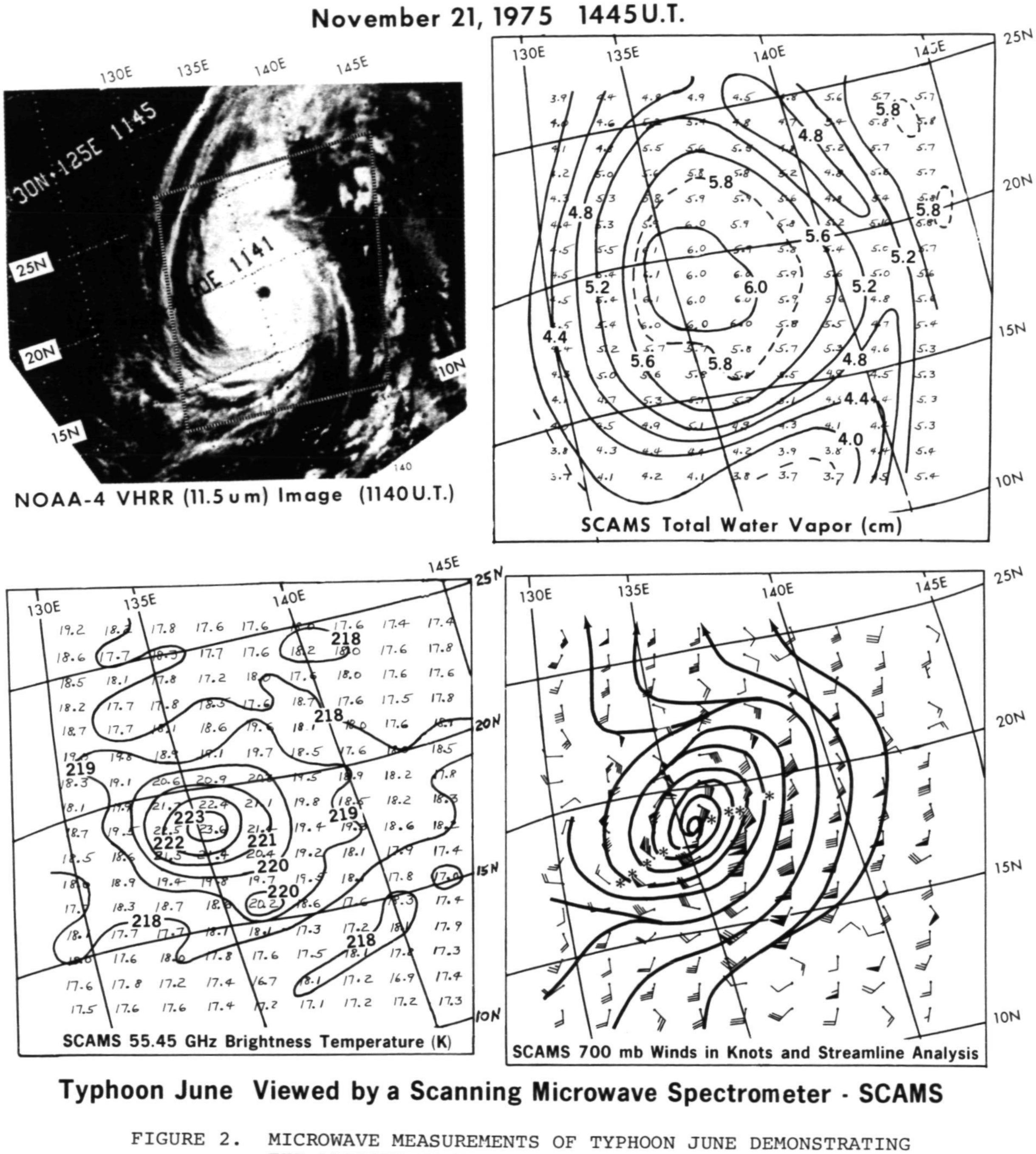


FIGURE 1. PERCENT OF POSSIBLE RETRIEVALS REJECTED AS BEING TOO CLOUDY BY THE CLEAR RADIANCE ALGORITHM BY WEEKLY INTERVALS FOR THE PERIOD FROM JANUARY 1976 THROUGH MARCH 1977.



Typhoon June Viewed by a Scanning Microwave Spectrometer - SCAMS

FIGURE 2. MICROWAVE MEASUREMENTS OF TYPHOON JUNE DEMONSTRATING THE ABILITY OF MICROWAVE MEASUREMENTS TO PROVIDE METEOROLOGICAL INFORMATION IN CLOUDY AREAS.

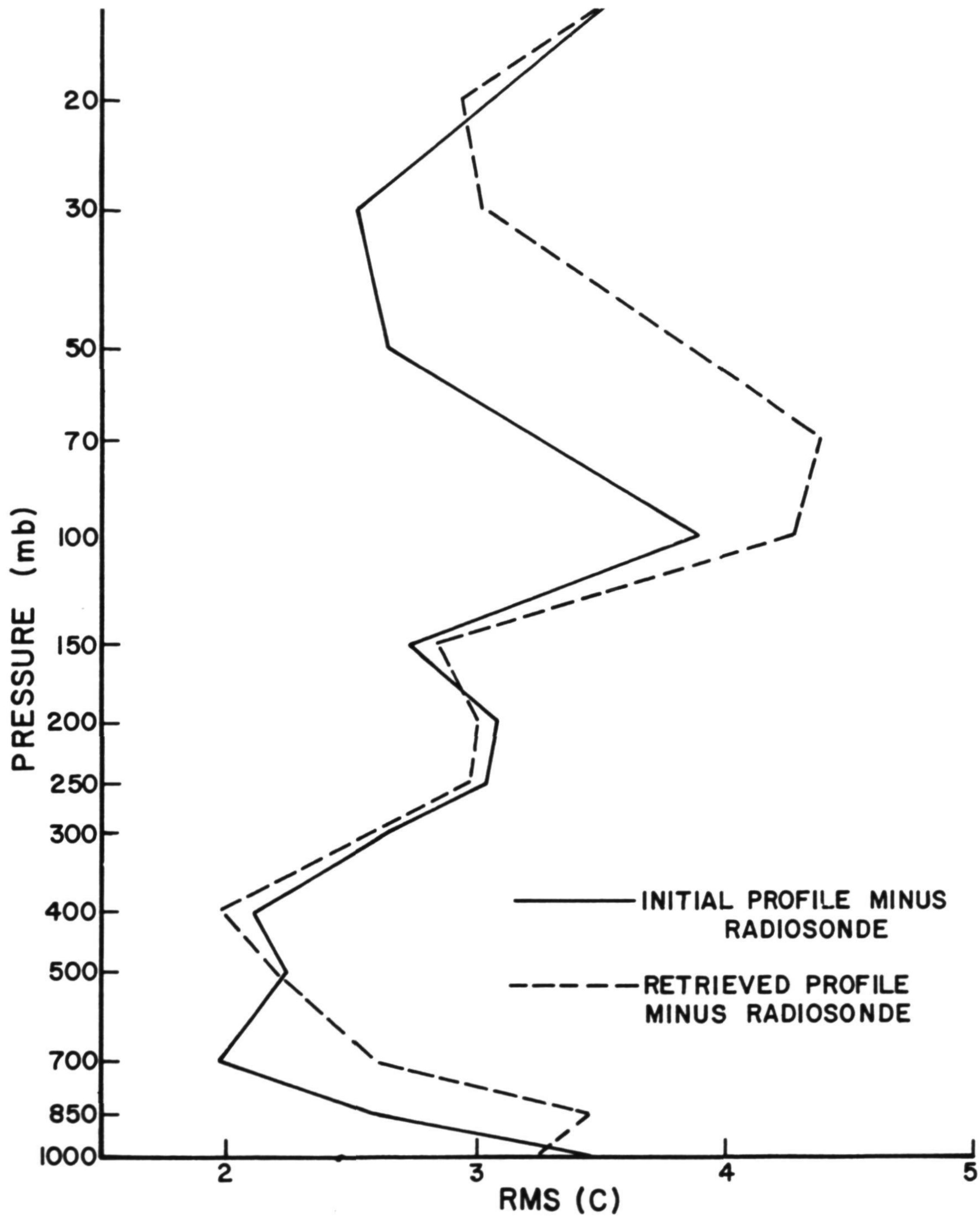


FIGURE 3. DIFFERENCES BETWEEN SATELLITES SOUNDINGS AND RADIOSONDES FOR NEARLY COINCIDENT AND NEARLY SIMULTANEOUS SOUNDINGS COLLECTED DURING MARCH 1973.