AN INITIAL APPROACH TO THE UTILIZATION OF VAS SATELLITE SOUNDING DATA

by

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FOREWORD

This report is not complete and, therefore, not ready for printing as a NASA Contractor Report. It documents the status of the research to date as required by the contract.

The research reported herein represents an extension to the scope of work in the contract. Much of the effort required to perform this research was not paid for by NASA, but the authors felt the research was too important to terminate until a point was reached when meaningful results could be presented. This point has been reached; however, additional research is required before conclusions can be reached. Hence, neither an abstract nor conclusions was prepared.

A proposal has been submitted to NASA to continue this valuable research. Hopefully, it will be funded and we will be permitted to continue in the near future.

1. INTRODUCTION

Since the first studies of Wark and Hilleary (1969) and Hanel and Canarth (1969) were reported, the satellite derived soundings of atmospheric temperature and moisture have been expected to provide additional data over data-sparse regions as well as between existing rawinsonde stations. Numerous studies have been performed to identify or improve the quality of satellite derived soundings. But their usefulness in numerical weather prediction remains in question. Different satellites have different types of radiometers for the vertical temperature and moisture soundings, but their retrieval algorithms are basically similar. Therefore, it might be worth discussing the results gained from different satellites.

Diagnostic studies of the quality of satellite derived soundings in relation to synoptic conditions have been made. Staelin et al. (1973), Waters et al. (1975), Arnold et al. (1976), and Horn et al. (1976) examined the qualities of NIMBUS-5 satellite soundings by comparing them to the colocated rawinsonde soundings, vertical cross-sections, and/or winds and other meteorological parameters of the two systems. Petersen and Horn (1977) and Scoggins et al. (1981) examined how well NIMBUS-6 and TIROS-N data can be used to depict the structure of the atmosphere. In their general results, the patterns of satellite derived soundings were consistent with the changing synoptic situation, but considerably less detail was present in the satellite soundings in both the vertical and horizontal.

McMillin et al. (1983) also analyzed data from TIROS-N. They found a pronounced annual cycle of differences between satellite and rawinsonde profiles which were smaller in summer and larger in winter. Koehler et al. (1983) analyzed the differences between TIROS-N and NOAA-6 temperature soundings and radiosonde observations. They found that the difference fields between the satellites and conventional thickness propagated eastward with the propagating synoptic systems, strongly suggesting a correlation of satellite sounding errors with synoptic patterns.

The impact of satellite data on numerical weather forecasting, and examination of the desirable attributes of satellite data have also progressed in many ways. The quality of satellite soundings must ultimately be justified by a demonstrated usefulness in operational weather analysis and prediction. Atkins and Jones (1975) assessed the impact of NOAA-2 soundings on the British Meteorological Office Forecasting Model. Bonner et al. (1976) assessed the impact of NOAA-2 soundings on the U.S. NMC forecasting model. The model results were slightly improved, but differences with and without satellite data were probably not significant, statistically or synoptically, in both cases. Kelly et al. (1978) tested the impact of high resolution NIMBUS-6 soundings on Australian region forecasts. They found that significant improvements in forecast accuracy were achieved in the Australian region. Druyan et al. (1978) performed a similar analysis using NOAA-4 data. Small, but statistically significant, improvements in forecasts were noted, although both positive and negative impacts were observed in individual cases. Ohring (1979) examined the impact of NOAA-2 and NIMBUS-6 soundings on numerical models. His results showed inconsistent but slightly positive impacts in the Northern Hemisphere. More recently, Thomasell et al. (1983) investigated the impact of satellite soundings on forecasting accuracy by comparing the results with and without satellite data on numerical weather forecasts. They concluded that the impact of satellite data was generally small, but a marked positive impact was found in the lower and middle troposphere over oceanic regions where conventional data are sparse.

The first VISSR Atmospheric Sounder (VAS) on GOES-4 was launched in the Fall of 1980. VAS can measure low noise radiances at 15 km resolution and can provide vertical soundings at 75-100 km horizontal resolution. Along with this fine horizontal resolution, the geosynchronous location of GOES satellites provides the capability for observing the development of mesoscale weather systems. Ground truth AVE/VAS experiments were conducted in the Spring of 1982 over the central Texas region to verify the quality of VAS soundings. These data sets now provide a unique opportunity to examine the accuracy, representativeness, and utility of VAS soundings. If the representativeness of VAS soundings can be understood in a meaningful way, the utility of VAS sounding data can be improved.

Using the AVE/VAS data, Rhodes and Scoggins (1984) and Jedlovec (1984) compared rawinsonde and VAS sounding data in the area of the special network (Fig. 1). Both studies used two different types of satellite data which were retrieved by NOAA-NESS and by NASA-GLAS. The analyses showed that the differences were not consistent in space and time, and the horizontal gradients determined from VAS soundings were generally weaker than those determined from rawinsonde soundings. Both studies suggested that two factors may be significant for the quality of VAS soundings: atmospheric structure and the retrieval scheme. Neither study addressed the significance of the differences in numerical model prediction, but both studies conclude that VAS soundings are inadequate for the purpose of conventional mesoscale analysis.

The common conclusion relative to satellite derived soundings is that these data contain less resolution in both horizontal and vertical direction than does rawinsonde data. The smaller resolution was expected. It should be emphasized that satellite soundings do not represent point values as do rawinsonde measurements. Satellite soundings average over many pixels in the horizontal, and over as much as several km in the vertical. Therefore, some degree of horizontal and vertical smoothing is inevitable. The VAS sounder uses six infrared channels for temperature retrieval, three for the surface skin temperature, and three for the moisture retrieval. Hence, only six independent channels which provide approximately 4 km vertical resolution are available. Therefore, the differences between the rawinsonde and satellite soundings are strongly affected by the ever changing day-to-day weather events which cannot be resolved in the retrieval process (Koehler et al., 1983). Fig. 2 shows that most major differences in the satellite profiles were produced by frontal inversions in the lower atmosphere. Therefore, a serious problem inherent in satellite soundings is their inability to detect small scale features. The inclusion of these local variations in the retrieval process is an important requirement for more successful satellite soundings.

The primary objective of this study is the development of methods to utilize satellite soundings. To achieve that, a more precise

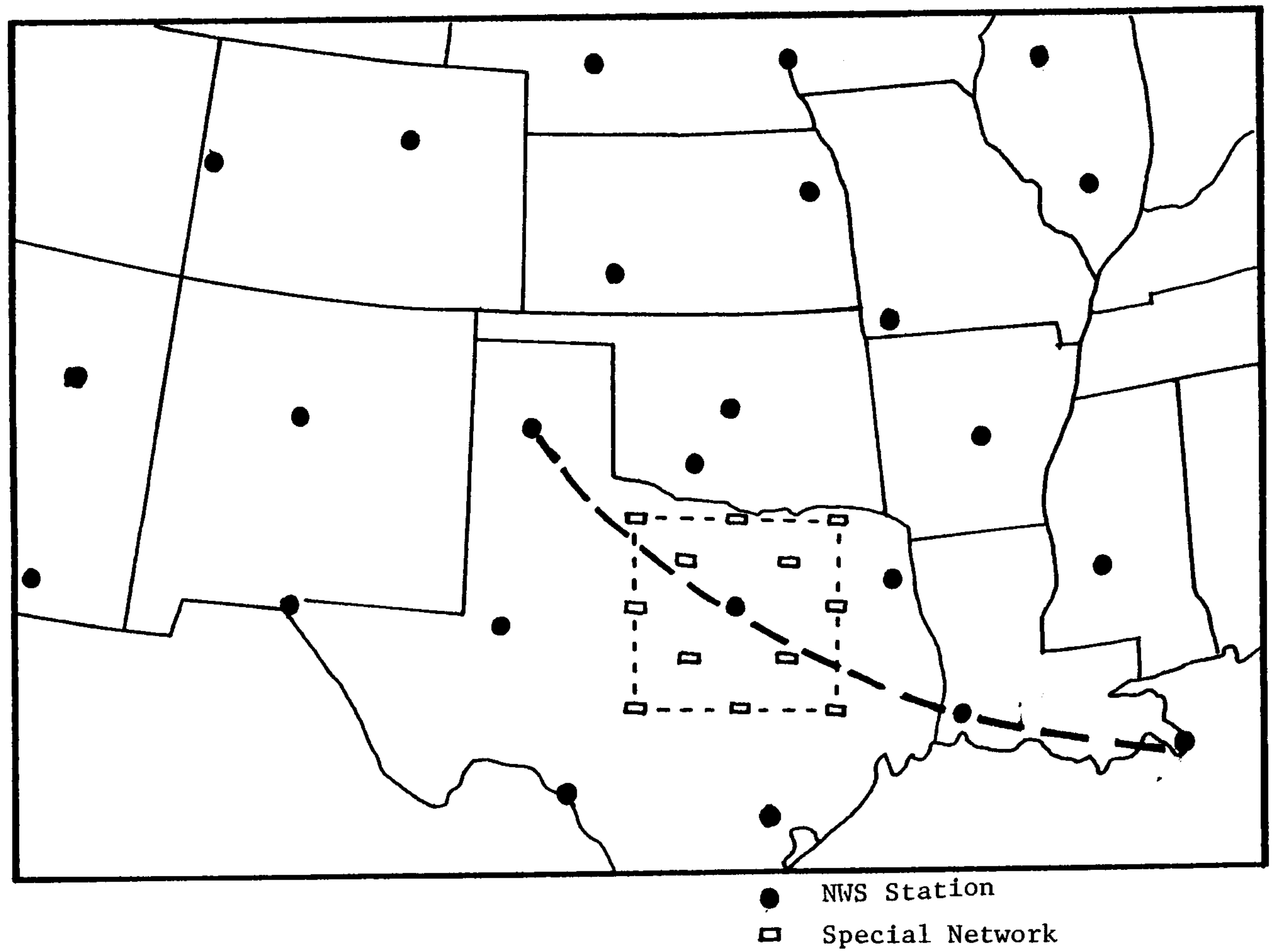


Fig. 1 The 1982 AVE/VAS Ground Truth Experiment rawinsonde network. The heavy dashed line indicates the crossection (see Fig. 2)

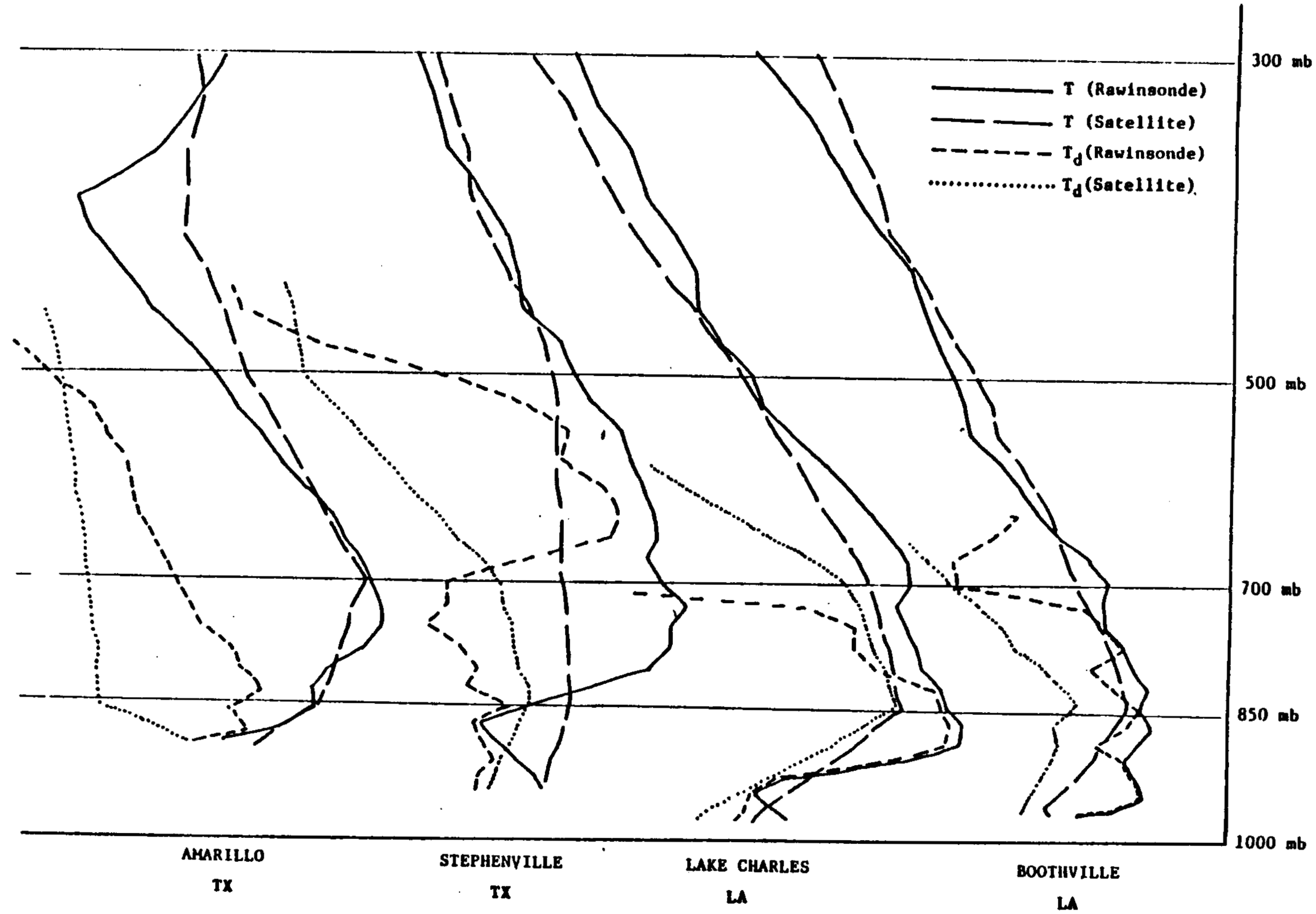


Fig. 2 Soundings plotted on a Skew T-log p diagram along the cross-section shown in Fig. 1 for 1100 GMT 6 March 1982.

understanding of the characteristics of satellite derived soundings is required. This goal has been partially achieved by Thodes and Scoggins (1984) and Jedlovec (1984). The initial approach in the utilization of satellite soundings is to find a way to combine rawinsonde and satellite data into a unified data set. If this can be done in a meaningful way, satellite data could be integrated into existing data and interpretation would be enhanced. In this attempt, both rawinsonde and satellite soundings will be decomposed by use of Fourier cosine series. Then, each harmonic will be compared to get a better understanding of the representativeness of the satellite sounding data. Harmonics taken from satellite and rawinsonde soundings will be combined to provide a unified data set that can be used both over data sparse ocean areas as well as over land where rawinsonde data are available.

2. DATA

Two types of data were used in this study: rawinsonde and satellite soundings. The rawinsonde data were collected during the AVE/VAS ground truth experiment. It contains the soundings which were observed at the regular synoptic stations, and soundings observed at the special network conducted by Texas A&M University personnel (Fig. 1). The special network has approximately 125 km spacing to detect mesoscale variability. The satellite data retrieved by the University of Wisconsin (NOAA-NESS) were used. Details of these data were described by Greaves et al. (1982) and Smith (1983). Both rawinsonde and satellite data were interpolated to 25-mb levels from the surface to 100 mb. Soundings were made at 3-hour intervals from 1200 GMT 6 March to 1200 GMT 7 March 1982. Examples of profile pairs are shown in Fig. 2.

The satellite measures the entire vertical extent of the sounding at a given location at one time, while the rawinsonde provides measurements as the balloon rises and drifts downstream. Disagreements in space and with time at some degree can be neglected for the purpose of synoptic scale analysis, while they can be significant in mesoscale analysis. Since the AVE/VAS ground truth experiment was well organized, the balloon release times differ only a few minutes from the time satellite soundings were taken in most cases. The balloon drift was generally 70-80 km from the origin and it took almost 1 hour to reach the 100 mb level.

An attempt was made to adjust the rawinsonde data for the time difference due to balloon draft between rawinsonde and satellite measurements. Based on the assumption of constancy of the upper level wind over a short time period, the position of the radiosonde corresponding to the time of the satellite sounding was determined at each level. If we let $(X_p(t), Y_p(t))$ be the location of the balloon at level p and time t after release, then the position of the radiosonde at level p at the time of the satellite sounding would be

$$(X_p(t_o), Y_p(t_o)) = (X_p(t) - U_p t, Y_p(t) - V_p(t))$$

where U_p and V_p are measured wind components at level p. Fig. 3 shows the example of adjustment to the sounding taken at Stephenville, TX, at 0200 GMT 7 March. If we compare the balloon drift distance to the range in which satellite data was averaged (75 km x 75 km), the drift range was placed inside the vertical column of the satellite sounding. With the uncertainties of the upper level wind with time, the rawinsonde soundings do not need to be adjusted for the time difference. As long as the soundings were colocated, the rawinsonde soundings represent atmospheric conditions reasonably well through the entire vertical column at the same time. Consequently, no adjustments were made to the rawinsonde data.

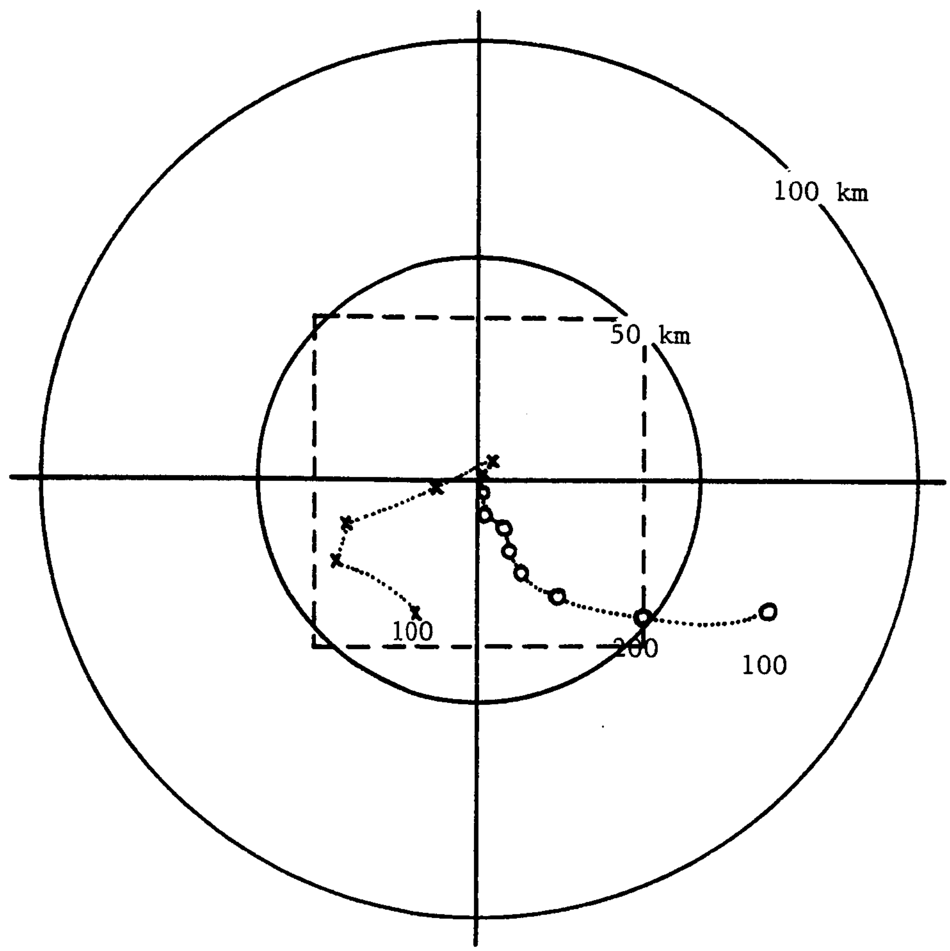


Fig. 3 Balloon location at each pressure level.
o represents the observed location and
x represents the adjusted location based
on the consistency of upper level wind.
Dashed box represents 75 km x 75 km satellite
averaging area. Some values indicate the
pressure level. Stephenville, TX, 0200 GMT
7 March 1982.

3. SPECTRAL REPRESENTATION OF VAS SOUNDINGS

3.1. Fourier Cosine Series

The characteristics of soundings can be represented by the sum of Fourier components. In application of Fourier series, however, the convergence criterion should be considered. Atmospheric temperature is continuous in the vertical, but the presence of sharp low-level inversions or changes in slope of the profile at the tropopause may represent discontinuities. There is no doubt that the profile is at least piecewise continuous. Therefore, the notion of pointwise convergence can be applied. This means that the sum of an infinite number of harmonics will exactly express the vertical profile, although the speed of convergence is not uniform, *i. e.*, not uniformly convergent in the presence of discontinuities. Practically, the sum of an infinite number of Fourier components is impossible when only a finite number of points are available. The sum of a few harmonics may be a good approximation for some levels, but it may be a bad approximation at or near the discontinuities.

Another important aspect in the application of Fourier series is the boundary conditions. Since the Fourier series is complete in the interval 0 to 2π, the periodic extension of the temperature profile requires that $T(0) = T(2\pi)$ for pointwise convergence. Otherwise, the Fourier series converges to the mean at or near the end points since discontinuities occur. This constraint hinders the actual application of Fourier series in order to represent the temperature profiles. Instead of using Fourier series, Fourier cosine series have more advantages in this analysis because no constraint is required for the boundary values to converge. In order to use the Fourier cosine series, the domain 1000 to 100 mb is transformed into 0 to π and assume an even extension from 0 to 2π. Then all sine terms vanish due to the evenness of the function. A Fourier cosine series guarantees at least pointwise convergence as long as the profile is piecewise continuous. Therefore, the Fourier cosine series was adopted to represent the vertical temperature profiles by the sum of harmonics. Since the cosine series is complete in the interval 0 to π, the fundamental frequencies will be multiples of $1/2(p_b - p_t)$, where p_b and p_t were chosen to be 1000 mb and 100 mb, respectively. The fundamental wavelength, therefore, would be 1800 mb, 900 mb, 450 mb, etc. In order to obtain the same harmonic frequencies for all profiles, each sounding was linearly interpolated from the surface to the 1000 mb level when necessary. Some rawinsonde profiles that did not reach 100 mb were eliminated.

Let T(p) be the temperature profile. Since T(p) contains vertical dependence, the layer mean lapse rate was subtracted first. That is,

$$T'(p) = T(p) - \bar{T}(p) \ .$$

$\bar{T}(p)$ was determined by

$$\bar{T}(p) = \frac{\bar{T}(100) - \bar{T}(1000)}{(P_b - P_t)} \times (p_b - p) \quad .$$

In this analysis the pressure coordinate system was used. The T'(p) profile was expressed by a Fourier cosine series as follows:

$$T'(p) \sim \frac{a_0}{2} + \sum_{n=1}^{N} a_n \cos(n\pi p^*)$$

where

$$p^* = \frac{(p_b - p)}{(p_b - p_t)}$$

and

$$a_n = 2 \int_0^1 T'(p) \cos(n\pi p^*) \, dp^* \quad .$$

Therefore, p* is 0 at 1000 mb and 1 at 100 mb. Both rawinsonde and satellite profiles were decomposed into Fourier cosine series. Since the objective is to represent profiles by harmonic components, the harmonic amplitude, a_n, of both rawinsonde and satellite profiles will be compared in various ways.

Fig. 4 and Table 1 are examples of Fourier cosine series decomposition. Table 1 shows that the amplitude generally decreases with increasing harmonic number, especially for satellite soundings. The amplitudes of lower harmonics were comparable in the two profiles, but considerably smaller for the satellite profile in the higher harmonics. This shows that higher harmonics in satellite soundings were filtered by smoothing. This will be discussed more in a later section. Fig. 4 illustrates how well the sum of a few harmonics represents the actual temperature profiles. Results for rawinsonde profiles clearly show that the speed of convergence is slow at or near discontinuities. The partial sum up to the 5th harmonic may be a good approximation in the mid-troposphere, but a bad approximation in the lower troposphere and near the tropopause. The sum up to the 10th harmonic is a good approximation for all levels. On the other hand, satellite profiles can be represented by the sum of up to the 5th harmonic since these profiles are smoothed. Even the sum of the first three harmonics gives a reasonably good fit for the profiles.

3.2. Comparison at the paired locations

The amplitude of each harmonic of a satellite profile was compared to that of the colocated rawinsonde profile to evaluate the representativeness of satellite soundings in the spectral domain. Although the rawinsonde sounding itself contains measurement errors, it can be treated as a good representation of atmospheric conditions. The paired soundings were selected if the satellite sounding was observed within a range of 50 km of the rawinsonde sounding location. It is expected that this difference in location can potentially produce discrepancies between the rawinsonde and satellite soundings. However, this discrepancy can be assumed small, and is ignored in this analysis.

Two data sets at 2300 GMT 6 March, and 0200 GMT 7 March 1982 were selected for this analysis. At other times most of the sounding area was covered by clouds and satellite soundings were not available for much of the region. There were 21 pairs at 2300 GMT and 27 pairs at 0200 GMT. Figs. 5 and 6 show, respectively, the mean absolute value of

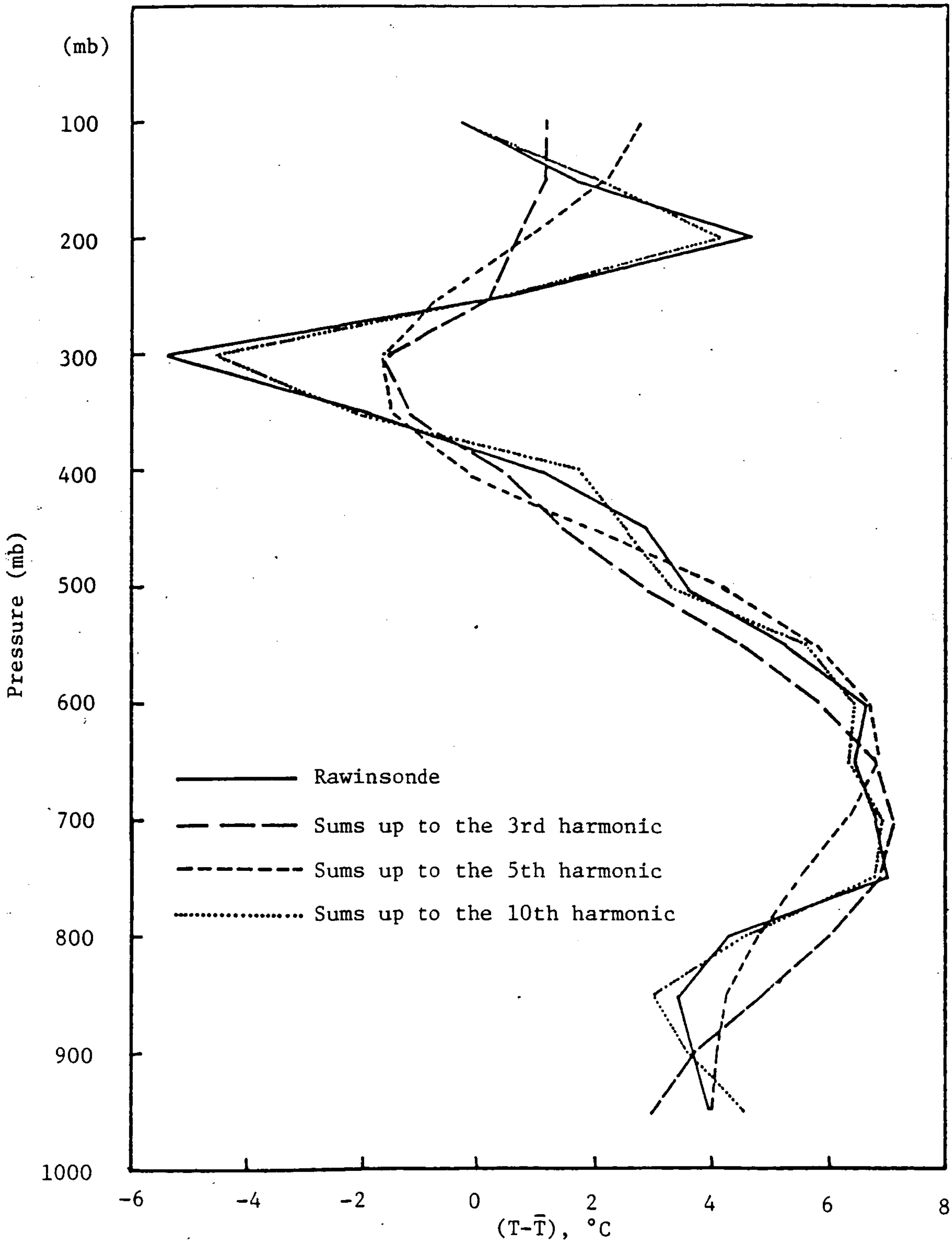


Fig. 4. a) Comparisons of partial sums of the Fourier Cosine series. Rawinsonde profile after removing vertical means. Stephanville, TX, 0200 GMT 7 March 1982.

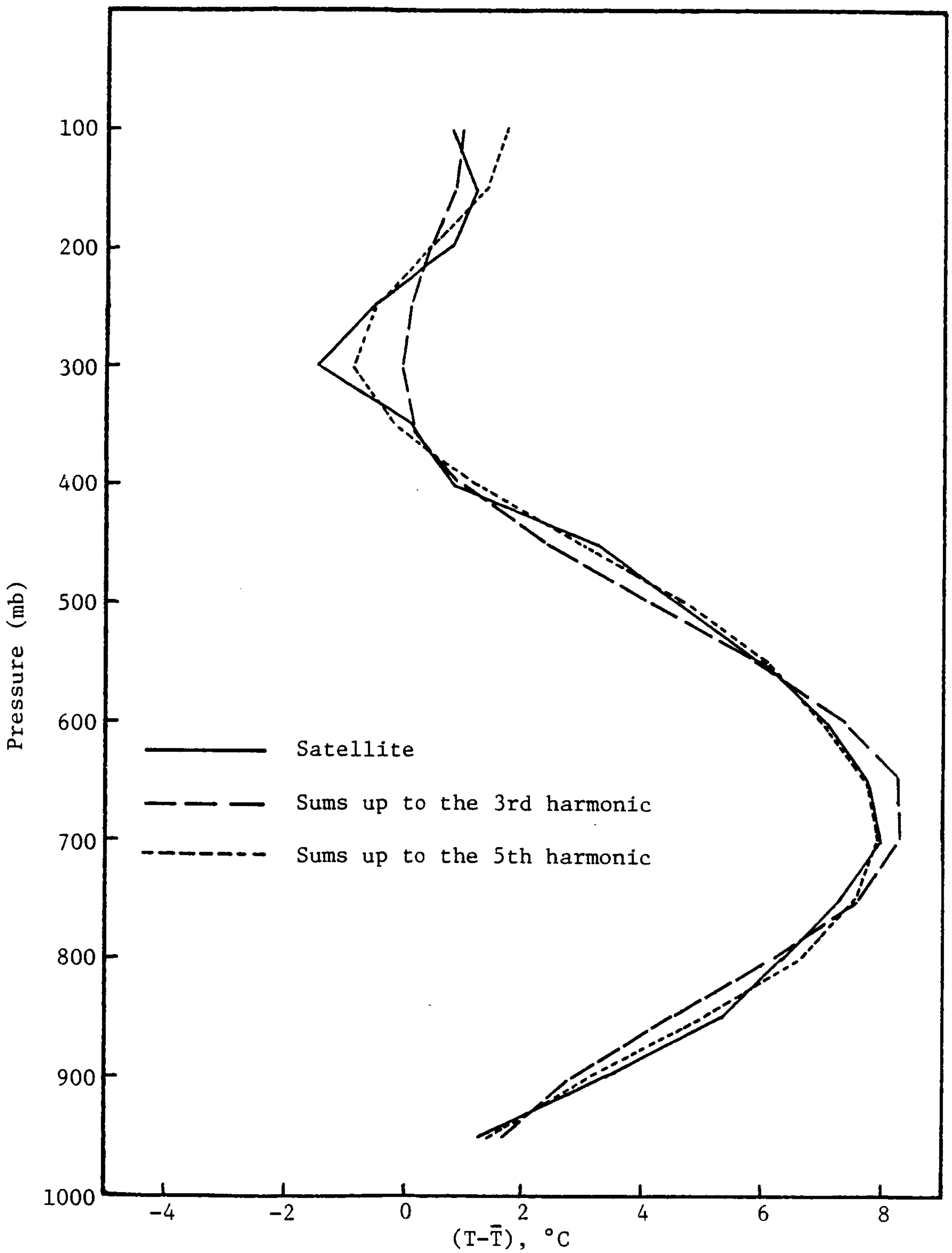


Fig. 4. b) Same as Fig. 4.a) except for the satellite.

Table 1. An example of the harmonic amplitude of rawinsonde and satellite temperature profiles at Stephenville, TX, 0200 GMT 7 March 1982.

Harmonic number	Amplitude: Rawinsonde sounding 32.22N 98.18W	Amplitude: Satellite sounding 32.49N 98.15W
0	3.15	3.46
1	2.75	2.54
2	-1.22	-2.40
3	-1.98	-2.40
4	1.45	0.18
5	-0.17	-0.64
6	0.43	-0.17
7	0.93	-0.11
8	-0.78	-0.23
9	1.15	-0.02
10	-0.94	-0.15
.	.	.
.	.	.
.	.	.

the amplitude of each harmonic component and its standard deviation for the paired profiles. The absolute value was taken of the amplitude at each pressure since a negative amplitude simply means a phase shift.

In Fig. 5, the amplitudes of higher harmonics drop off quickly with increasing harmonic number. Most of the important portion of the vertical temperature profiles is contributed by harmonics up to the 5th in both types of soundings, but the contribution is greater for satellite profiles than for rawinsonde profiles. Some portion of the amplitude still remains in the higher harmonics for rawinsonde profiles. Generally speaking, the amplitude of harmonic components in the lower harmonics in the satellite profiles were comparable to those of rawinsonde prifiles, while those of satellite profiles in the higher harmonics were not. This shows clearly the smoothing inherent in the satellite profiles.

Fig. 6 shows that the large standard deviations in the lower harmonics, generally up to the 5th harmonic, suggest that the harmonic amplitude of temperature profiles may vary a lot from sounding to sounding. Therefore, the mean absolute amplitude in Fig. 5 may not be a proper statistic. However, the small standard deviations beyond the 5th harmonic also suggest that the contributions of higher harmonics were generally insignificant, even in the individual profiles. In any case, the dispersion of each harmonic amplitude of the satellite soundings was smaller than that of rawinsonde soundings.

Fig. 7 shows the average percentage of variance explained by each harmonic in the soundings. This is different from Fig. 5 since the relative importance of each harmonic in the soundings is presented. The zeroth harmonic, the mean value of the profiles, was excluded because it does not contribute to the variance. It is obvious that most of the variance is contributed by the first five harmonics with higher harmonics contributing negligibly, especially in the satellite profiles. It is interesting that the relative distribution of variance over frequency is almost constant for the rawinsonde profiles for the two times shown in Fig. 7. However, the absolute values of the amplitudes of each harmonic are different at both times (see Fig. 5), which indicates that differences in the rawinsonde profiles were present over the

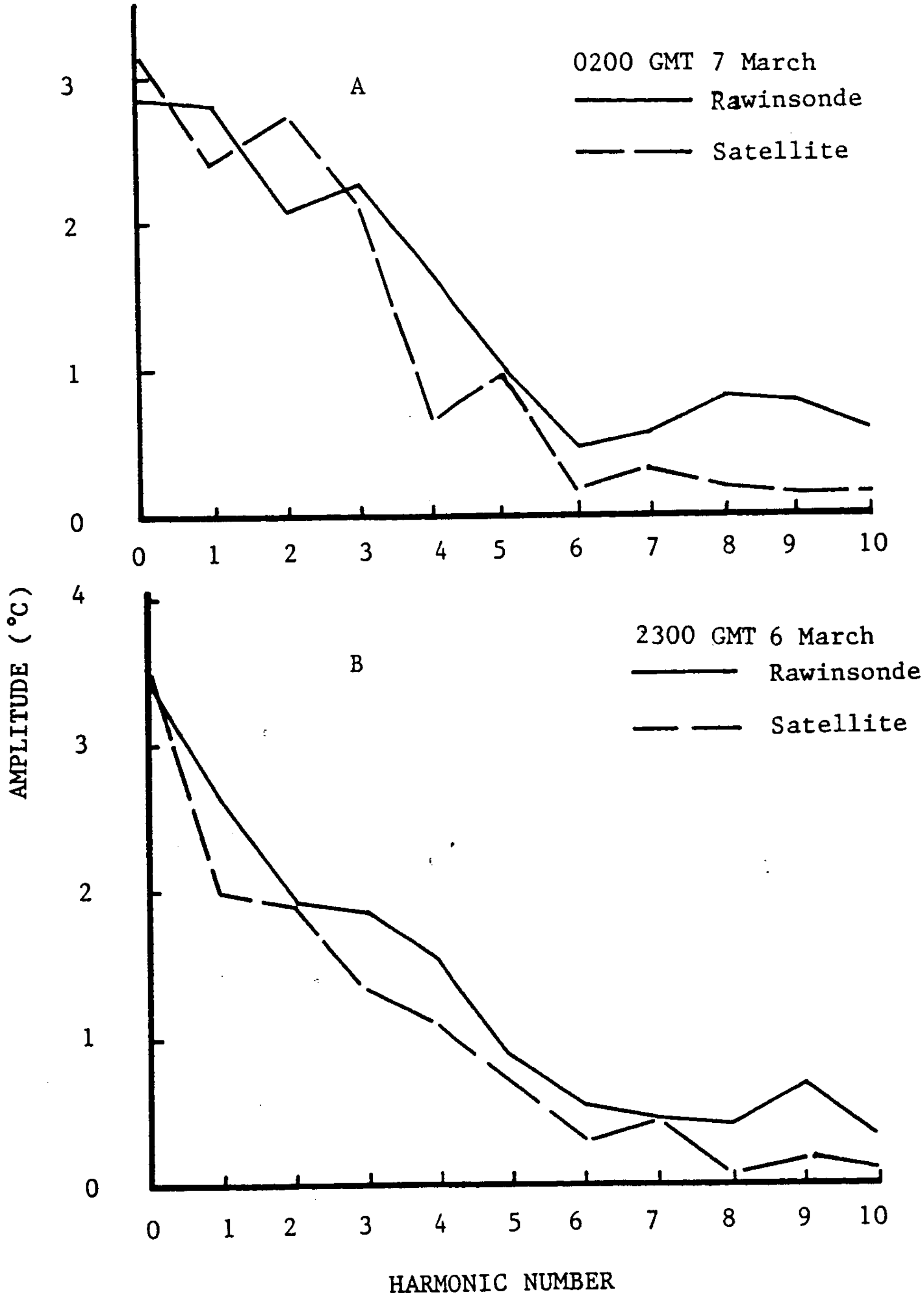


Fig. 5. The comparisons of mean absolute amplitude of each harmonic between rawinsonde and satellite profiles. A: 0200 GMT 7 March; B: 2300 GMT 6 March 1982.

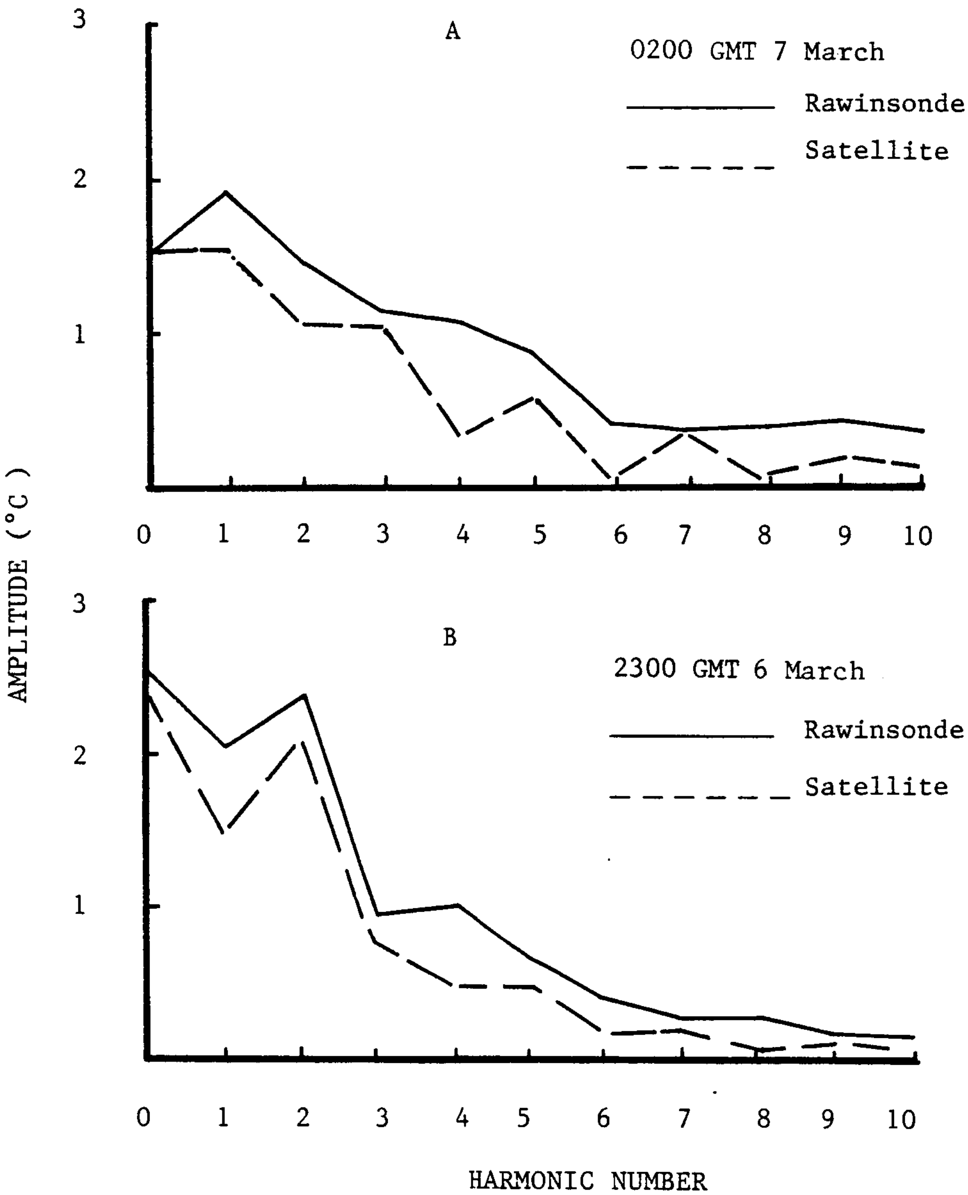


Fig. 6. Same as Fig. 5 except for the standard deviation.

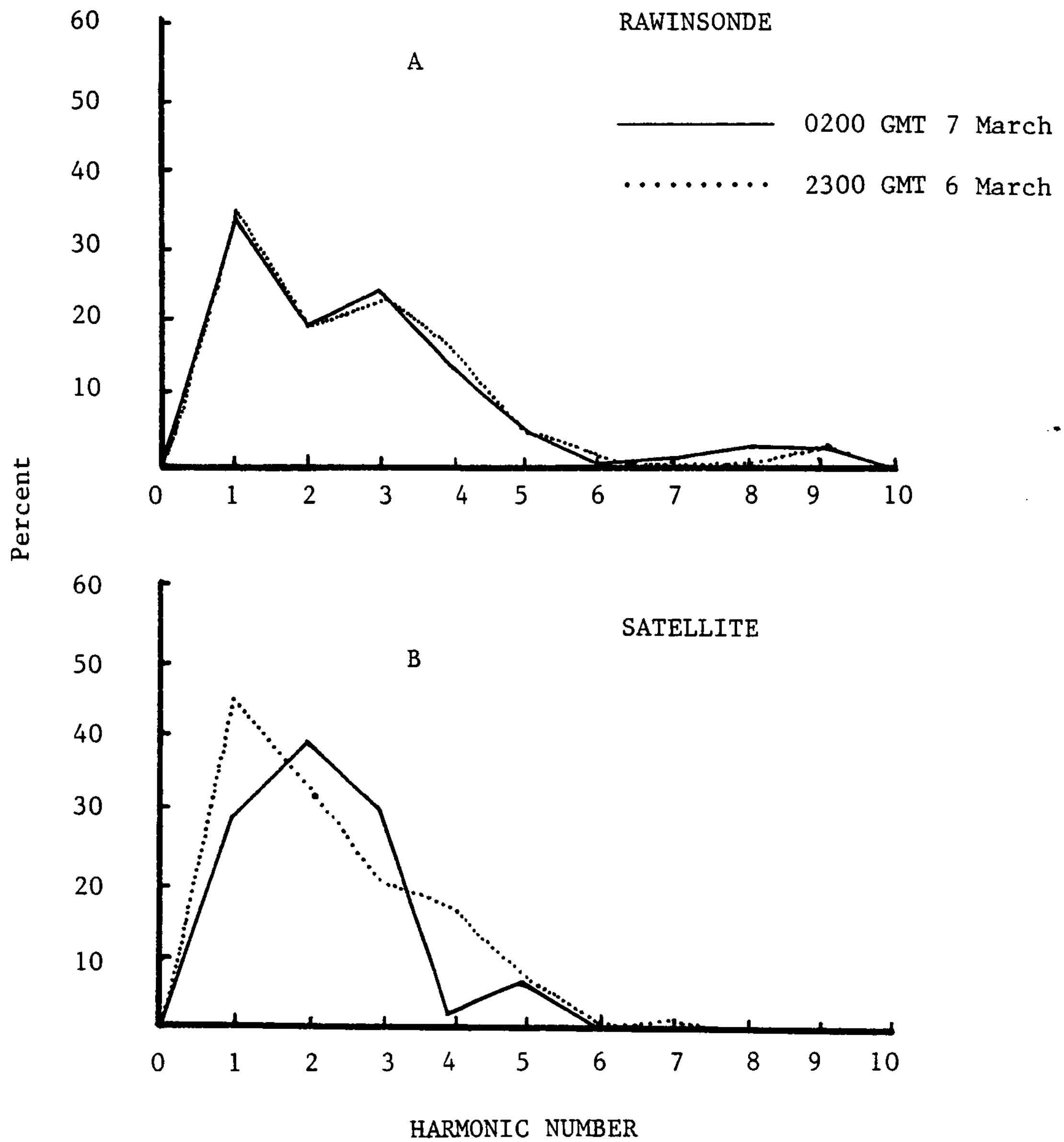


Fig. 7. Percentage of variance accounted for by each harmonic.
A: Rawinsonde profiles; B: Satellite profiles.

3-hour period. The relative importance of each harmonic in rawinsonde data may not change during a 3 hour interval even though the variances may be reduced or increased during that time. The statistics for satellite profiles (Fig. 7) are different at the two times. Due to the different cloud coverage at different times and perhaps other factors, satellite data are not as consistent as the rawinsonde data.

3.3. Comparison at Grid Points

It is helpful in describing the characteristics of satellite soundings to see how the amplitude of each harmonic was distributed in the horizontal. If the horizontal distribution patterns of amplitude of any harmonic component are similar for satellite and rawinsonde profiles, the relative horizontal variation is represented by the satellite soundings for that harmonic component.

The amplitudes of harmonics were interpolated to a grid with equal spacing of grid points. A grid of 15 x 11 points with a spacing of 158 km was established. The analysis technique proposed by Barnes (1964) was used with four iterations. Since the average distance between synoptic upper air sounding stations over the continental United States is approximately 400 km, the minimum resolvable wavelength in this network is 800 km in the horizontal. Any weather pattern which has wavelengths smaller than this scale would not be detected or not be properly represented. The scan radius was chosen to be four times of grid distance which suppresses the amplitudes of wavelengths less than the minimum resolvable wavelength. The filter function for this gridding procedure is presented in Fig. 8. The same scan radius was applied to satellite data.

The mean and variance of the amplitude of each harmonic, and the corelation coefficient between rawinsonde and satellite data were calculated from grid point data. The correlation coefficient was calculated by

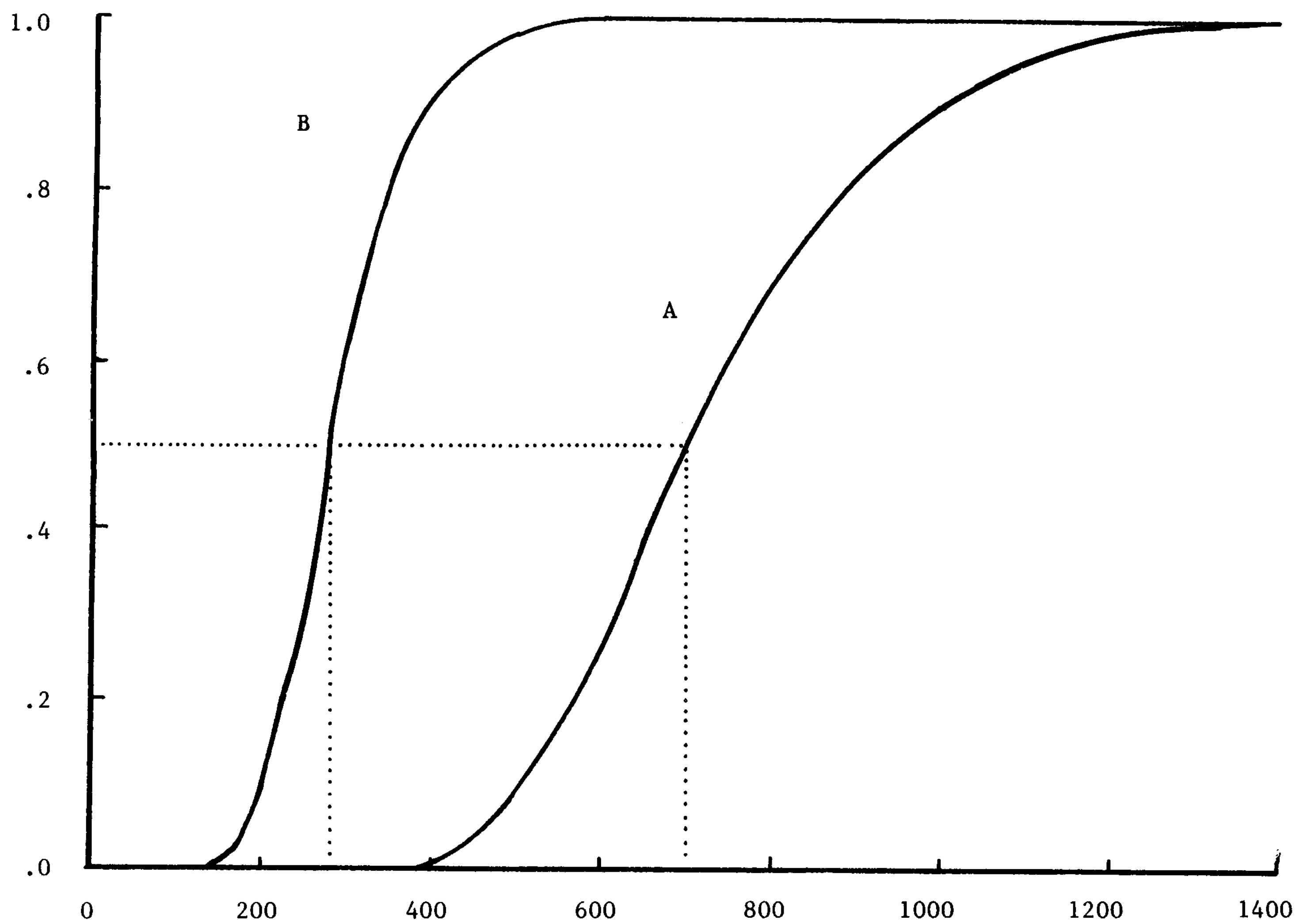


Fig. 8. The filter functions for the Barnes' grid interpolation method with four iterations. A: For synoptic scale analysis with 640 km scan radius; B: for mesoscale analysis with 250 km scan radius (see Section 4.3). The dotted lines show cut-off wavelengths corresponding to 50% amplitude resolution.

$$C_k = \frac{\sum_{i=1}^{N} \sum_{j=1}^{M} (A_{ijk} - \bar{A}_k)(B_{ijk} - \bar{B}_k)}{(N \times M) \sqrt{\sigma_k^{2}(A)\ \sigma_k^{2}(B)}}$$

where i and j represent the grid points in the N by M grid system, k is the kth harmonic, A and B are the harmonic amplitudes of rawinsonde and satellite, respectively, C is the correlation coefficient, and σ^2 is the variance. The mean and variance of each harmonic component, and the correlation coefficient may be used to determine similarity of the horizontal patterns and intensity for satellite and rawinsonde data. If the satellite field is exactly the same as the rawinsonde field, then the correlation coefficient would be one and the means and variances would be equal. However, it is possible for the correlation to be different from one with the same means and variances. Therefore, all of these three statistics are equally important. The correlation coefficient is particularly useful for the similarity of patterns, and the variance for the similarity of intensity. Table 2 shows the results for 2300 GMT and 0200 GMT.

The results in Table 2 show some unique features. At both times, the mean amplitude of the harmonics decreases rapidly with harmonic number. The corresponding decrease of variance may be due either to the fact that the higher harmonic amplitudes are initially small, or that filtering during retrieval and gridding suppressed the higher harmonics. These results confirm that satellite profiles contain less detail than rawinsonde profiles as many previous investigators have reported.

An interesting feature is the tendency for the correlation

Table 2. Statistics for comparison at grid points. The mean, variance, and correlation coefficient are presented for each harmonic.

0200 GMT 7 March

Harmonic number	0	1	2	3	4	5	6	7	8	9	10
Mean of RAW.	2.7	2.6	-3.2	-1.8	1.3	-1.4	0.5	0.1	0.0	0.4	-0.4
Mean of SAT.	2.7	1.4	-3.3	-1.5	0.4	-1.0	0.1	-0.3	-0.1	-0.0	-0.2
Variance of RAW.	11.0	10.5	6.7	4.6	2.2	1.1	0.4	0.3	0.8	0.3	0.1
Variance of SAT.	10.1	7.2	4.2	2.2	1.0	0.7	0.1	0.2	0.0	0.1	0.0
Correlation RAW. vs SAT.	.98	.96	.74	.91	.82	.73	.22	.42	.26	.28	.24

2300 GMT 6 March

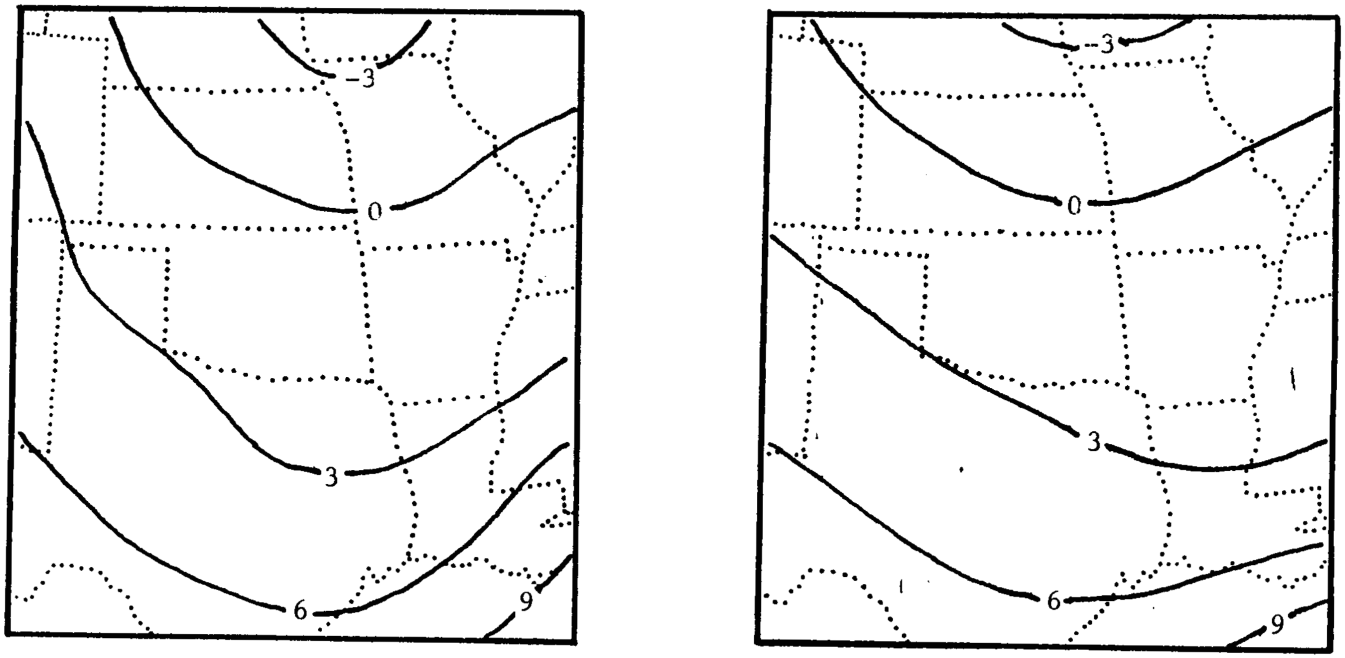
Harmonic number	0	1	2	3	4	5	6	7	8	9	10
Mean of RAW.	3.8	3.1	-2.7	-1.2	1.5	-1.5	0.7	0.1	0.0	0.4	-0.2
Mean of SAT.	3.5	2.2	-2.4	-0.4	0.8	-0.3	0.3	0.0	0.0	0.1	-0.1
Variance of RAW.	9.2	7.4	10.7	5.0	2.6	1.0	0.2	0.4	0.3	0.3	0.2
Variance of SAT.	7.1	5.5	4.0	3.2	1.1	1.2	0.1	0.2	0.0	0.0	0.0
Correlation RAW. vs SAT.	.98	.97	.89	.87	.84	.54	-.02	.54	.35	.23	.23

coefficient between satellite and rawinsonde to decrease with harmonic number and the sudden drop beyond the 5th harmonic. This suggests that the satellite patterns for higher harmonics are erronously represented and almost useless. The high correlation for the lower harmonics suggests that these harmonics are quite useful since their horizontal patterns agree well with changing weather patterns except for less detail. This conclusion is consistent with previous findings that the patterns of satellite derived soundings were consistent with the synoptic weather patterns but with less detail. The horizontal patterns of harmonics up to the 5th are presented in Fig. 9.

3.4. Characteristics of VAS Soundings

The comparison of paired soundings and data interpolated to grid points showed that satellite profiles were well represented by up to the 5th harmonic, and that these amplitudes well represent the real variations of weather patterns but not intensity. Harmonics higher than the 5th incorrectly represent the real variations and their contributions were small. The harmonic content of satellite profiles is directly related to the vertical resolution of the satellite sounding system. In order to represent the first five harmonics, at least five data points are required. Although VAS has six infrared channels for the vertical temperature retrieval, there are five available channels between 100 mb and 1000 mb. The 14.7 μm wavelength channel has its peak weight at 70 mb. Therefore, the resolution is limited to the 5th harmonic. However, the peak weight is not equally distributed with pressure. Therefore, it is expected that some degree of uncertainties will be present in the harmonic amplitudes.

The computation of harmonics beyond the available resolution incorrectly represents real variations, and this must be the obvious limitation of the satellite sounding system.

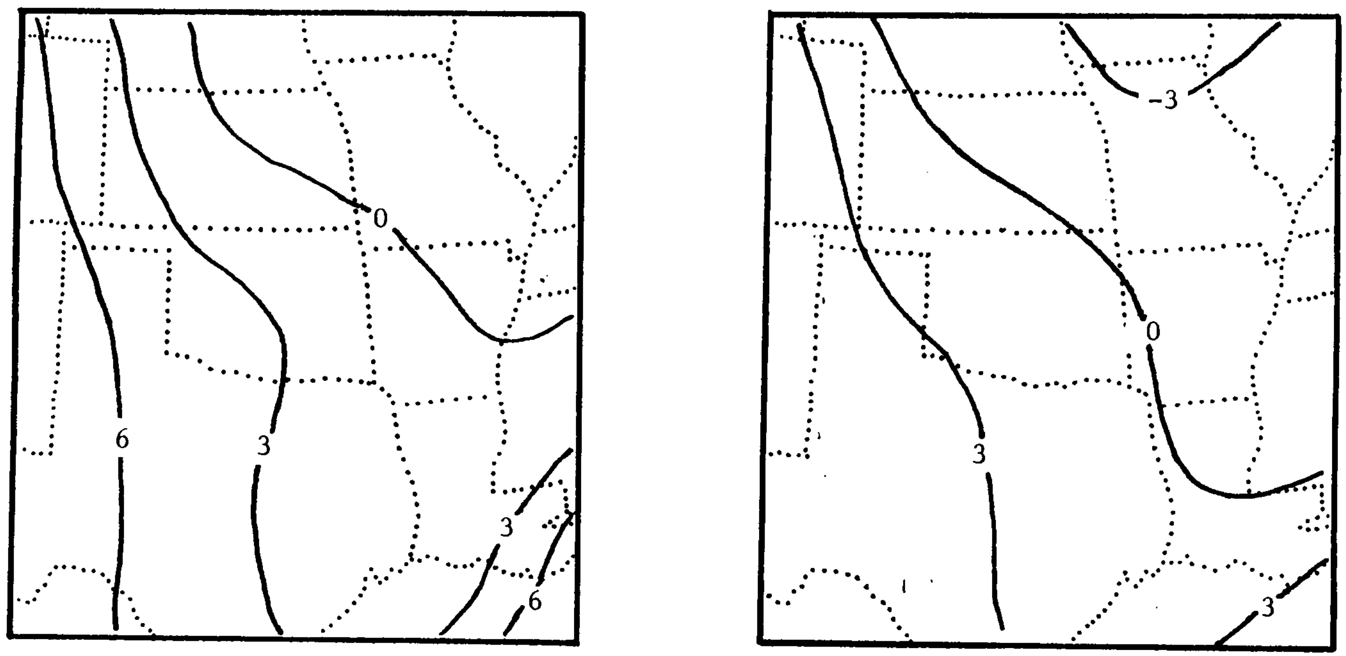


Rawinsonde

Satellite

Zeroth harmonic

Fig. 9. The horizontal patterns of harmonic amplitude, 0200 GMT 7 March.

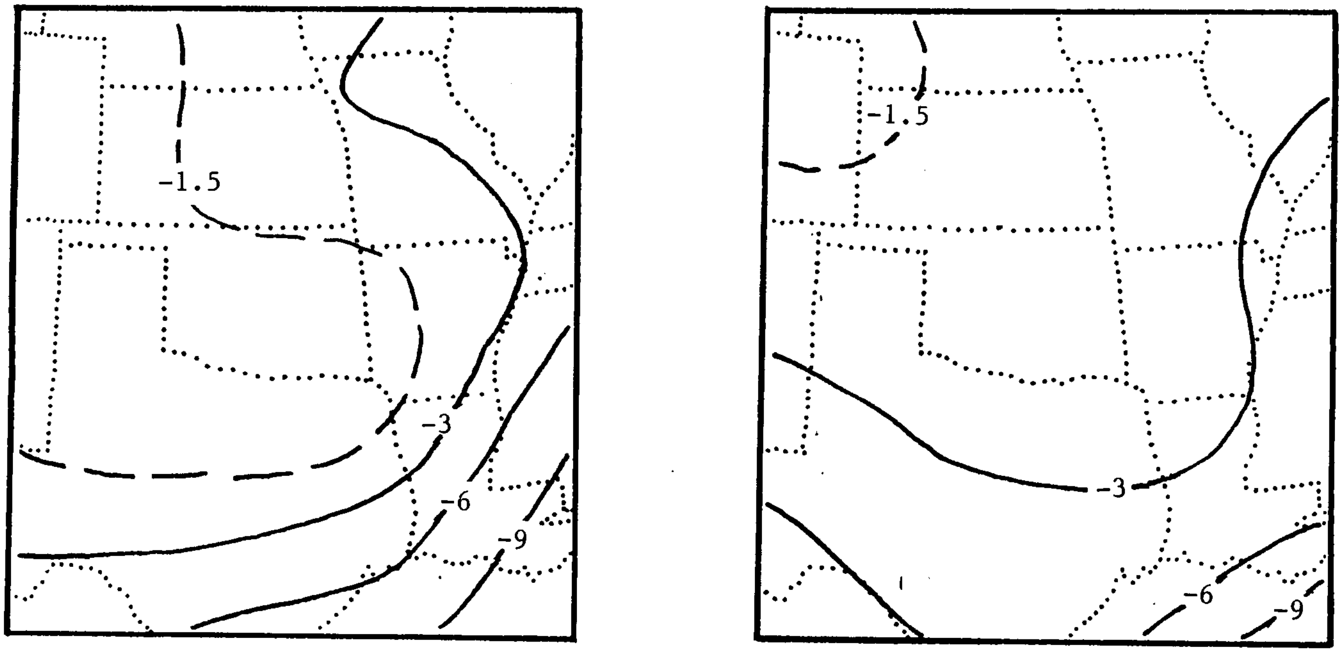


Rawinsonde

Satellite

First harmonic

Fig. 9. (Continued).



Rawinsonde Satellite

Second harmonic

Fig. 9. (Continued).

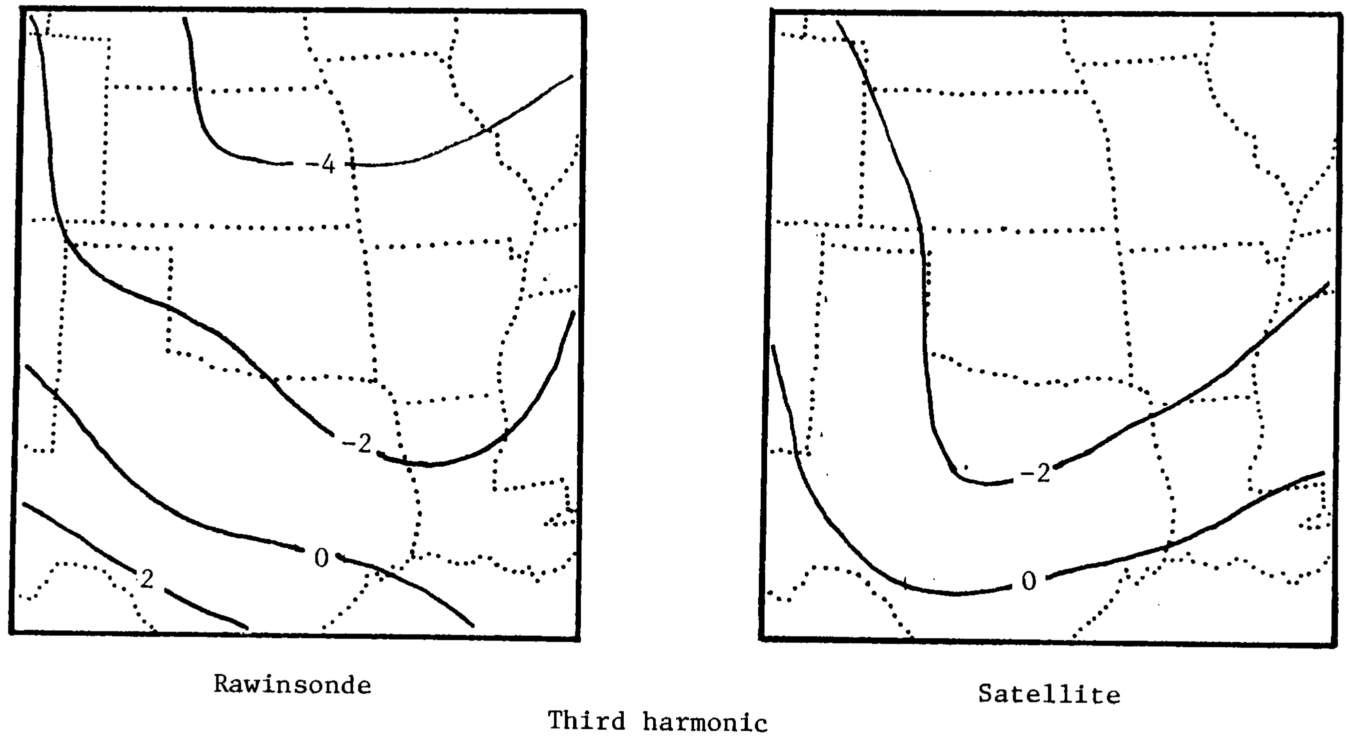


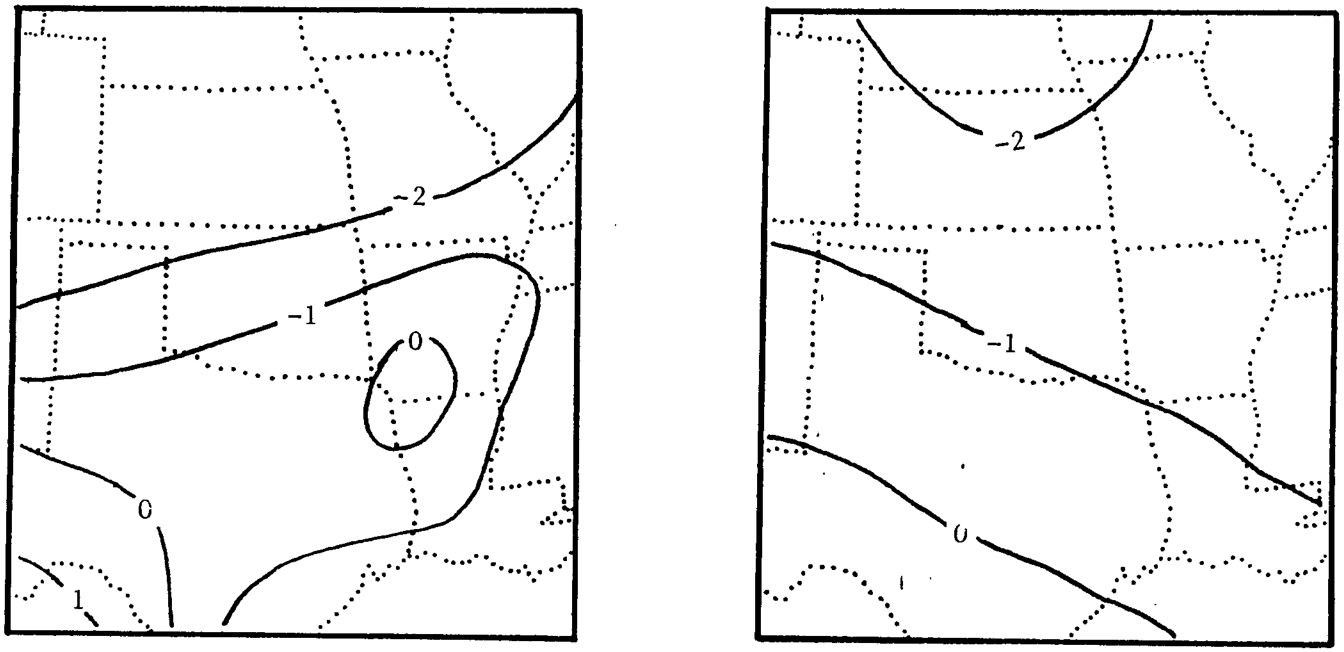
Fig. 9. (Continued).

Rawinsonde

Satellite

Fourth harmonic

Fig. 9. (Continued).



Rawinsonde

Satellite

Fifth harmonic

Fig. 9. (Continued).

4. THE UNIFICATION OF RAWINSONDE AND SATELLITE PROFILES

4.1. Problems

The VAS satellite sounding system has the potential for providing soundings over data-sparse regions such as over oceans, and additional soundings between rawinsonde observations needed to improve the horizontal resolution for mesoscale analysis. However, as discussed earlier, the satellite data contain uncertainties and its representativeness differs from that of rawinsonde data. In the case of synoptic analysis, large scale patterns with strong gradients are represented quite well by satellite data, but for mesoscale analysis both the gradients and patterns are poorly represented. Therefore, without any modification, the direct use of satellite-derived vertical soundings is restricted in many cases.

The origin of weak horizontal gradients might be the result of smoothing during the retrieval process. This weak horizontal gradient is illustrated in Table 2 by the small horizontal variance of the amplitude of each harmonic in the satellite soundings. Therefore, horizontal variability and gradients can be improved only by improving the retrieval process.

The disagreement in mesoscale patterns may be the result of weak correlation coefficients between rawinsonde and satellite data with increasing harmonic number. In Table 2, relatively small correlation coefficients between the 2nd harmonic and harmonics higher than the 4th significantly affect the mesoscale patterns at 0200 GMT. Therefore, improvement in the correlation pattern would improve the data quality and consistency in mesoscale analysis.

The approach used in this study is to combine simultaneous measurements of rawinsonde and satellite profiles to form a unified data set. The use of rawinsonde soundings to improve satellite soundings has been attempted previously by others. Weinreb and Fleming (1974) attempted the use of colocated rawinsonde soundings to adjust the measured satellite radiances. Although some improvements in reducing the rms discrepancy between retrieved temperatures and rawinsonde measurements were achieved, especially near the surface and tropopause, improvements were not significant in general. Smith et al. (1974) and Susskind et al. (1976) also used the colocated rawinsonde measurements to modify the transmittance functions which is one of the significant sources of uncertainties in the retrieval process.

The method requires rawinsonde soundings over the area of interest. Therefore, it may not be applicable to the region where rawinsonde observations are not available or severely restricted, such as over the oceans. Consequently, two separate methods have been investigated for the purpose of utilization of satellite data over data sparse regions as well as over regions where regular synoptic upper air soundings are available. Over oceans the satellite soundings may be used alone, or data extracted from computer-generated charts may replace the rawinsonde data.

4.2. The utility of satellite data over data sparse regions

Methods used in the evaluation of atmospheric conditions over oceans depend primarily on a limited number of observations most of which are made on islands. Of course, various analysis procedures and model results are used to maximize the utility of the data. Because of the limited amount of data available, the analyzed fields over ocean areas must be highly smoothed, thus eliminating the smaller scales. Although a number of sophisticated objective analysis methods are available to evaluate atmospheric conditions over oceans, their capabilities are restricted to large scale phenomena. Since these objective methods can reasonably evaluate the large scale variations, the lower harmonic amplitudes may be more accurately estimated from analyses based on conventional data than from those based on satellite observations alone. On the other hand, satellite soundings contain real variations through the fifth harmonic as indicated by correlation coefficients determined from the horizontal patterns. Therefore, over oceans where rawinsonde soundings are sparse to non-existant, some of the higher harmonics can be more reasonably accounted for by satellite data than by rawinsonde data.

It is believed that the combination of the zeroth and first harmonics obtained from rawinsonde data, and higher harmonics obtained from satellite data may improve the overall representation of fields over the oceans. The choice of the zeroth and first harmonics from rawinsonde data is mainly to improve vertical resolution and eliminate bias. The higher harmonics determined from satellite data are believed to represent the higher frequency horizontal variations not present in rawinsonde data. Over the oceans where rawinsonde soundings are not available, results from numerical prediction models may be used to determine the zeroth and first harmonics relatively accurately.

The procedure for combining the rawinsonde and satellite harmonics is as follows.

1. The zeroth and first harmonics for all satellite temperature profiles are computed, summed, and subtracted from the total profile in order to determine contributions from all harmonics higher than the first. The harmonics were calculated relative to a mean profile determined by linearly interpolating between the lowest and highest pressure surfaces. The remainder which represents the frequency content above the first harmonic was determined by subtracting the sum of the zeroth and first harmonics from the total profile.

2. The remainder determined in 1. was interpolated for each grid point.

3. The zeroth and first harmonics were computed from rawinsonde data and interpolated to the grid points.

4. The zeroth and first harmonics from rawinsonde data and the remainder defined above for satellite data were combined as a function of pressure to form a unified data set.

The logic for combining harmonics from two types of data in this fashion is based on the relative contribution to the profile by various harmonics and the desire to eliminate any bias that might be present in the satellite data. The zeroth and first harmonics obtained from rawinsonde data or from numerical models is intended to eliminate any systematic bias in the large scale variations of the parameter across an area, while the second and higher harmonics obtained from satellite profiles and determined relative to the mean lapse rate is intended to represent the higher frequency variations measured by satellite. Potentially, this unified data set should contain information on large scale systems with all biases eliminated, and information on higher frequencies (smaller scale systems) determined from satellite data and represented equally well over water as over land.

The combined data set was tested by using data from the AVE/VAS experiment. In this evaluation, the rawinsonde soundings collected at the special network were excluded, and only the regular synoptic upper air sounding data were used. These soundings were treated as the true state. The comparisons between the rawinsonde data and satellite data, and the rawinsonde data and combined data were made at the grid points. The grid interpolation method, the grid system, and the scan radius were the same as used in the previous section. The mean and standard deviation of the differences between the data sets as well as the correlation coefficients between the temperature fields were computed at each level. Table 3 summarizes the results at five selected levels (850, 700, 500, 300, and 200 mb).

In Table 3, most of the mean differences between the rawinsonde and unified data sets were smaller than those between rawinsonde and satellite data. The most improvement appears to be in the lower levels (850 and 700 mb). The standard deviations of the differences were reduced at all but one level at both times. The correlation coefficients, a measure of pattern agreement, also was improved for all layers except near the tropopause (200 mb level). The most significant improvements occurred at the 700 mb level where the initial correlation was relatively weak.

The decrease in the mean and standard deviation of the differences, and the increase in the correlation coefficients are indicators of improvement of the unified data set over the satellite data. These indicate that both the intensity and the pattern can be more closely represented by the unified data set than by the satellite data set. However, the significance of these improvements should be tested.

In general, the lower troposphere was improved more than the upper troposphere. The improvements in the mid-troposphere were relatively weak. This might be due to the fact that the first harmonic which has a

Table 3. The mean and standard deviation of the differences between original gridded rawinsonde data and satellite data, and between original gridded rawinsonde data and unified data.

0200 GMT 7 March

level	Data	Mean Difference	Stan. Dev. of Difference	Correlation Coefficient
850	SAT	-0.4	2.2	0.91
	UNI	1.0	1.7	0.95
700	SAT	-0.5	2.9	0.78
	UNI	0.2	2.4	0.86
500	SAT	-0.3	2.4	0.86
	UNI	-0.5	2.0	0.91
300	SAT	2.8	1.7	0.96
	UNI	2.0	1.6	0.97
200	SAT	0.2	2.9	0.70
	UNI	-0.8	2.0	0.67

2300 GMT 6 March

level	Data	Mean Difference	Stan. Dev. of Difference	Correlation Coeffiient
850	SAT	-1.5	2.1	0.91
	UNI	-0.2	1.9	0.91
700	SAT	-1.0	2.2	0.80
	UNI	-0.3	1.7	0.89
500	SAT	-1.2	1.9	0.93
	UNI	-1.1	1.7	0.95
300	SAT	2.9	1.4	0.96
	UNI	2.5	1.2	0.97
200	SAT	0.2	2.7	0.63
	UNI	-0.3	2.7	0.60

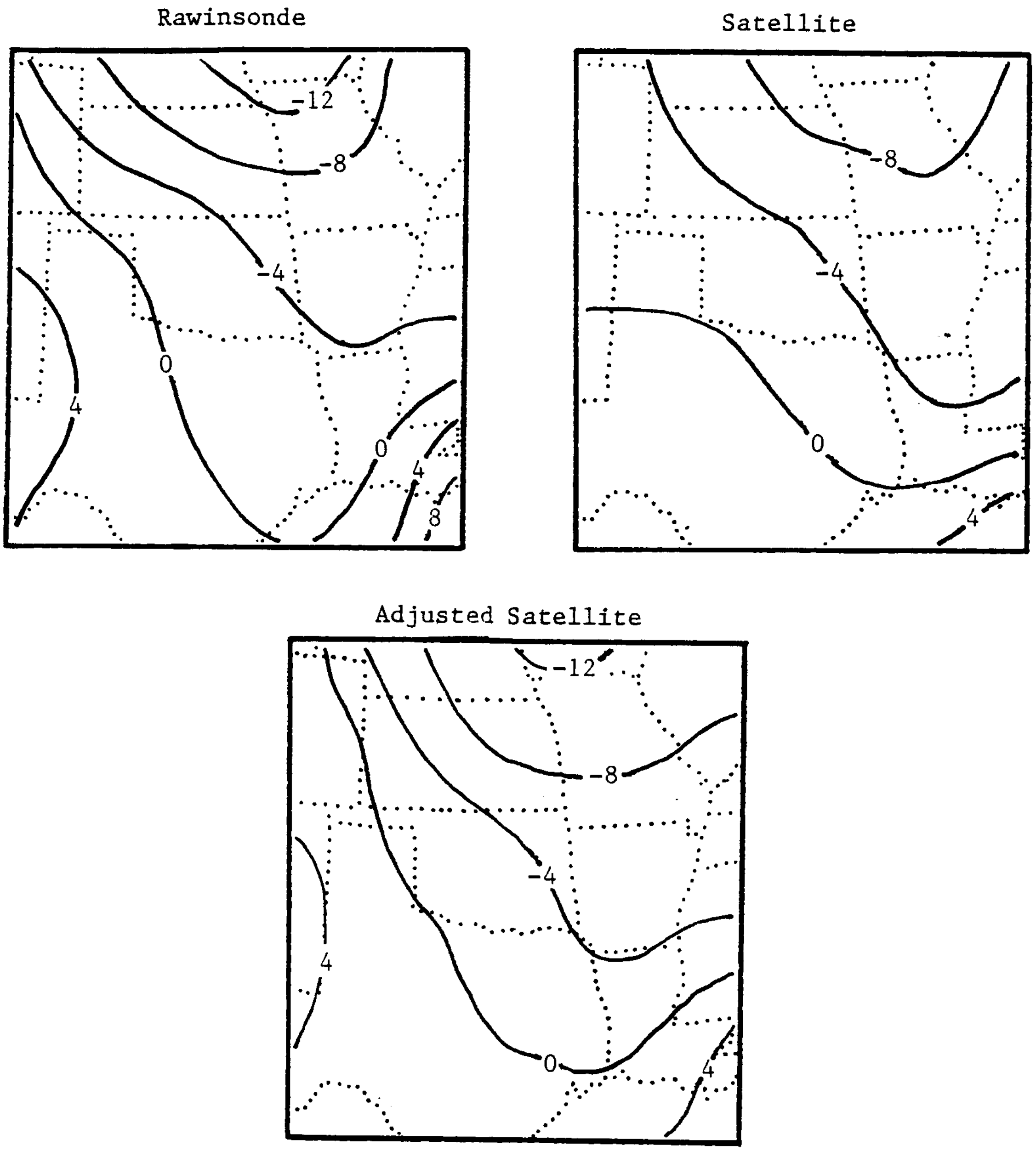
2 x (p_b - p_t) wavelength does not significantly affect the mid-troposphere. Therefore, the improvements at 500 mb were due primarily to the zeroth harmonic. The 1st harmonic affects largely the lower and upper layers where the greatest improvements occurred. With the existence of the tropopause near 200 mb, more harmonics are required to achieve improvements near the tropopause. Therefore, some special treatment should be made at the tropopause to improve the data quality of the unified data set. The actual temperature fields of rawinsonde, satellite, and the unified data set are shown in Fig. 10.

4.3 Utility of Satellite Soundings for Mesoscale Analysis

If the regular rawinsonde soundings are available, it is possible to estimate the true atmospheric conditions with given resolution. This is the case over the continent where the regular synoptic network is well organized. In this case, our prime interest with the satellite soundings may be a finer resolution. VAS provides soundings with 75 to 100 km horizontal resolution. It may be possible to resolve meso-α scale (Orlanski, 1975) weather phenomena using these data. However, as discussed earlier, reduced horizontal variations and somewhat inconsistent horizontal patterns in the satellite soundings make it difficult for direct application to mesoscale analysis. Therefore, some modifications must be made for the utilization of satellite data in mesoscale analysis.

One possible method to recover the variance and correlation pattern might be the use of simultaneous measurements of rawinsonde soundings and satellite soundings. In this case, the rawinsonde measurements are considered to represent the true state of the atmosphere, and each harmonic in each satellite sounding is adjusted by the corresponding harmonic amplitude in the nearby rawinsonde soundings.

The basic assumption in this approach is that the satellite profiles can provide the actual state of atmospheric variation at the lower harmonics although their variations are reduced. Therefore, the reduced portions can be recovered by adjustment based on nearby rawinsonde profiles. For colocated profiles, the direct comparison of the amplitude



0200 GMT 7 March
850 mb

Fig. 10. Comparisons of temperature fields at each pressure level for 0200 GMT 7 March. Contours represent isotherms (°C).

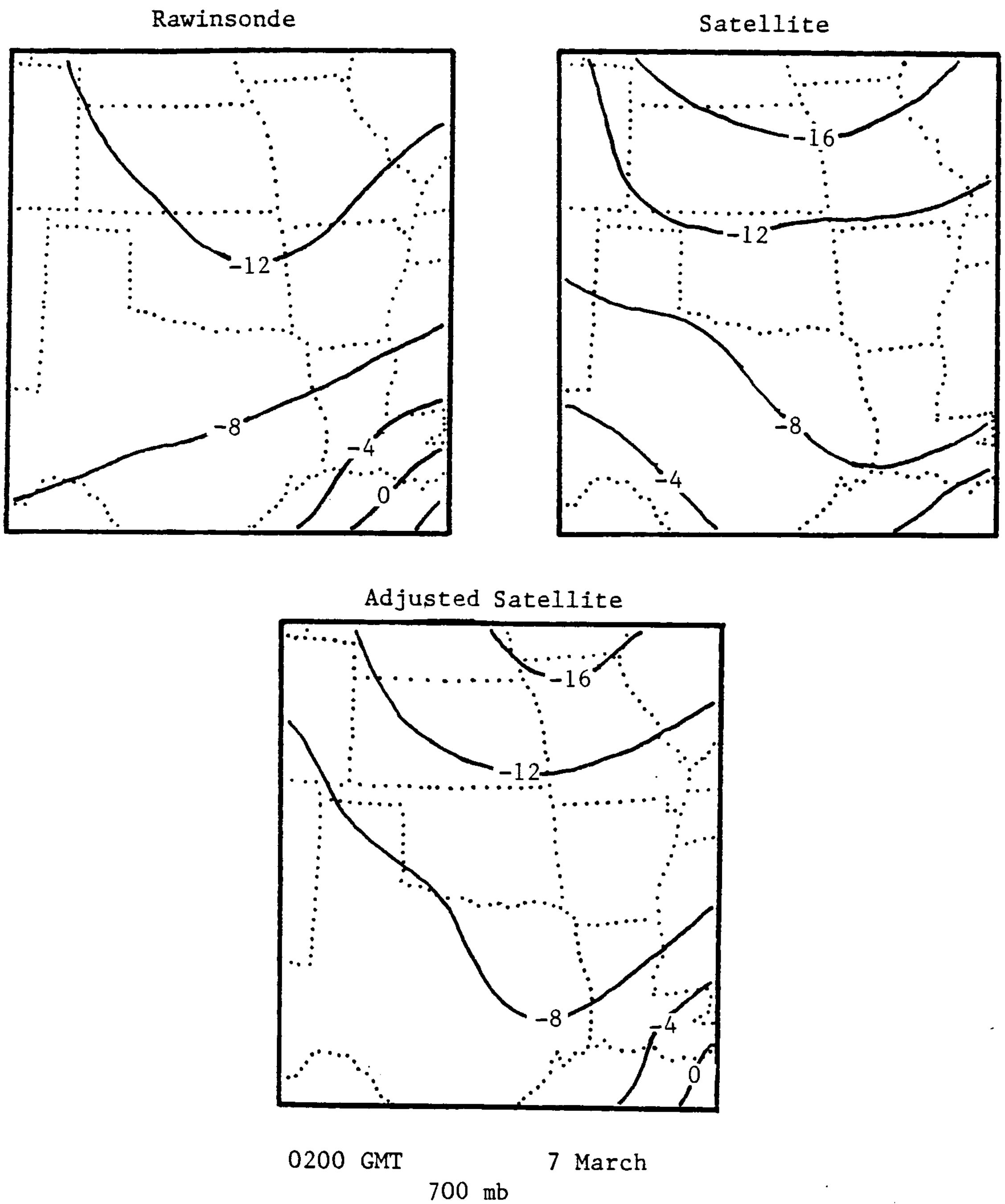
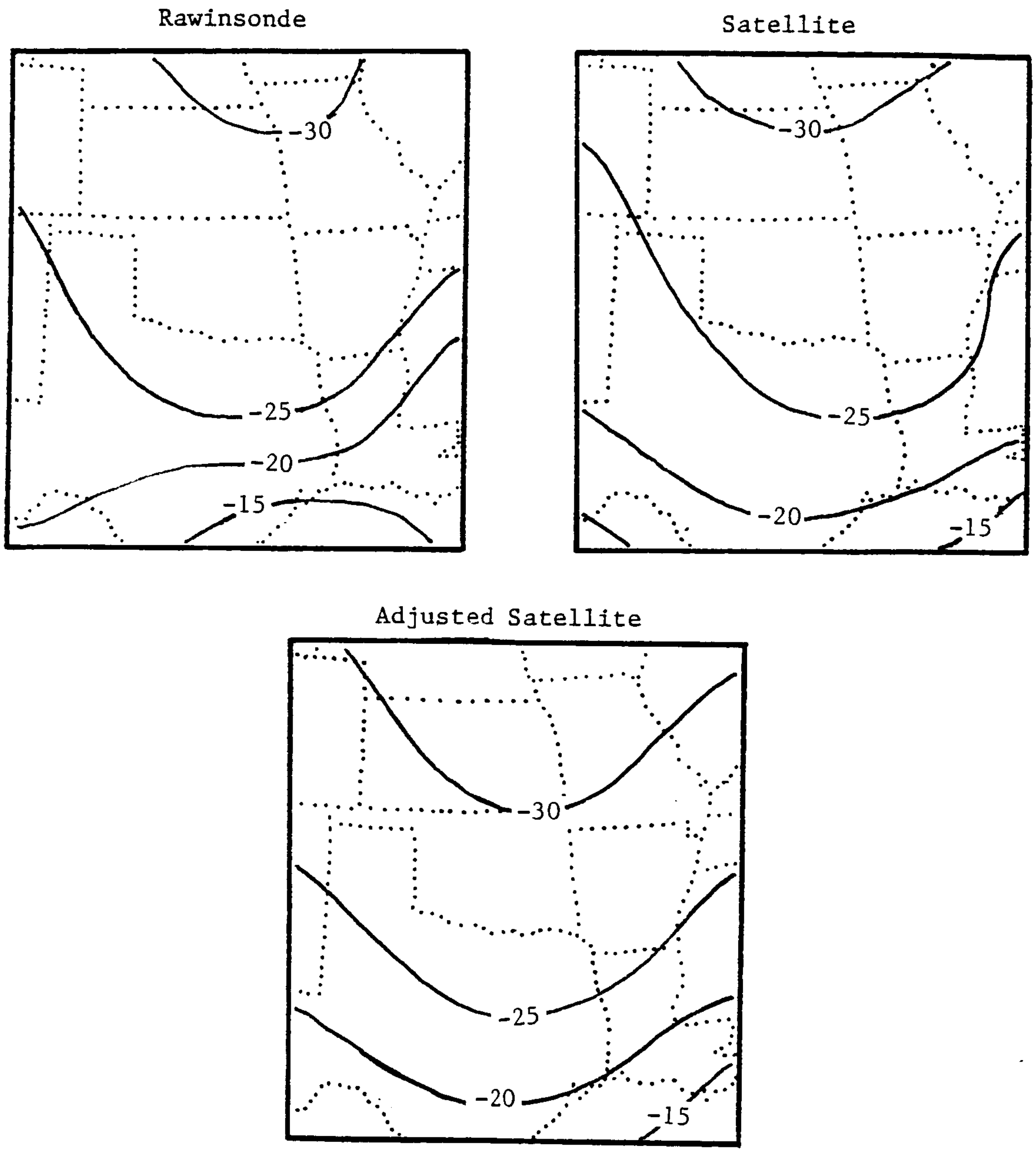


Fig. 10. (Continued).



0200 GMT 7 March
500 mb

Fig. 10. (Continued).

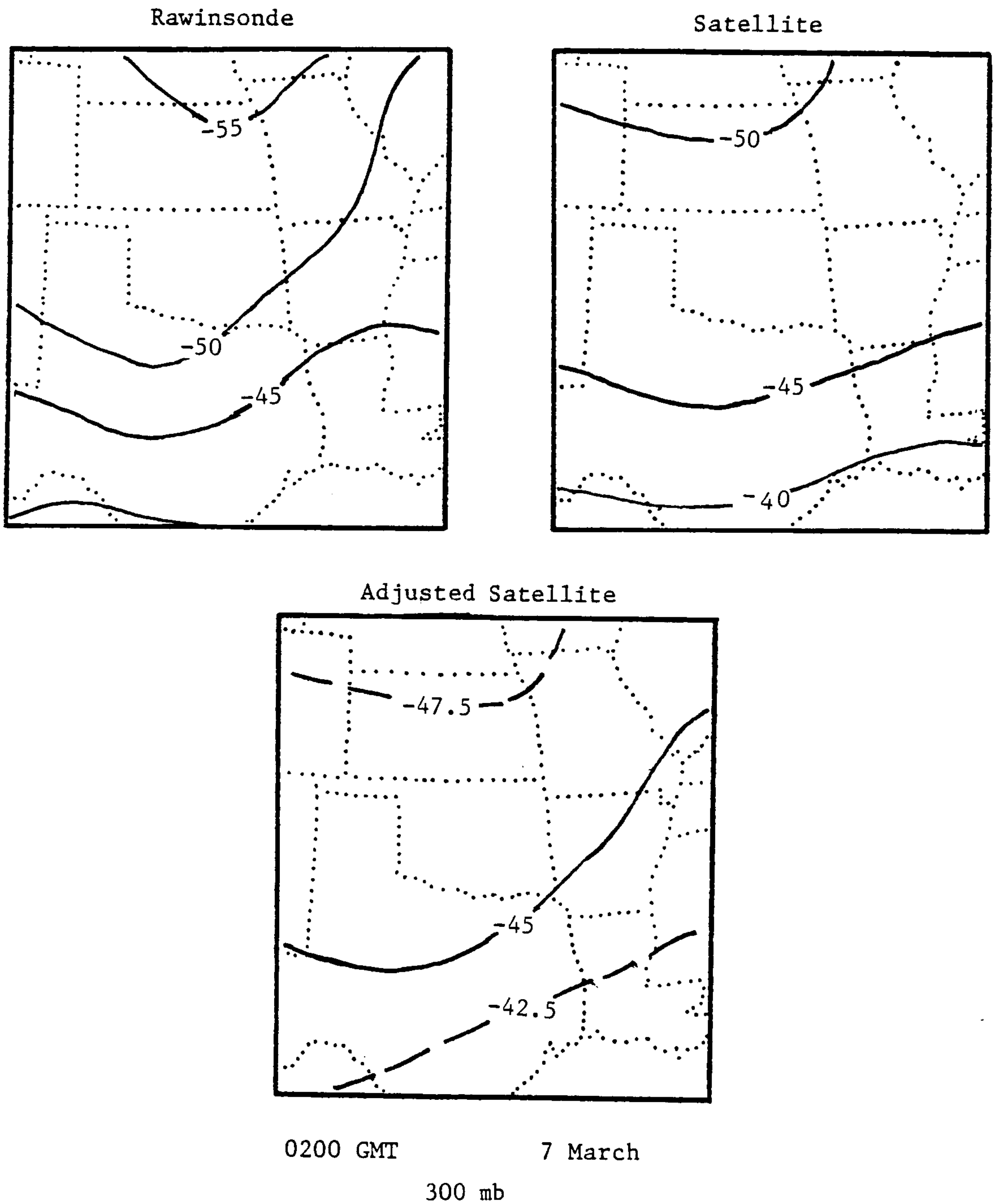


Fig. 10. (Continued).

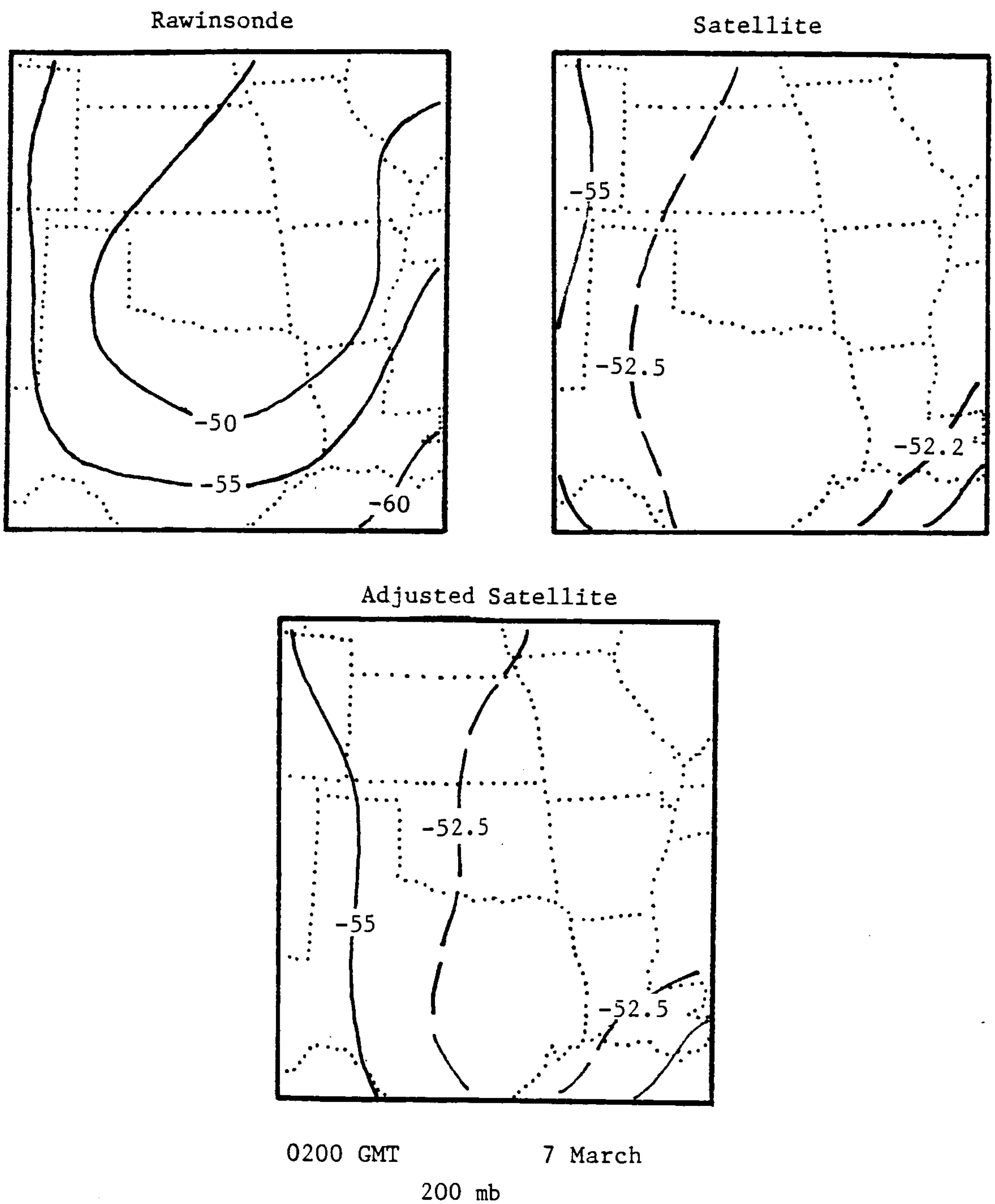


Fig. 10. (Continued).

ratio for each harmonic could easily recover the reduced portions. For profiles taken between the rawinsonde measurements, the interpolation of amplitude ratio from the nearby colocated profiles might reasonably recover the reduced portions. This is possible if the horizontal pattern between the rawinsonde and satellite data for each harmonic component is highly correlated. Table 2 showed correlations over 0.9 for the 0th and 1st harmonics and over 0.8 for harmonics up to the 4th except for the 2nd at 0200 GMT (0.74). Therefore, it is suggested that over these harmonic ranges, satellite data adjusted by the rawinsonde data as explained above may represent the true variations of the atmosphere.

The rawinsonde measurements taken from the NWS rawinsonde sites have synoptic scale horizontal resolution, while those taken from the AVE/VAS special network provide comparable horizontal resolution to the satellite soundings. The first data set was used for the purpose of tuning, and the second data set was used to verify the quality of the modified data for mesoscale analysis.

The procedures are as follows where N is the number of harmonics used.

1. Decompose all the available rawinsonde and satellite profiles into Fourier cosine series. The equations are:

$$T_r(p) = \bar{T}(p) + \frac{a_{r0}}{2} + \sum_{n=1}^{N} a_{rn} \cos(n\pi p^*) + R(p)$$

for rawinsonde, and

$$T_s(p) = \bar{T}(p) + \frac{a_{so}}{2} + \sum_{n=1}^{N} a_{sn} \cos(n\pi P^*) + R(p)$$

for satellite, where the subscripts r and s refer to the rawinsonde and satellite, respectively, and all other notations are self-explanatory.

2. Find the colocated soundings and compute the amplitude ratio at each location by

$$w_n = \frac{a_{rn}}{a_{sn}}$$

where n refers to the nth harmonic.

3. Interpolate the amplitude ratio at each satellite location by use of the proper scan radius and by taking a weighted average of M numbers of amplitude ratios at the colocated soundings within the scan radius. In a practical form,

$$W_n^*(X,y) = \frac{\overline{\sum_{j=1}^{M} \eta_j w_{nj}}}{\sum_{j=1}^{M} \eta_j}$$

where W_n^* is the interpolated weight for the nth harmonic and η is the weight.

4. Finally, recombine each satellite sounding by a Fourier cosine series using the adjusted amplitudes. That is,

$$T_s^*(p) = \bar{T}(p) + \frac{a_{s0}}{2} W_0^* + \sum_{n=1}^{N} W_n^* a_{sn} \cos(n\pi p^*) + R(p)$$

at each satellite sounding. T_s^* (p) is the modified temperature profile resulting from the "external tuning."

Therefore, the key procedure in this method could be a proper estimation of W_n^* (step 3). Since averaging was involved during interpolation, subsequent smoothing cannot be avoided in estimating the amplitude ratio. However, this smoothing might be desirable because of uncertainties in the amplitude ratio. One of the difficulties in this method is the computational instability occurring when the harmonic amplitude of the satellite profile is small. During the second step, the amplitude of the satellite profile is used as a denominator. Therefore, subsequent large amplitude ratios could result which could lead to troublesome results in the nearby soundings, especially for the higher harmonics since their amplitudes are initially small. To avoid this instability, no adjustment was applied to the amplitudes when they were small. In this analysis, exponentially decreasing weights were applied to η_j and the same scan radius (four times of grid space) was applied.

A test has been made with the rawinsonde data collected at the special network. As mentioned before, both data sets have comparable horizontal resolution to identify mesoscale weather phenomena. Three kinds of data sets were used: The rawinsonde data at the special network; the satellite data, and; the modified satellite data derived by external tuning. For the purpose of consistent comparison, these data sets were gridded at the 9 x 10 grid system with 50 km grid spacing. Again, Barnes' (1964) grid interpolation method was used with four iterations and a scan radius of five times the grid spacing (250 km). This scan radius will effectively filter out wave-lengths less than 250 km. The filter function is presented in Fig. 8.

Comparisons were made between the rawinsonde data and the modified satellite data for the 0th to the 5th harmonic to see how much improvement was achieved with increasing harmonic number. Table 4 shows the mean differences, the standard deviation of the differences, and the correlation coefficients of horizontal patterns at the grid points. The results of tuning improve the quality of satellite soundings at most levels while they do not at some levels. This is also true for individual harmonics. However, the tuning improves the satellite soundings in general.

Fig. 11 represents the mean statistics of the entire vertical column for the absolute value of the differences, standard deviations of the differences, and the correlation coefficients. In this presentation, the absolute value was applied to the layer mean differences because primary interest was the bias from the rawinsonde soundings. There are general tendencies in the adjusted data for decreasing the mean bias, increasing the standard deviation, and increasing the correlation coefficient with increasing harmonic number. These tendencies are desirable except for the standard deviation. However, the increasing tendency of the standard deviation may not be significant for the

Table 4. The mean difference (S-R) and standard deviation of differences at each level, and the correlation coefficient of the pattern for the subsequent tuning on each harmonic amplitude.

MEAN DIFFERENCES

LEVEL	SAT	0	1	2	3	4	5
1000	0.48	0.31	0.39	1.54	2.59	2.65	3.05
950	-2.42	-2.59	-2.38	-1.28	-0.36	-0.11	0.16
900	-0.25	-0.41	-0.21	0.68	1.21	1.27	1.20
850	1.66	1.50	1.69	2.27	2.27	2.10	1.75
800	1.97	1.81	1.97	2.18	1.65	1.33	0.95
750	1.86	1.69	1.83	1.63	0.71	0.40	0.26
700	1.75	1.59	1.70	1.11	0.05	-0.11	0.09
650	1.49	1.32	1.40	0.51	-0.41	-0.35	0.05
600	1.36	1.20	1.24	0.14	-0.39	-0.13	0.18
550	1.44	1.28	1.28	0.11	0.11	0.45	0.45
500	0.94	0.77	0.73	-0.36	0.17	0.42	0.11
450	0.09	-0.07	-0.15	-1.04	-0.12	-0.06	-0.46
400	-0.13	-0.30	-0.41	-0.99	0.07	-0.10	-0.30
350	1.96	1.79	1.65	1.45	2.37	2.05	2.19
300	3.33	3.21	3.05	3.25	3.78	3.46	3.85
250	0.31	0.14	-0.05	0.54	0.54	0.37	0.72
200	-2.47	-2.64	-2.84	-1.95	-2.48	-2.42	-2.35
150	-0.79	-0.96	-1.17	-0.08	-1.00	-0.74	-1.00
100	1.70	1.53	1.31	2.48	1.42	1.76	1.35
MEAN	1.40	1.31	1.35	1.21	1.09	1.00	0.99

STANDARD DEVIATION OF DIFFERENCES

LEVEL	SAT	0	1	2	3	4	5
1000	1.76	1.77	2.02	2.24	3.39	2.74	2.71
950	1.40	1.37	0.99	1.04	1.62	0.82	0.79
900	1.42	1.38	1.03	1.07	1.33	1.12	1.12
850	0.39	0.87	0.80	0.86	0.86	1.45	1.50
800	0.84	0.87	1.10	1.11	1.04	1.02	1.04
750	1.17	1.20	1.49	1.48	1.58	0.65	0.66
700	1.11	1.14	1.36	1.31	1.31	0.73	0.76
650	0.90	0.90	0.95	0.81	0.53	0.62	0.71
600	1.27	1.25	1.22	1.11	1.04	0.98	1.02
550	1.52	1.49	1.49	1.42	1.42	1.03	1.03
500	1.21	1.18	1.21	1.18	1.28	1.09	1.05
450	1.22	1.19	1.28	1.29	1.46	1.31	1.31
400	0.84	0.84	0.80	0.78	1.43	1.95	1.98
350	1.12	1.13	0.98	0.96	1.76	2.83	2.81
300	2.19	2.19	2.13	2.15	2.55	3.65	3.59
250	0.86	0.89	0.69	0.68	0.68	0.97	0.88
200	0.99	0.97	1.20	1.14	1.37	1.37	1.37
150	0.83	0.83	1.06	0.97	1.57	2.21	2.16
100	0.79	0.73	0.95	1.02	1.15	1.64	1.58
MEAN	1.17	1.17	1.18	1.16	1.31	1.38	1.39

CORRELATION COEFFICIENTS

LEVEL	SAT	0	1	2	3	4	5
1000	-0.75	-0.74	-0.64	-0.70	-0.81	-0.40	-0.36
950	0.54	0.59	0.82	0.77	0.62	0.91	0.92
900	0.59	0.62	0.81	0.79	0.73	0.80	0.80
850	0.73	0.75	0.85	0.84	0.84	0.67	0.66
800	0.72	0.71	0.64	0.65	0.54	0.82	0.93
750	0.45	0.43	0.29	0.27	-0.43	0.85	0.85
700	0.24	0.23	0.14	0.10	-0.60	0.41	0.32
650	0.33	0.36	0.41	0.45	0.64	0.60	0.54
600	0.10	0.15	0.22	0.26	0.40	0.65	0.65
550	-0.14	-0.08	-0.08	-0.18	-0.18	0.64	0.64
500	0.10	0.13	0.09	0.01	0.20	0.19	0.25
450	0.48	0.50	0.45	0.41	0.50	0.51	0.55
400	0.85	0.85	0.87	0.88	0.72	0.72	0.73
350	0.80	0.79	0.86	0.86	0.64	0.64	0.64
300	0.44	0.43	0.51	0.50	0.37	0.34	0.34
250	0.85	0.84	0.89	0.85	0.89	0.86	0.88
200	0.28	0.30	0.09	0.05	0.15	0.26	0.26
150	0.68	0.68	0.54	0.51	0.57	0.69	0.69
100	0.95	0.95	0.86	0.86	0.84	0.95	0.95
MEAN	0.45	0.47	0.47	0.45	0.36	0.60	0.60

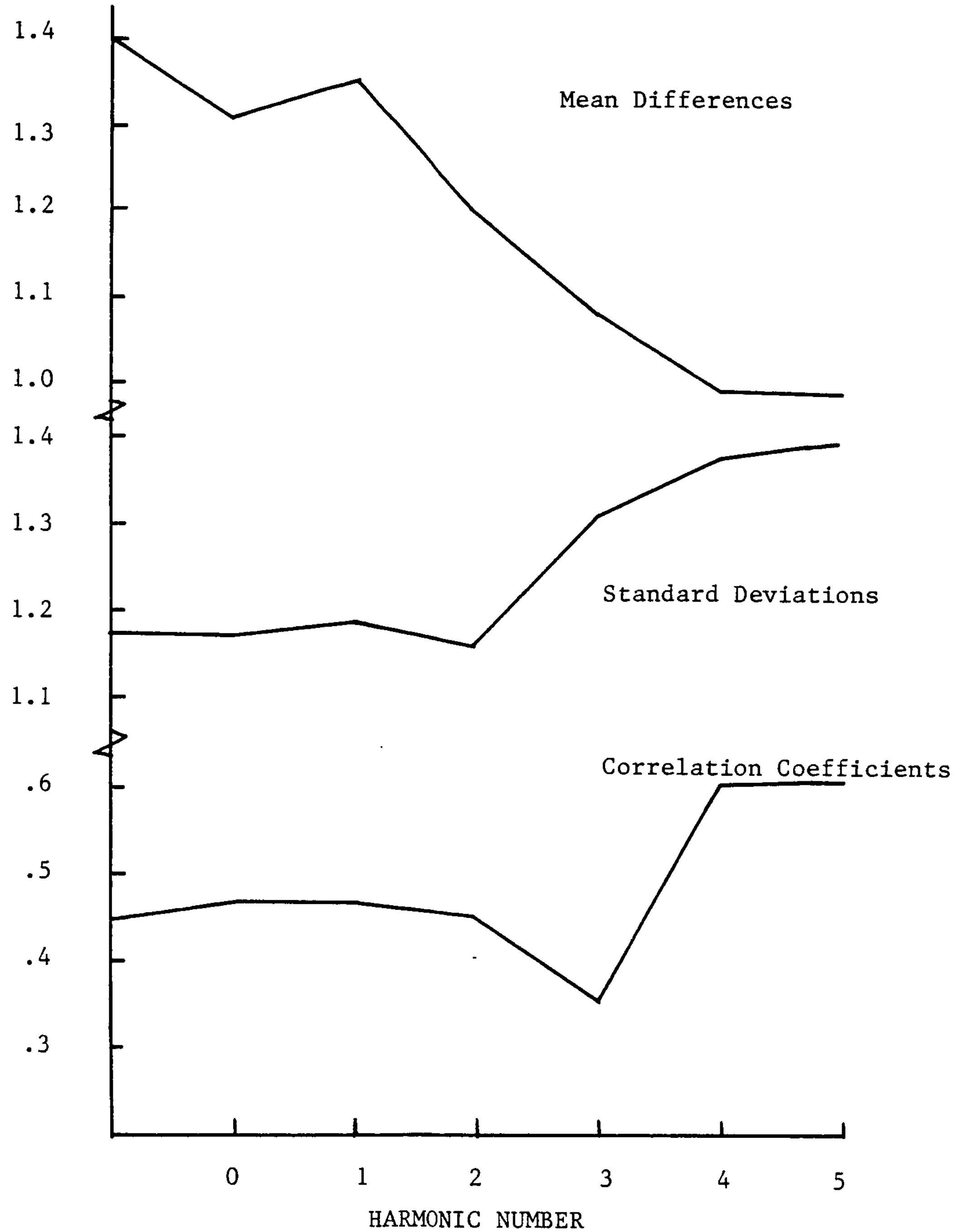


Fig. 11. Plot of the mean statistics in Table 4 for each harmonic.

following two reasons. The first reason is the high correlation in the horizontal pattern. As long as high correlation exists, this variability might be a part of the horizontal pattern. The second reason is the small magnitude of the increase. Only an increase of 0.2°C resulted from the tuning up to the 5th harmonic. This increase may be in the noise level.

One noticeable result is the rapid improvement between the second and the fourth harmonic. The results of tuning, up to the second harmonic, did not improve much (see Fig. 11). This might be due to the fact that the lower harmonics, up to the second in the satellite soundings, quite closely approximate those of the rawinsonde soundings. Therefore, tuning may not be significant to those components. But beyond these components, tuning significantly affected the mean bias and the correlation pattern because the harmonic amplitudes of satellite soundings may not be correctly estimated during the retrieval process.

Fig. 12 shows the comparison in the vertical column between the satellite soundings without and with tuning up to the 5th harmonic. Both soundings were compared with the rawinsonde soundings at the same grid points and average values were presented at each level. Most improvements were confined between the 850 and 400 mb levels by the tuning. The mean differences and the standard deviations were decreased, and the correlation coefficients were increased. Improvements were not achieved in the other levels but were even worse, especially for the standard deviations near the tropopause level. Two factors may be responsible. The Fourier series generally fit the center of the domain first, that is, the convergence speed is faster at the center than near the ends. Therefore, the mid-layers can be adjusted more quickly than lower and higher levels with a finite number of harmonics. Another reason must be the existence of sharp discontinuities near the surface inversion and tropopause. More harmonics should be used to get reasonable estimations near these discontinuities because convergence is slow. Another important feature shown in Fig. 12 is the periodic change of correlation coefficients by tuning in the vertical. The changing pattern corresponds well to the wave pattern of the 5th harmonic. This can be interpreted by tuning only up to the 5th harmonic. If tuning

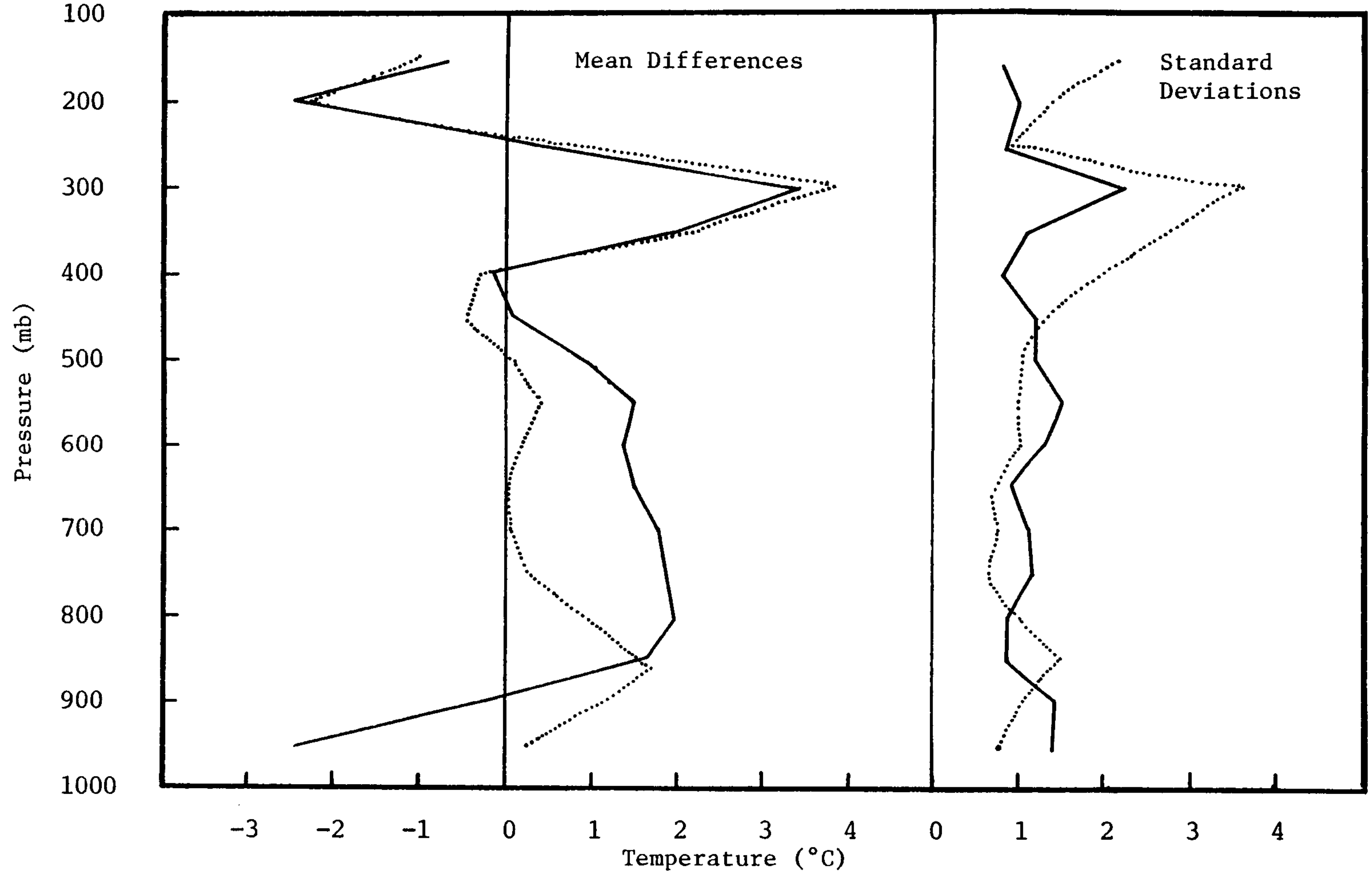


Fig. 12. The vertical plot of mean differences, standard deviations, and correlation coefficients vs. pressure. Solid lines are satellite vs. rawinsonde (S-R), and dotted lines are for satellite with tuning up to the 5th harmonic vs. rawinsonde profiles.

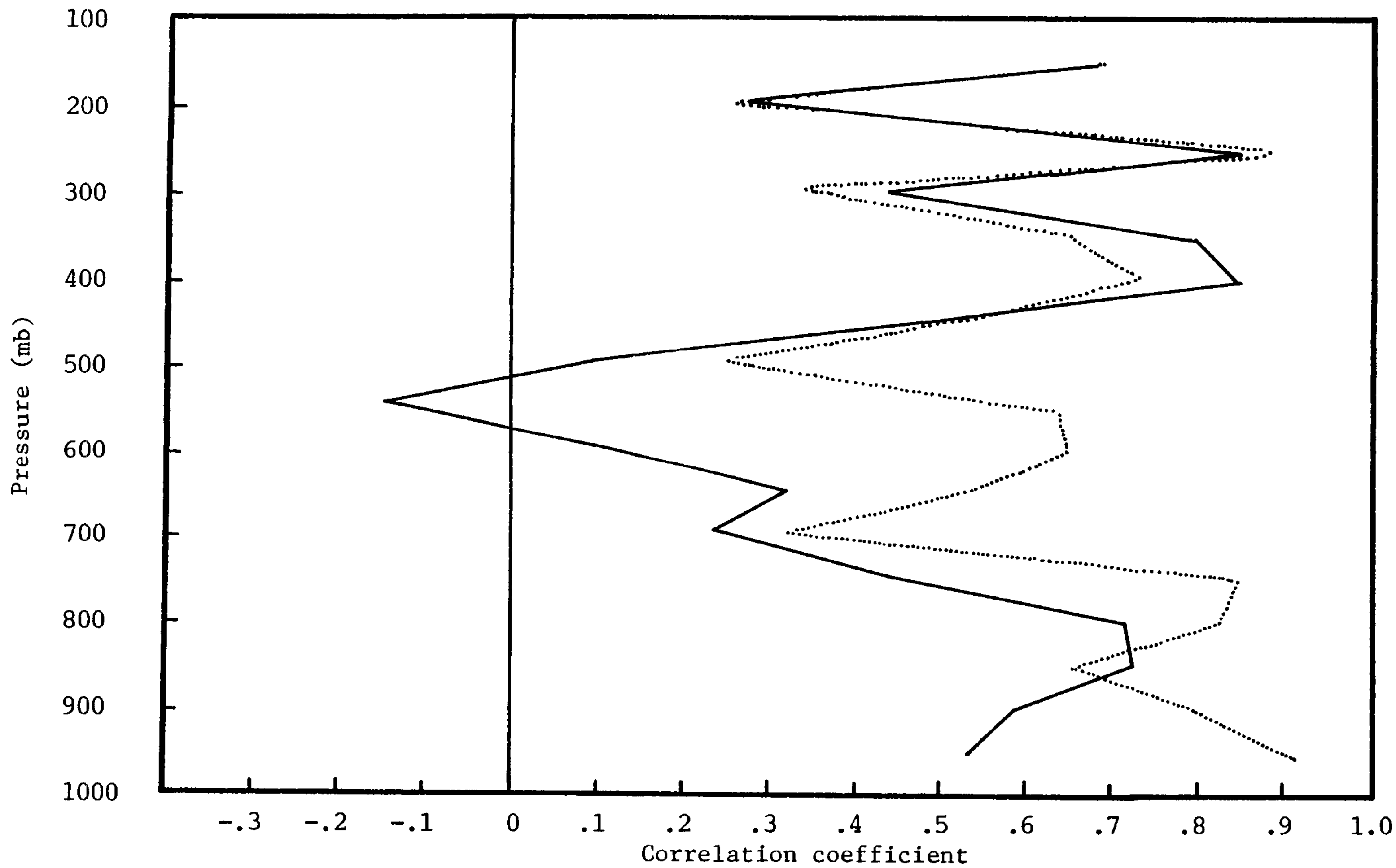


Fig. 12. (Continued).

with higher harmonics were used, the lower correlations might be improved by the higher harmonics. Subsequently, better improvements may be achieved for all levels. Unfortunately, this is not applicable in practice because, as presented earlier, the amplitudes of higher harmonics of satellite soundings primarily represent noise. Their amplitudes were small and their horizontal patterns were not correlated to those of rawinsonde soundings. As a consequence, this method may not be valid near discontinuities.

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