An Analysis of Mesoscale VAS Retrievals Using Statistical Structure Functions

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ABSTRACT

Statistical structure functions are used to evaluate sounding data from the 6–7 March day of the 1982 AVE/VAS Ground Truth Field Experiment. Functional analyses are performed for five observation times starting at 1200 GMT 6 March and ending at 0000 GMT 7 March, and for the composite 12-h period. Data consist of mesoscale soundings from a special ground truth rawinsonde network and VAS-derived soundings from both a physical algorithm and a regression technique. The standard parameters of temperature, geopotential height, and mixing ratio are evaluated at the 850, 700, 500, 300, and 200 mb levels. Integrated parameters of thickness and precipitable water also are investigated.

Using structure function analyses, estimates of root-mean-square (rms) data uncertainty are obtained for the three data sources. Then, VAS soundings from the physical retrieval scheme are compared with those from the regression technique. Results indicate that both schemes have similar error characteristics and capabilities for determining gradients of mesoscale temperature and geopotential height. Signal-to-noise ratios for these parameters were quite favorable and greater than those of mixing ratio. Finally, sounding retrievals are evaluated against those from the ground-truth rawinsonde network. These results show that the VAS data generally describe weaker gradients than observed with the radiosondes. A notable exception is physically-derived mixing ratio at 850 mb.

1. Introduction

An advanced version of the Visible-Infrared Spin-Scan Radiometer (VISSR) is contained on board the recently launched series of GOES geostationary satellites. This new instrument, called the VISSR Atmospheric Sounder (VAS), has imaging capabilities in numerous spectral channels from which profiles of temperature and humidity can be retrieved. Details about the VAS system are provided by Smith et al. (1981) and Chesters et al. (1983). An important point is that sounding quality radiances are possible every hour along a full Earth west-to-east swath covering the conterminous United States. Thus, VAS has the potential for providing a major new source of mesoscale data.

A variety of qualitative and quantitative techniques are needed to fully assess VAS’s capabilities. This paper emphasizes statistical procedures involving structure functions. Thus far, due to the recent availability of VAS data, there have been few statistical evaluations of observed sounding profiles, and none has employed structure function analyses. Lee et al. (1983) and Smith (1983) presented statistics for regression and physical retrievals, respectively, while Chesters et al. (1984) and Jedlovec (1985) evaluated soundings from the same case to be considered here.

Structure functions possess several characteristics that are particularly useful for the evaluation of satellite-derived data. First, most other schemes rely on the satellite retrievals being co-located in time and space with those from another “standard” source. Structure functions, however, avoid the co-location requirement as well as data uncertainties associated with the “standard.” This is especially helpful when evaluating mesoscale satellite retrievals for which there is usually no corresponding scale of ground truth measurements. An additional attribute of the functions is that they are powerful tools for quantifying the nature of horizontal gradients.

Based on the work of Gandin (1963) in optimal interpolation studies, various researchers have utilized statistical structure functions. Barnes and Lilly (1975) applied them to mesoscale rawinsonde data from the sounding network of the National Severe Storms Laboratory (NSSL) and found considerable variance in meso $\beta$-scale (20–200 km) fields of wind and moisture. Using rawinsonde data from the 10–11 April (Red River Valley tornado outbreak) day of the 1979 Atmospheric Variability Experiment–Severe Environmental Storms and Mesoscale Experiment (AVE-SESAME), Fuelberg and Meyer (1984) documented prominent meso $\alpha$-scale (200–2,000 km) features associated with the convective storm outbreak.

Structure function analyses also have been applied to various forms of satellite data. Probably their most extensive application was by Hillger and Vonder Haar.
(1979) who examined data from NOAA-4. They calculated root-mean-square (rms) errors for both radiance- and sounding-derived parameters and noted that structure functions of radiance data seemed to indicate those days having the potential for severe thunderstorm activity. Maddox and Vonder Haar (1979) employed structure functions to develop quantitative estimates of random errors inherent in satellite-derived (cloud-tracked) winds.

The purpose of this paper is to evaluate VAS soundings generated using a physical retrieval algorithm with those from a regression technique. Statistical structure function analyses are employed. VAS retrievals also are evaluated against those from a special mesoscale network of radiosonde stations that was operated as part of the 1982 AVE/VAS Field Experiment. An additional task is to compute random errors associated with the VAS retrievals.

2. Methodology

a. Theoretical development

Formulations used in the present study are fashioned after those of Hillger and Vonder Haar (1979), Maddox and Vonder Haar (1979), and Fuelberg and Meyer (1984). The structure function (STR) of quantity \( f \) is given by

\[
\text{STR}(R) = \frac{1}{N} \sum \{ f'(r_i) - f'(r_j) \}^2,
\]

where \( r_i \) and \( r_j \) are position vectors of observation sites \( i \) and \( j \). Each data pair is considered only once, and coincident points are not included, i.e., \( j > i \). Here, \( N \) is the number of station pairs whose scalar separation distance

\[
\rho = |r_i - r_j|,
\]

is within the interval \( R \), and

\[
f'(\mathbf{r}) = f(\mathbf{r}) - \bar{f},
\]

where \( \bar{f} \) is the spatial mean of variable \( f \). A separation interval \( R \) of 100 km was used in this study; thus, scalar separation categories are 0–100 km, >100–200 km, etc.

When calculations of (1)–(3) do not consider orientations of station pairs or their positions within the field, the interpretation of results rests on the assumptions of homogeneity and isotropy. Thus, structure is dependent only on the scalar separation, \( \rho \), between observation pairs. Also, since the present study is a single statistical event, the stationarity assumption is invoked when interpreting the results.

Structure functions quantitatively describe meteorological patterns about which an analyst has only qualitative notions. Specifically, Hillger and Vonder Haar (1979) noted that the slope of the structure profile is related to mean non-directional gradients in the data field, i.e., rapid changes in structure with increasing station separation indicate large horizontal gradients.

An important characteristic of structure functions is their measure of random error within a data set (Hillger and Vonder Haar, 1979; Fuelberg and Meyer, 1984). With the further assumption of no spatially correlated errors, the structure function approaches twice the inherent variance of the measuring system as the data separation approaches zero. Thus, uncertainty estimates can be obtained by extrapolating structure curves to zero separation distance, i.e.,

\[
\text{STR}(0) = 2\sigma^2,
\]

where \( \sigma^2 \) is the mean squared uncertainty. Hillger and Vonder Haar noted that spatially correlated errors decrease magnitudes of estimated uncertainties. It should be emphasized that structure-derived uncertainties do not include bias or systematic errors due, for example, to undetected clouds, surface characteristics, viewing angle, etc. Although some of these systematic errors may have spatial correlations, this effect is neglected in current calculations.

Once error estimates are obtained, values of structure can be corrected so that only meteorologically related variations are retained (Gandin, 1963). In the current study, this was achieved using procedures described by Hillger and Vonder Haar (1979) and Fuelberg and Meyer (1984).

b. Data

The period selected for study was the 6–7 March day of the 1982 AVE/VAS Ground Truth Field Experiment. Details about the experiment are given by Hill and Turner (1983). Available data consisted of VAS retrievals as well as special mesoscale radiosonde soundings for establishing ground truth. Five time periods were considered, i.e., 1200, 1500, 1800 and 2100 GMT 6 March 1982 and 0000 GMT 7 March 1982.

VAS profiles from two retrieval schemes were investigated. The first procedure is a physical technique described by Smith (1983). First guess data consisted of a linear interpolation between the Limited Fine Mesh (LFM) model analysis at 1200 GMT 6 March 1982 and the 12 h LFM forecast for 0000 GMT 7 March 1982. An iterative technique was employed to compute the profiles of temperature and moisture. After obtaining initial profiles, an analytical least squares procedure was used to enhance the vertical structure of the soundings. These data were prepared by the National Environmental Satellite, Data and Information Service (NESDIS) at the University of Wisconsin-Madison and will be denoted as "physical" retrievals. Jedlovec (1985) has called them "modified physical retrievals."

The second set of VAS profiles was produced using a linear regression scheme (Lee et al., 1983). The technique first develops statistical relationships by com-
paring radiosonde and surface observations with corresponding satellite radiances. These relations then are applied to the remaining radiances to retrieve the desired profiles. In the current case, the regression coefficients were obtained using National Weather Service (NWS) soundings at 1200 GMT 6 March and 0000 GMT 7 March. In addition, linear interpolation was used to generate soundings at 1800 GMT in order to include diurnal effects in the statistical training. It should be noted that the computational domain to be used in the current evaluations is a subset of the area used to train the regression scheme. Also, the regression technique employs less horizontal averaging of the radiance data than does the physical procedure, i.e., radiances over ~75 km distance are used in the modified physical procedure (Smith, 1983), but the corresponding value for the regression technique is ~20 km (Lee et al., 1983). These soundings were generated at the NASA Goddard Space Flight Center and will be referred to as “regression” soundings.

Both sets of VAS retrievals were provided by the NASA Marshall Space Flight Center. In each case, the sounding spacing was between 75–100 km over cloud free regions of the area. The five observation times, corresponding to the beginning of the satellite scan, were 1100, 1435, 1735, 2035 and 2335 GMT 6 March 1982.

To provide mesoscale ground-truth data during the 1982 AVE/VAS Field Experiment, a network of 13 special site rawinsonde stations was operated in conjunction with twenty-four NWS sites (Fig. 1). The average station spacing of the special network was approximately 125 km, compared to 400 km for the standard NWS network. Soundings were taken at 3 h intervals, providing the usual meteorological parameters at 25 mb intervals from the surface to 25 mb. These data also were provided by the NASA Marshall Space Flight Center.

c. Computational procedures

Several procedures were performed at NASA Marshall (Jedlovec, 1985) to render the data sets more consistent with one another. The rawinsonde data were adjusted to a common time at all levels using a linear interpolation scheme similar to that described by Fuelberg and Jedlovec (1982). The times specified for this procedure were 1100, 1445, 1745, 2045 and 2345 GMT 6 March 1982, corresponding to 10 minutes after the beginning satellite scan time. For the satellite retrievals, mixing ratios were computed from the originally reported values of dew point temperature. Since geopotential heights were not included with the regression soundings, these values were calculated at NASA Marshall using standard techniques. The final data sets are identical to those created and employed by Jedlovec (1985). As a final task, the derived parameters of thickness and precipitable water were calculated from each sounding at Saint Louis University.

Since our goals included a comparison with the mesoscale ground truth data, a computational domain centered over the special rawinsonde network was chosen. This region was bounded by latitudes 28–38°N and longitudes 92–103°W (Fig. 2). One should note that only the special sites and eleven nearby NWS stations were utilized. Locations of the VAS soundings are given in Fig. 3 while Table 1 gives their totals within the region of interest (Fig. 2). Sounding density as well as areal coverage are similar for the two sets of satellite retrievals.

Structure functions were computed for all three datasets using the approach given in (1)–(3). We investigated the basic parameters of temperature, geopotential height, and mixing ratio at five levels: 850, 700, 500, 300 and 200 mb. Calculations also were performed on thickness for the 850–500 and 500–200 mb layers,
TABLE 1. Number of VAS soundings at each observation time.

<table>
<thead>
<tr>
<th>Time (GMT)</th>
<th>Physical</th>
<th>Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td>1100</td>
<td>36</td>
<td>37</td>
</tr>
<tr>
<td>1435</td>
<td>48</td>
<td>69</td>
</tr>
<tr>
<td>1735</td>
<td>57</td>
<td>67</td>
</tr>
<tr>
<td>2035</td>
<td>84</td>
<td>87</td>
</tr>
<tr>
<td>2335</td>
<td>99</td>
<td>113</td>
</tr>
</tbody>
</table>

as well as precipitable water for the surface-700 and 700–350 mb layers. Both individual observation times and the composite 12 h period were evaluated, i.e., the combination of the five 3 h times. In the diagrams which follow, results are plotted midway between separation intervals of 100 km. Table 2 shows the number of data pairings within each separation category. Intervals beyond 700–800 km were not used because of the rapidly decreasing number of pairings. Rawinsonde pairings decrease approximately 10% between 500 and 200 mb due to the early termination of some soundings. Sensitivity analyses (Fuelberg and Meyer, 1984) show that the current number of pairings, even for the rawinsonde data, are sufficient for the interpretations which follow.

Based on Fuelberg and Meyer (1984), random error estimates were obtained by extrapolating the structure curves to zero separation distance. Instead of a subjective scheme, a least squares technique was used to fit two functional forms to the structure values. First, exponential curves were fit using the relation

\[
\text{STR}(X) = A \exp(BX),
\]

where \( X \) is scalar separation, \( A \) is the intercept value at \( X = 0 \), and \( B \) is the coefficient of curvature (slope). A second fit was obtained using the linear function

\[
\text{STR}(X) = A + BX.
\]

The first six points generally were used for the exponential equation, while four points were deemed sufficient for the linear technique. The function giving the best agreement with original values was selected. Then, based on (4), rms errors (\( \sigma \)) were obtained from the fitted curves at \( X = 0 \).

TABLE 2. Number of data pairs within each distance interval.

<table>
<thead>
<tr>
<th>Distance (km)</th>
<th>Physical</th>
<th>Regression</th>
<th>Rawinsonde (500 mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–100</td>
<td>445</td>
<td>542</td>
<td>16</td>
</tr>
<tr>
<td>100–200</td>
<td>1217</td>
<td>1616</td>
<td>132</td>
</tr>
<tr>
<td>200–300</td>
<td>2000</td>
<td>2444</td>
<td>144</td>
</tr>
<tr>
<td>300–400</td>
<td>1732</td>
<td>2414</td>
<td>152</td>
</tr>
<tr>
<td>400–500</td>
<td>1849</td>
<td>2379</td>
<td>88</td>
</tr>
<tr>
<td>500–600</td>
<td>1340</td>
<td>1983</td>
<td>80</td>
</tr>
<tr>
<td>600–700</td>
<td>1136</td>
<td>1460</td>
<td>42</td>
</tr>
<tr>
<td>700–800</td>
<td>769</td>
<td>993</td>
<td>25</td>
</tr>
</tbody>
</table>

FIG. 3. VAS sounding locations. Physical retrievals are in the left column, while the regression soundings are given on the right. Times are in GMT.
FIG. 4. Horizontal analyses for the surface and 500 mb levels. Solid lines at 500 mb are height contours in decameters while dashed lines are isotherms in °C.
3. Weather conditions

Strong gradients of temperature and moisture are the important characteristic of the 6–7 March 1982 case. The National Meteorological Center (NMC) surface analysis for 1200 GMT 6 March (Fig. 4) reveals a weak low pressure center over southern Georgia, with a stationary front extending southwestward along the Gulf Coast into Mexico. The front was associated with temperature inversions in the lower troposphere over the southeastern portion of the analysis domain (Fig. 2). Satellite systems have traditionally displayed only limited success in resolving such features, and this was also the case on 6–7 March (Jedlovec, 1985). Shallow high pressure (Fig. 4) was centered over western Oklahoma while to the north, a cold front extended from a low over Canada into the Northern Plains States. A strong surface temperature gradient (not shown) of approximately 15°C was evident between the Texas panhandle and the Gulf Coast. Dewpoints (not shown) also showed pronounced variability, ranging from near 5°C over the southeast corner of the special network to near −10°C in the northeast section. At 500 mb (Fig. 4), the dominant feature is a trough with a northeast–southwest orientation. Strong temperature gradients also are quite evident at this level. Clouds (Fig. 5) and precipitation in the form of snow and rain were occurring over the eastern half of Texas; thus, VAS soundings were not possible in that region (Fig. 3).

Surface features at 0000 GMT 7 March, the last time being studied, also are shown in Fig. 4. The stationary front remains over the Gulf, and the region of weak high pressure is now centered over Texas. The cold front which had been in the Northern Plains has moved southward. The thermal gradient over Texas (not shown) has weakened considerably during the past 12 h due to solar heating over the western half of the region, but gradients of dewpoint remain strong. The trough at 500 mb has moved eastward and is now positioned along a north–south orientation. During the day of 6 March, a well defined line of clearing advanced eastward through the area. Figure 5 reveals that by 0000 GMT 7 March, all but the eastern edge of the analysis region (Fig. 2) was virtually cloud free.

4. Results

Results are divided into three major sections. First, uncertainty estimates of both VAS- and rawinsonde-derived soundings are described. Then, the second section evaluates gradients from the two VAS-derived datasets. Finally, differences in structure between ground truth rawinsonde data and special sets of co-located VAS retrievals are explored.

a. Data uncertainty analysis

Random error estimates for the VAS sounding retrievals, along with corresponding means and standard deviations of the original data, are presented in Table 3 as a function of pressure. Uncertainties for temperature range from 0.5 to 1.2°C at individual levels. Vertical averages of the random errors are 0.7°C for the physical retrievals and 0.9°C for the regression soundings. Using similar techniques, Hillger and Vonder Haar (1979) obtained 0.5°C for soundings from NOAA-4. These uncertainties are considerably smaller than values based on pairings of rawinsonde and satellite data. For example, concerning regression retrievals for 6–7 March, Chesnuts el al. (1984) obtained rms differences of 3.5, 1.6, and 1.9°C at 500, 700, and 850 mb, respectively. Jedlovec (1985) also evaluated the 6–7 March case; however, he computed standard deviations of differences between objectively analyzed fields of VAS and rawinsonde data. His average standard deviation of the five levels described here was 1.4°C for both the physical (his “modified physical” data) and regression retrievals.

At least two studies have investigated the effects of co-location errors and uncertainties in rawinsonde data...
Table 3. VAS sounding rms errors with means, standard deviations, and signal-to-noise ratios (S/N) for the composite 12 h period. Physical retrievals are denoted by P, and regression by R.

<table>
<thead>
<tr>
<th>Level (mb)</th>
<th>Scheme used</th>
<th>Temperature (°C)</th>
<th>Height (m)</th>
<th>Mixing ratio (g kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>Std. dev.</td>
<td>rms error</td>
</tr>
<tr>
<td>200</td>
<td>P</td>
<td>-50.3</td>
<td>1.2</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>-50.7</td>
<td>1.7</td>
<td>0.9</td>
</tr>
<tr>
<td>300</td>
<td>P</td>
<td>-45.7</td>
<td>3.0</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>-47.3</td>
<td>2.6</td>
<td>0.9</td>
</tr>
<tr>
<td>500</td>
<td>P</td>
<td>-25.8</td>
<td>2.6</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>-25.5</td>
<td>3.1</td>
<td>1.0</td>
</tr>
<tr>
<td>700</td>
<td>P</td>
<td>-10.6</td>
<td>2.1</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>-9.6</td>
<td>2.1</td>
<td>0.7</td>
</tr>
<tr>
<td>850</td>
<td>P</td>
<td>-3.6</td>
<td>2.2</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>-2.2</td>
<td>3.4</td>
<td>1.2</td>
</tr>
</tbody>
</table>

On retrieval assessments, Bruce et al. (1977) concluded that differences of 1.4 to 1.7°C should be expected between simultaneous satellite and rawinsonde measurements. As a result, they suggested that only simultaneous differences greater than 1.7°C should be attributed to errors in radiometric procedures. McMillin et al. (1983) also have emphasized the combined effects of errors in radiosondes, time differences, and sounding locations in producing excessive estimates of satellite retrieval discrepancies. Thus, as noted earlier, the current procedure is valuable because it avoids uncertainties due to these factors. However, one must remember that it does not include systematic error.

An important point from Table 3 is that all values of structure-derived temperature uncertainty are much smaller than corresponding standard deviations of temperature itself which describe horizontal variability. Observed standard deviations represent the atmospheric signal which the satellite is to measure. Thus, quotients of these deviations to the VAS rms errors represent a type of signal to noise ratio. Current ratios range from 1.9 to 3.8. Finally, mean values of temperature (Table 3) indicate slight differences between the datasets; however, a discussion of this topic is provided by Jedlovec (1985).

Uncertainty estimates for geopotential height (Table 3) show the expected increase with altitude that is attributable to integration of virtual temperature over progressively deeper layers. Values range from 3.1 m at 850 mb to 26.2 m in the upper levels. Errors from the regression procedure are somewhat greater than those of the physical retrievals. Current values are smaller than those of Jedlovec (1985), whose results for the “modified physical” and regression schemes were 6.6 and 6.4 m, respectively at 850 mb, and 20.0 and 27.0 m at 200 mb. As observed with the temperature data, uncertainties in geopotential height are much less than the observed variability that is described by the standard deviations. Thus, signal to noise ratios again are quite good (2.8–4.8).

Error estimates for mixing ratio, also shown in Table 3, range from 0.04 to 0.34 g kg⁻¹. Even though the regression algorithm produces the smallest uncertainties, Section 4b will show that it also yields the weakest horizontal gradients. It should be noted that signal to noise ratios for both data sets (1.6–2.2) are not as favorable as those of temperature and geopotential height. This aspect also will be discussed in a later section.

It is informative to compare uncertainty estimates of VAS retrievals with those of rawinsonde data. Using procedures identical to those employed on the VAS retrievals, error estimates for the ground truth radiosonde-derived temperatures (not shown) range from 0.3 to 1.1°C, with a vertically averaged value of 0.7°C. Based on paired, simultaneous radiosonde ascents, Hoehne (1980) obtained an average uncertainty of 0.6°C, whereas Lenhard (1970) noted the value of 0.35°C. Thus, it appears that VAS's random temperature uncertainty (Table 3) is somewhat greater than that of radiosondes; however, the differences are not pronounced.

Random error estimates for rawinsonde-derived geopotential height based on structure functions are given in Table 4, as are the values of Hoehne (1980).

Table 4. Root-mean-square errors for geopotential height (m).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>19.0</td>
<td>30</td>
<td>44</td>
</tr>
<tr>
<td>300</td>
<td>17.3</td>
<td>27</td>
<td>31</td>
</tr>
<tr>
<td>500</td>
<td>13.1</td>
<td>19</td>
<td>26</td>
</tr>
<tr>
<td>700</td>
<td>6.3</td>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td>850</td>
<td>2.4</td>
<td>6</td>
<td>—</td>
</tr>
</tbody>
</table>
and Lenhard (1970). Structure-derived uncertainty estimates for the rawinsonde data (RAOB) are smaller than those from paired radiosonde ascents. However, the important point is that uncertainties in the VAS retrievals (Table 3) are comparable to the RAOB values (Table 4). Finally, uncertainties in rawinsonde-derived mixing ratio (not shown) are approximately 0.31 g kg⁻¹ at 850 mb, 0.22 g kg⁻¹ at 700 mb, and 0.16 g kg⁻¹ at 500 mb. These results are similar to those of the VAS retrievals (Table 3).

Estimates of uncertainty also were obtained for the derived parameters of thickness and precipitable water (Table 5). For the 850–500 mb layer, random errors in thickness are comparable among the three data sources. On the other hand, for the 500–200 mb layer, uncertainties in both VAS retrieval schemes are somewhat larger than those from the radiosonde data. Layer-mean virtual temperatures corresponding to the thickness uncertainties (parentheses, Table 5) generally are smaller than rms temperature errors at the individual levels (Table 3). This finding is consistent with the concept that a satellite’s vertically integrated parameters should be more accurate than those at individual levels due to the broad nature of the weighting functions (Lee et al., 1983; Smith, 1983). Errors in precipitable water for the surface–700 and 700–350 mb layers also are given in Table 5. Estimates range from 0.047 to 0.077 cm for the surface–700 mb layer, whereas values for the 700–350 mb layer range from 0.012 to 0.050 cm.

As a brief summary, results indicate that random errors within VAS retrievals generally are comparable to those of radiosondes on 6–7 March 1982. Integrated parameters are more accurate than those at individual levels, and random errors in the physical retrievals are slightly less than those of the regression procedure.

b. Comparison of VAS retrieval gradients

This section evaluates horizontal gradients of sounding parameters from the two retrieval algorithms. Unless otherwise stated, effects of data uncertainty have been removed from the diagrams that follow. Thus, as noted in Section 2a, only meteorologically related variations are retained. Figure 6 presents structure

<table>
<thead>
<tr>
<th>Thickness (mb)</th>
<th>Precipitable water (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retrieval</td>
<td></td>
</tr>
<tr>
<td>Physical</td>
<td>11.2 (0.72) 15.2 (0.57)</td>
</tr>
<tr>
<td>Regression</td>
<td>11.2 (0.72) 16.6 (0.62)</td>
</tr>
<tr>
<td>RAOB</td>
<td>12.0 (0.77) 10.8 (0.40)</td>
</tr>
</tbody>
</table>

Fig. 6. Structure functions of temperature at 700 and 300 mb from the physical (PHY) and regression soundings (REG).
Structure functions also were calculated separately for each observation time. One should recall that areas of sounding availability increased during the 12 h period (Fig. 3) and that locations and numbers of soundings varied with retrieval type and time (Table 1). With these comments in mind, two points can be made about structures of 300 mb temperature (Fig. 7). First, for both schemes, diagnosed gradients generally increase with time. Also, as observed with the composite results (Fig. 6), greatest differences between schemes occur at the longer separations.

Structure functions of geopotential height at the 700 and 300 mb levels are shown in Fig. 8. Near the surface, the slightly steeper slope for the regression retrievals indicates somewhat stronger gradients. Differences in structure are greatest at separations of approximately 400 km where the contrast reaches 200 m². Since the physically derived gradients are weaker, corresponding values of geostrophic wind (not shown) also would be smaller. Differences in structure decrease with altitude so that by 300 mb, the curves for the two datasets are virtually identical. Once again, it is evident that gradients are stronger at the upper levels. Thus, magnitudes of geostrophic wind (not shown) increase with altitude.

We have assumed that the data fields are isotropic. To investigate this aspect, additional calculations categorized structure results according to the directions of separation vectors between station pairs. Intervals of 150 km and 30° were used. Unlike previous diagrams, values for the anisotropic cases do not have the effects of rms error removed. As an example, Fig. 9 shows that 300 mb heights are highly anisotropic during the composite period. Gradients are maximized along a north–south orientation, approximately perpendicular to the area averaged flow. An important point is that orientations from the two datasets are similar; thus, each portrays mean directional gradients in a similar manner. Although horizontal analyses of the height data (not shown) reveal that orientations at specific times and locations exhibit more pronounced differences than those of Fig. 9, it is nonetheless significant that overall patterns are similar. The anisotropy and degree of agreement in Fig. 9 are comparable to that seen at other levels and also for temperature (not shown).

In spite of the anisotropy, a comparison of both types of results verifies the general conclusions about relative strengths of gradients, i.e., the procedure yielding strongest gradients in an omnidirectional analysis also provides strongest values in most directions of the anisotropic depiction. One can hypothesize situations in which isotropic versions could provide overly optimistic assessments about the resolvability of gradients. For example, calculations along obvious gradients would not contain contributions from positive correlations along the perpendicular direction. This more detailed type of structure function analysis is a topic for future research.

FIG. 7. Structure functions of temperature at 300 mb for individual observation times. Times 1–5 represent 1100, 1435, 1735, 2035 and 2335 GMT, respectively.
Fig. 8. As in Fig. 6 except for geopotential height.

Structure functions of mixing ratio at 700 mb are given in Fig. 10. It is evident that the physical retrievals produce considerably stronger gradients (steeper slope) than those of the regression algorithm. Diagrams for individual times (Fig. 11) reveal that this major contrast is observed consistently and that there are no obvious

Fig. 9. Anisotropic structure functions for geopotential height at 300 mb from the physical and regression retrievals. Structure units are $10^3$ m$^2$ while separations are $10^2$ km.

Fig. 10. As in Fig. 6 except for mixing ratio at 700 mb.
Despite these similarities, however, the major difference is the much weaker regression-derived gradients, and there are differences in orientations of features as well. Several aspects of both satellite analyses are consistent with those from the special radiosonde network (Fig. 13), but of course, there are disagreements as well. Section 4c will consider relative strengths of radiosonde-derived gradients.

Even though structure functions from the physical technique are greater than those of the regression approach, this statistic alone does not indicate whether the enhanced gradients are meteorologically significant. Thus, it is appropriate to consider time continuities of the horizontal analyses (not shown). Although continuity provides valuable qualitative insight, it too is not without limitations. Specifically, since mesoscale data have not been readily available, analysts often disagree as to what constitutes a reasonable progression of pat-

![Diagram](image1)

**Fig. 11.** As in Fig. 7 except for mixing ratio at 700 mb.

temporal trends in gradient magnitude. Furthermore, from the anisotropic representations (Fig. 12), physically-derived gradients are stronger than the regression version along every direction. Results for 850 mb (not shown) are similar to those of Figs. 10–12. Structure functions of precipitable water for the surface–700 mb layer (not shown) also indicate stronger physically-derived gradients. Thus, gradient differences occur over a broad layer of the atmosphere, although the contrasts seen at 700 mb appear to be reduced somewhat during the integration process.

In light of the major statistical differences in mixing ratio, it is informative to examine the horizontal analyses. Figure 13 contains depictions at 700 mb for 2335 GMT, the time of most abundant data. Its features are representative of those for the entire experiment period. It is clear that the functions have achieved their purpose of quantifying the contrasting analyses. Common features of both versions include humid conditions over south Texas, a dry tongue bisecting the domain from northeast to southwest, dry air over the Texas panhandle, and moist air over the Oklahoma panhandle. De-

![Diagram](image2)

**Fig. 12.** As in Fig. 9 except for mixing ratio at 700 mb. Structure units are $10^{-4} \text{ g}^2 \text{ kg}^{-2}$ while separations are $10^5 \text{ km}$. 
terns. In the current case, for example, Chester et al. (1984) concluded that regression soundings yielded more "coherent spatial detail" than the radiosonde data. However, we note that the ground based soundings also indicate complex horizontal variations (e.g., Fig. 13), and satellite-derived water vapor imagery (not shown) reveals major horizontal and temporal variability as well. Therefore, what appears to be poor continuity may actually be quite appropriate. In fact, we believe that many, but certainly not all features of the physically-derived patterns do have reasonable time continuity, thereby suggesting that the enhanced gradients represent atmospheric features, at least to a large extent. The regression-derived patterns also exhibit reasonable continuity, (see Fig. 8 of Chester et al., 1984), but they contain fewer small scale details. Based on all of these comments, it is obvious that additional research is needed to firmly establish the superiority of either algorithm for determining water vapor content.

In summary, even though the physical and regression algorithms are entirely different procedures for deriving soundings, statistical structure functions show that resulting gradients of temperature and geopotential height are quite similar. On the other hand, considerably larger differences occur in gradients of mixing ratio. It is interesting that the increased horizontal averaging of radiances in calculating the physical retrievals (see Section 2b) generally does not result in weaker gradients. Finally, both retrieval schemes depict similar orientations of gradients when the entire data set is considered.

c. Ground truth comparison

An important goal of this study is to compare mean nondirectional gradients from the VAS data with those from the special ground truth rawinsonde network. This necessitated several changes to the methodology described earlier. A major point was that radiosonde soundings were available in both clear and cloudy areas; however, the VAS retrievals were made only in relatively clear regions. Therefore, to provide a better comparison between the two types of data, radiosonde soundings in cloudy areas were not considered. Delineation of the cloudy region was relatively simple, since a single, well defined line of clearing moved eastward through the area (Fig. 5). Also, to account for downwind drift of the radiosonde instruments, all computations utilized sonde positions at individual levels instead of surface station locations.

To further improve the evaluation technique, two subsets of soundings were created, i.e., one of physical and the other of regression-derived data. The procedure was to subjectively pair each rawinsonde site with the nearest physical and regression profile. All other soundings then were excluded. Thus, each subset (physical or regression) contained the same number of soundings as the rawinsonde network (Table 2). To
provide as much data as possible, the appropriately paired VAS sounding was within 100 km of the rawinsonde site. The result of these procedures is that both the areas being studied as well as the data density are comparable for the three data sources. Thus, any differences in results should be due mostly to the fundamentally different nature of the sensing systems and the contrasting retrieval algorithms. As a final step, estimates of rms errors were made for each data subset by using the procedures previously described. These estimates, which were similar to those of the entire data set (Table 3), then were used to correct structure values for data uncertainty.

Structure functions of temperature at 700 and 300 mb (Fig. 14) reveal that the subsets of VAS retrievals generally describe somewhat weaker gradients than observed by the rawinsondes. At 300 mb, for example, the difference between radiosonde and physical structures is approximately 7.6°C² at a separation of 400 km. Based on Hillger and Vonder Haar (1979), this corresponds to a systematic gradient difference of 2.8°C over 400 km. One should note that structures from the two subsets of satellite data generally are similar, as was observed with the complete versions (Fig. 6). Also, results based on the subsets of soundings are slightly greater at longer separations than those from the complete version (Fig. 6). This apparently results from the particular placement of the selected retrievals within the thermal field. Thus, if all the satellite soundings had been used in the current evaluations, VAS/rawinsonde differences would have been even more pronounced.

Satellite-derived temperature gradients have been weaker than those from ground-based sources in several previous investigations, e.g., with TIROS-N (Phillips et al., 1979; Schlatter, 1981), Nimbus 6 (Tracton et al., 1980), and NOAA 4 (Hillger and Vonder Haar, 1979). There is no complete agreement as to the cause of these differences. Schlatter noted that they may result from the statistical retrieval algorithms being used, but current results show that weaker gradients occur with the physical procedure as well. We believe that the differences may be attributable, in part at least, to the smoothing that occurs with the satellite's volumetric sampling. In addition to the horizontal effect, vertical filtering leads to indirect reduction of horizontal features as well, thereby further reducing the gradients. This hypothesis is consistent with that of Hillger and Vonder Haar.

Structure functions of geopotential height for the 700 and 300 mb levels are presented in Fig. 15. At 700 mb, the two satellite-derived structures are steeper at the shortest separations than the radiosonde versions. Slopes are more similar at longer separation distances. This agrees with findings for 700 mb temperature (Fig. 14). In an overall sense, however, all three height profiles basically have similar characteristics. At 300 mb, both retrieval algorithms produce slightly weaker gradients than the sondes. Again considering results at 700 mb, it is not without precedent for satellite-derived gradients to be stronger than ground-based versions. Consistent with current results, Schlatter (1981) found

Fig. 14. Structure functions of temperature at 700 and 300 mb from rawinsonde data (RAOB) and the subsets of physical (SPHY) and regression (SREG) retrievals.
that temperature gradients from TIROS-N occasionally exceeded those of NMC analyses, but only when the gradient was weak and the separation distance small. In those cases the random component of retrieval error was thought to dominate the gradient. In the current study, we attempted to remove random errors via the procedure described in section 2. However, since that technique is not exact, a portion of the greater satellite-derived gradients at small separations may be due to undetected random error. On the other hand, since some small scale features of the horizontal analyses do have reasonable time continuity (not shown), one should not totally attribute the current finding to data errors or procedural inadequacies.

Structure functions for mixing ratio at 850 mb (Fig. 16) are atypical of those seen previously for height and temperature (Figs. 14, 15). In this case, the subset of physical retrievals describes much larger structure (stronger horizontal gradients) than do the rawinsonde soundings. On the other hand, gradients from the regression soundings correspond more closely to those of the ground based data. Jedlovec (personal communication, 1983) observed a similar relationship for the 6–7 March case, and his evaluation procedures were much different from those employed here. As noted

FIG. 15. As in Fig. 14 except for geopotential height.

FIG. 16. As in Fig. 14 except for mixing ratio at 850 and 700 mb.
earlier, continuities of physically-derived mixing ratios (not shown) suggest that much of the procedure's stronger gradients represent true atmospheric features. However, since the algorithm often was unable to capture vertical variations associated with the frontal inversions (Jedlovec, 1985), a part of the stronger gradients may result from vertical aliasing or some other type of systematic error as well. Thus, the physical retrievals may have yielded exaggerated spatial details at 850 mb.

In contrast to the lower level, both subsets of VAS soundings at 700 mb contain weaker gradients of mixing ratio than the radiosonde data (Fig. 15). Regression-derived values are especially small. Although Fig. 13 suggests that the physical retrievals provide more horizontal detail than the radiosonde network, those analyses were based on a greatly differing number of soundings (99 physical versus 24 radiosonde). Current statistical evaluations utilize only 24 stations for each data subset. Thus, as noted earlier, current procedures do not evaluate differences in analyses that are attributable to varying numbers of sounding sites. That is a topic for additional research. Finally, differences between 850 and 700 mb probably are attributable to vapor variations associated with the frontal inversion.

Agreements between VAS- and rawinsonde-derived parameters should be more favorable for vertically integrated parameters. Structure curves of thickness for the 500–200 mb layer (Fig. 17) and the 850–500 mb layer (not shown) indicate that this is indeed the case. Profiles of precipitable water for the surface–700 mb layer (Fig. 17) reveal that the physical soundings still contain somewhat stronger mean moisture gradients than do the rawinsonde data; however, vertical integration appears to have removed some of the difference between the two data sets. On the other hand, regression-derived precipitable water continues to exhibit very weak structure.

To assess directional characteristics of gradients from the limited data sets, anisotropic structure functions were computed over intervals of 200 km and 30°. For geopotential height at 300 mb (Fig. 18), one first should note that both sets of satellite retrievals produce weaker gradients than do the radiosondes, thereby verifying the isotropic results seen earlier in Fig. 15. Also, it again is apparent that the data field is highly anisotropic; however, as noted previously, the important point is that each data source orients the gradients along a general north–south direction. Anisotropic structures for geopotential height at other levels show a similar consistency.

All parameters do not produce the close agreements that are observed for height. For example, Fig. 19 shows the anisotropic structure of temperature at 850 mb. Gradients for the physical soundings are weaker than for the ground truth data, and there also is a discrepancy in their orientation. Specifically, the rawinsonde network depicts an east–west orientation, whereas the physical retrievals indicate a northwest–southeast direction. With the regression soundings (Fig. 19), the maximum gradient is along a northeast–southwest direction. Diagrams for mixing ratio (not shown) also reveal major differences in the orientations of gradients.

5. Summary and conclusions

Statistical structure functions have been used to evaluate sounding data from the 6–7 March day of the 1982 AVE/VAS Ground Truth Field Experiment. Analyses were performed for the composite 12 h period of five observation times between 1200 GMT 6 March and 0000 GMT 7 March as well as the individual times.
Fig. 18. Anisotropic structure functions for geopotential height at 300 mb from the rawinsonde data and special subsets of physical and regression retrievals. Structure units are $10^3$ m² while separations are $10^2$ km.

Fig. 19. As in Fig. 18 except for temperature at 850 mb. Structure units are °C².
Rawinsonde and VAS-derived values of temperature, geopotential height, mixing ratio, thickness and precipitable water were investigated.

By extrapolating structure values to zero separation distance, data uncertainty was estimated. Results indicated that random errors within the VAS retrievals generally were comparable to those from corresponding ground truth radiosondes. These estimates did not include systematic errors, and uncertainties in the rawinsonde data did not influence the satellite statistics. Thus, current values were smaller than those from a direct comparison of satellite and rawinsonde data — the more widely used procedure. The physical retrievals tended to have somewhat smaller random error than those from the regression technique; however, the differences were not pronounced. Signal-to-noise ratios for temperature (1.9–3.8) and geopotential height (2.8–4.8) were quite favorable and somewhat greater than those of mixing ratios (1.6–2.2).

Mean non-directional gradients of temperature and geopotential height were similar for soundings from the physical and regression procedures. On the other hand, gradients of mixing ratio from the physical scheme were considerably stronger than those from the regression approach. Although data fields were highly anisotropic, both retrieval procedures determined the orientations of mean gradients in a similar manner.

Comparisons with the ground truth data showed that the subsets of physical and regression soundings generally described weaker horizontal gradients than those from the special rawinsonde network. This is expected since the VAS provides a volumetric sample of the atmosphere. A major exception was that physically-derived gradients of 850 mb mixing ratio were much stronger than those from sonde data. Some differences between structure profiles at individual levels were removed with the vertical integration used to calculate thickness and precipitable water. One should note that the current evaluation was based on equal numbers of satellite and rawinsonde sites. Therefore, analysis details due to differing numbers of soundings were not considered. Since VAS provides retrievals at mesoscale horizontal spacings, the added amount of data may more than compensate for its volume averaged nature in some applications.

Current results suggest that VAS retrievals will provide valuable data at the synoptic- and meso α-scales. However, its utility as a meso β-scale data source is more uncertain at this time because the atmospheric signal may approach the noise level within the soundings. In fact, current results showed that there was little structure in any of the parameters at separations less than 100 km. Additional verification studies for different synoptic situations and for larger areas and longer time periods are needed to further understand the characteristics of VAS retrievals. A better understanding of VAS data hopefully will lead to improved data handling techniques that will enable us to take maximum advantage of VAS's strengths and to correct or cope with its limitations.

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