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ABSTRACT

Surface temperature and dewpoint reports are added to the infrared radiances from the VISSR Atmospheric Sounder (VAS) in order to improve the retrieval of temperature and moisture profiles in the lower troposphere. The conventional (airways) surface data are combined with the twelve VAS channels as additional predictors in a ridge regression retrieval scheme, with the aim of using all available data to make high resolution space-time interpolations of the radiosonde network. For one day of VAS observations, retrievals using only VAS radiances are compared with retrievals using VAS radiances plus surface data. Temperature retrieval accuracy evaluated at coincident radiosonde sites shows a significant impact within the boundary layer. Dewpoint retrieval accuracy shows a broader improvement within the lowest tropospheric layers. The most dramatic impact of surface data is observed in the improved relative spatial and temporal continuity of low-level fields retrieved over the Midwestern United States. The statistical evaluations and analyses in this sounding study demonstrate the improvement in mesoscale accuracy which can be obtained when frequent VAS observations are meshed with the hourly surface reports available over the continental United States.

1. INTRODUCTION

1.1 Background

The study of mesoscale meteorology requires more detailed, frequent and accurate observations of the temperature and moisture structure of the lower troposphere than can be provided by the current synoptic scale system of radiosonde stations and polar-orbiting satellites. The horizontal resolution of temperature and water vapor soundings derived from the High-resolution Infrared Radiometric Sounder (HIRS) on NIMBUS appears to be adequate to delineate mesoscale variability in a preconvective environment (Hillger and Vonder Haar, 1981). However, HIRS views a given region only twice per day, which is not often enough to monitor mesoscale developments. In addition, the accuracy of satellite soundings based upon infrared radiances suffer from systematic calibration errors and limited vertical resolution. The accuracy of satellite soundings in the lower troposphere is further limited by unresolved clouds and surface variations in topography and emittance. Consequently, HIRS soundings provide poor absolute values and gradient estimates near the earth's surface (Phillips et al., 1979; Schlatter, 1981).

The Visible Infrared Spin Scan Radiometer (VISSR) Atmospheric Sounder (VAS) is a twelve-channel infrared instrument on the operational GOES-4, -5 and -6 satellites. VAS is designed to observe mesoscale temperature and moisture structures in the atmosphere by taking advantage of its geosynchronous position to observe the United States once per hour at 15 km horizontal resolution (Smith et al., 1981), so that VAS radiances can be acquired frequently from the same region at a fixed observing angle. The instrument is a good multi-spectral imager and a relatively stable radiometer, but the absolute calibration is somewhat uncertain (Chesters at al., 1981; Menzel et al., 1981). Nevertheless, bias-compensated VAS soundings have residual errors comparable to the polar-orbiting systems (Petersen et al., 1982). It is more difficult to compute accurate soundings from the VAS radiances because the geosynchronous instrument has no microwave channels, fewer infrared channels, more detector noise, less vertical resolution, and less accurate calibration than the polar-orbiting system. A simulation study of temperature and moisture profiles retrieved from a pre-convective environment established a benchmark for VAS mesoscale sounding accuracy (Chesters et al., 1982a). This simulation study demonstrated that VAS soundings derived from infrared radiances alone will significantly underestimate the extremal values and the horizontal gradients of the retrieved temperature and moisture fields in the lower troposphere.

Until the vertical resolution of infrared sounders can be narrowed down, conventional observations must be utilized in order to improve retrievals in the lower troposphere. Fritz (1977) suggests that geosynchronous satellite radiances be used purely for spatial interpolation by applying a linear regression scheme with special adjustments to force agreement at the radiosonde sites. Unfortunately, this approach does not apply to atmospheric changes during the twelve hours between synoptic observations. One also needs to address the problem of determining the mesoscale structures in the lower troposphere, where the radiosonde network lacks horizontal and temporal resolution and the satellite lacks vertical resolution. Chesters (1980) describes a physical retrieval algorithm which employs statistics from previously observed vertical profiles in order to help resolve the radiometric ambiguities about the structure of the lower troposphere. Hayden (1980) suggests that VAS moisture retrievals can be improved in the lower troposphere by incorporating the hourly dewpoint reports from the network of surface (airways) stations. Adopting these notions, this paper demonstrates that a linear regression scheme which uses the joint VAS/surface observation field can improve the accuracy of the retrieved temperature and moisture profiles in the lower troposphere. This approach to VAS soundings is statistically valid for any mesoscale region which provides an appropriate variety of coincident satellite/surface and radiosonde observations.

Statistical retrievals are a proven technique for calculating atmospheric parameters from satellite radiances in a manner which removes biases and other systematic errors (Smith and Woolf, 1976). Physical retrievals which invert a radiation transfer model are potentially more incisive, but they are also more difficult to apply, especially over landscapes where topographic and skin temperature variations dominate the radiances arising from the lower troposphere. Consequently, VAS data are used to make mesoscale space-time interpolations within an area which can be trained statistically from coincident satellite/conventional observations selected from a time series of multi-spectral fields. The empirical training contains a naturally low correlation between the window channels and the tropospheric conditions. This avoids over-interpretation of skin effects but also masks the modest radiometric information about the lower troposphere. Therefore, surface data are introduced into the statistical method as ancillary independent predictors. The multivariate regression coefficients are preconditioned with realistic noise estimates in order to diminish the practical difficulties normally encountered with the inversion of a large, noisy, ill-conditioned covariance matrix of redundant predictors (Marquardt and Snee, 1975). While regression retrievals cannot be exceptionally accurate, they are good enough to demonstrate the impact of ancillary data upon a remote sensing system which is unable to determine all atmospheric information from satellite data alone.

1.2 Objectives

This study evaluates the impact of conventional surface data as additional statistical predictors in a regression retrieval scheme. VAS data fields are combined with radiosonde and airways reports available for a twelve hour case study across the central and eastern United States on 13 July 1981. Impact is assessed by intercomparing three retrieval sets from:

1. VAS twelve-channel data alone (VAS only),

2. surface temperature and dewpoint reports alone (SFC only),

3. combined VAS and surface data (VAS plus SFC).

Impact assessments are made from these three retrieval sets upon:

1. the absolute accuracy from residual errors in the temperature and dewpoint profiles retrieved at selected radiosonde sites,

2. the relative accuracy displayed by the spatial and temporal continuity in the mesoscale temperature and moisture fields.

These assessments will provide a benchmark of the impact of ancillary surface data upon parameters which characterize the lower troposphere.

1.3 Outline

The linear regression technique is reviewed in Section 2 and the incorporation of ancillary surface data into the retrieval process is addressed. Section 3 describes the database of VAS radiances, radiosonde observations, and conventional surface reports. Section 4 describes the calculation of regression coefficients, the selection of coincidental data sets, the grouping of "training" and "testing" sets, and the establishment of quality control parameters in the process. A comparison is made between the most important predictors found in the regression coefficients with and without the ancillary surface data. Section 5 evaluates the absolute retrieval accuracies of temperature and dewpoint profiles at independent radiosonde sites and re-evaluates the field retrievals at all training sites. The direct retrieval of certain integrated or derived meteorological parameters is also evaluated. Emphasis is given to the improvements made by including the surface data as additional predictors. The statistical validity of regression training with only a modest number of clear radiosonde sites is tested with additional independent datasets. In Section 6, comparisons are made between objectively analyzed temperature and dewpoint fields derived from the VAS soundings to show the impact of using ancillary surface data. The validity of diurnal retrievals which are based upon dawn/dusk training is examined, and some tests are made to establish the influence of the VAS window channels upon the midday soundings. A time sequence of 5 gridded sounding fields is shown to illustrate the impact of surface reports upon the time continuity of the low-level dewpoint field. The findings of this study are summarized and discussed in Section 7.

2. VAS REGRESSION RETRIEVALS

2.1 Review of the Regression Technique

Linear regression has become the operational method for retrieving atmospheric structures (temperature, moisture, and other parameters) from remote-sensing radiometric measurements (see e.g., Smith et al., 1970; Fritz et al., 1972; Smith and Wolf, 1976). This empirical technique is able to predict (estimate) unknown atmospheric parameters from a given radiance dataset based on previously established parameter/radiance correlations without any _a priori_ knowledge of instrumental bias or transmission functions.

Regression retrievals assume that the radiance response, $\delta R(\nu)$ in a channel at wavenumber ν, is a linear combination of atmospheric variations from a reference state, $\delta X(p) = X(p) - X_0(p)$, where $X(p)$ is temperature, moisture, or other state parameter in the atmosphere as a function of pressure, p. Consequently, an estimate of the atmospheric variation, $\delta X'(p)$, can be made from a corresponding linear combination of variations in the observed radiances:

$$\delta X'(p) = C(p,\nu) * \delta R(\nu). \tag{1}$$

The "*" symbolizes matrix multiplication with terms being summed over repeated independent variables, such as v in Eq. (1). With many observations of X and R, a retrieval matrix, $C(p,\nu)$, which minimizes the differences between $\delta X'(p)$ and $\delta X(p)$, can be obtained by the least squares technique:

$$C(p,\nu)=<\delta X(p)\delta R(\nu')>*[<\delta R(\nu')\delta R(\nu)>]^{-1}. \qquad (2)$$

The "<...>" symbolizes a statistical average over a sample learning set of simultaneous, collocated observations, and the "$[...]^{-1}$" symbolizes matrix inversion.

Direct application of the simple regression algorithm (2) to a small set of available satellite and radiosonde data usually leads to a retrieval matrix with large coefficients and opposing signs, which over-interprets the small fluctuations normally encountered in real data. The solutions can be stabilized or "conditioned" by taking into account the radiometric noise $e(\nu)$ in each channel, thus $\delta X'=C*[\delta R+e]$. With a minimum-information scheme, which assumes no correlation between e and R, a new retrieval matrix is found:

$$C=<\delta X\delta R>*[<\delta R\delta R>+<e^2>]^{-1}. \qquad (3)$$

When $<e^2>$ is the same value for all predictors, this method is known as ridge regression. The statistical role of the conditioning factor was studied semi-analytically by Marquardt and Snee (1975). Their study established that ridge regression produces coefficients which predict and extrapolate data much better than least squares when the predictor variables are highly correlated. Marquardt and Snee's successful experiments involve statistical training with sample sets which are only a few times more numerous than the number of predictor variables. Therefore, the conditioning factor has a stabilizing influence against the uncertainties which small training sets inflict upon the classical least squares solution.

The conditioning factor introduced in calculating the regression matrix from Eq. (3) is simply the inverse of the rms "signal" to "noise" ratio G(ν):

$$G^2(\nu)=<\delta R^2>/<e^2>. \tag{4}$$

Note that the "signal" is the variance about the mean field of clear radiances, not the total brightness of a channel. The "noise" in a broader sense may include errors introduced by any uncertainty in δX and δR, and even by the nonlinearities between R and X. In a preliminary VAS simulation study, the sensitivity of linear regression retrievals to conditioning factors was reported and values of G between 5 and 20 were found to produce acceptable results (Lee and Yap, 1980). Artificially small values of the signal/noise ratio can be imposed upon questionable predictor variables to assess the impact of suppressing potentially harmful input. Such a test is applied in Section 6.3 to the infrared window channel at 3.9 μm.

Because the impact of surface data is based upon statistical prediction, we exhaustively validate the results with four distinct procedures:

1. The regression coefficients should be consistent with radiation transfer in the VAS channels (e.g., the altitude of greatest statistical predictability should correspond to the peak of the physical weighting function for each channel).

2. The retrievals should be consistent with atmospheric physics (e.g., surface reports should predict atmospheric conditions with decreasing confidence at greater altitudes).

3. The main features of the retrievals and the impact of ancillary surface data should be independent of modest alterations to the training set (e.g., add more training sites or suppress a non-essential predictor).

4. The main features of the retrievals and the impact of ancillary surface data should be reproducible when a completely independent training set is applied (e.g., train with a different day of coincident satellite and radiosonde sites).

These issues are addressed in Sections 4.3, 5 and 6.3.

2.2 The Need to Improve VAS Soundings of the Lower Troposphere

The VAS instrument consists of 12 infrared channels: Five in the 15μm CO_2 band, two in the 4.3 μm CO_2 band, two in the 6.9 μm H_2O band, two in the 11-12 μm window, and one in the 3.9 μm window (Table 1). Weighting functions of all 12 channels calculated for a Standard U.S. Atmosphere between the 100 mb and 1000 mb levels are shown in Fig. 1. Although eight of the weighting functions peak between the 500 mb level and the Earth's surface, the lower troposphere is still not well resolved because of the broad response curves. Uncertainties due to radiometer noise, clouds and surface irregularities further hinder the separation of the overlapping sensitivities of all the channels.

Single sample noise for each spectral band varies greatly, from 0.1 to 7.0 K in brightness temperature units. The noise for a sounding field of view can theoretically be reduced to less than 0.5 K (see Table 1). This reduction is achieved by averaging the radiances through multiple spins taken across the same line (dwell-mode) and also by averaging the radiances of several overlapping instantaneous fields-of-view (7 or 15 km resolution at nadir). However, systematic calibration errors (Menzel, 1980, and Menzel et al., 1981) limit the usefulness of radiance averaging as an error reduction technique.

A simulated VAS regression study for a pre-convective environment showed that retrieval accuracies could be within ±1.5 K for temperature and ±25% for mixing ratio in layers below the 500 mb level (Chesters et al., 1982a). In that study, the low-level temperatures were retrieved well because the simulation assumed a uniformly black surface and no discontinuity between the surface (skin) temperature and the boundary (air) temperature. However, low-level retrievals done with actual data are not as accurate as those from simulated data, because of the poor correlation between the air temperature of the boundary layer and the skin temperature detected by the window channels. Low-level moisture information is not retrieved very well, even in the simulation experiment, due to the fine structures in the vertical water vapor distribution, the radiometric confusion with air temperature, and the limitation of only one low-level

H2O channel on VAS. In reality, the large topographic variability in the skin temperature interferes with the window channels' potential usefulness as a predictor of conditions in the lower troposphere. In addition, the diurnal cycle of skin temperature limits the usefulness of the window channels as a statistical predictor, because training at radiosonde sites in the United States is only available under local morning and evening conditions. Thus, midday regression retrievals of the lower troposphere can be systematically biased to unrealistic levels by VAS data alone.

2.3 The Use of Ancillary Surface Data

As suggested in VAS simulation studies (Chesters, 1980; Chesters et al., 1982a; Hayden, 1980), the lower tropospheric retrievals can be improved significantly by using statistical conditioning specifically for a local situation and by incorporating timely conventional surface data to supplement the badly needed boundary layer information. Conventional weather reports are available every hour at more than 1100 surface (airways) stations across North America in near real time via the National Weather Service (NWS) 604 transmission line. This relatively dense network provides a wealth of information that is essential to studies of short-lived mesoscale meteorological developments.

The high correlations between the temperature or moisture close to the ground and that in the lowest atmospheric layers (Steyaert and Darkow, 1973) justify the use of conventional surface data to supplement VAS radiometric data for soundings in the lower troposphere. The horizontal spacing and frequency of observations from the NWS network (about 100 km and 1 hr) mesh fairly well with the corresponding VAS observations (about 20 km and 3 hr). Because temperature and moisture in the boundary layer are not strongly correlated with infrared skin temperature, the ancillary surface data should replace the irrelevant and possibly misleading window channel radiances as leading statistical indicators of atmospheric conditions.

3. DESCRIPTION AND PREPARATION OF THE DATABASE

Three types of data needed for this study are VAS dwell-sounding radiances, radiosonde observations and conventional surface reports. The main portion of the database spans from 1200 GMT 13 July to 0000 GMT 14 July 1981 and covers the central and eastern United States (roughly 25° to 50° N and 70° to 110° W). For the purpose of independent testing, a supplemental database is also included, which contains available data around 1200 GMT 20 July and 0000 GMT 21 July 1981 at corresponding radiosonde sites selected within a slightly smaller area in the central and eastern United States.

The raw datasets utilized in this study are summarized in Table 2 which shows the nominal time, VAS data coverage, and numbers of radiosonde or surface reports available. More specific information on grouping and labeling of subsets will be discussed in the next section.

3.1 The General Weather Conditions

The weather conditions of both 13 and 20 July 1981 are interesting for mesoscale studies. Both days are characterized by frontal systems and by the development of several distinct areas of convection. The surface weather maps of the central and eastern United States at 1200 GMT 13 July and 0000 GMT 14 July 1981 are shown in Fig. 2. The dominant feature at 1200 GMT was a low pressure system, located over eastern Colorado, with a front extending to the east across Nebraska, Iowa, northern Illinois and Indiana. During the next twelve hour period, the surface low moved slowly northeastward while the eastern portion of the front was pushed southward by the circulation of another low pressure area over Ohio. By 2100 GMT, intense surface heating coupled with low-level moisture convergence destabilized the lower troposphere along the front from South Dakota through the Ohio River Valley. Very strong convection took place over eastern Iowa, between 2100 and 2300 GMT, and later moved southeastward into central Illinois. Convective clouds and rainfall also developed along the Texas coast, across Kansas, Oklahoma and in the southeastern United States during the twelve hour period.

The variations in temperature and dewpoint structure of 20 July are somewhat larger due to the existence of a stronger baroclinic condition. Throughout the day of 20 July, a strong cold front extended from central Colorado to a diffuse low pressure system in Michigan and drifted southward. By 1800 GMT, the combination of low-level warm moist air, frontal convergence and destabilization aloft contributed to both the growth of an isolated short-lived convective cell in north-central Illinois and the development of massive thunderstorms over central Missouri, which moved southward all afternoon. After 2100 GMT, a second line of thunderstorms also formed across Oklahoma, in an area of little upper-level forcing.

The infrared images of the VAS 3.9 μm window radiances provide high contrast pictures of the cloud cover and surface features with approximately 15 km resolution. Figure 3 shows locations both of the selected radiosonde stations and of the available surface weather reports, plotted on the 2300 GMT 13 July image.

3.2 Radiosonde Temperature and Moisture Data

The "ground truth" data used in this study are temperature and dewpoint temperature profiles observed at radiosonde sites in the central and eastern United States at 1200 GMT on 13 and 20 July and 0000 GMT 14 and 21 July 1981. These profiles are used in the calculation of regression coefficients and for the evaluation of retrieval errors.

At each site, temperature and dewpoint values were extracted at 15 pressure levels between 100 mb and 1000 mb from the observed profiles (see the pressure levels marked on Fig. 1). For those sites located above the 1000 mb level, the first reported values were extended isothermally down to "1000 mb". The uncertainties in the resampled profiles are small for temperature but larger for dewpoint because the original reports often contain boundary layer inversions, large vertical gradients and/or nominal 30° C dewpoint depressions at several levels. The vertical details of the <u>in situ</u> dewpoint soundings are difficult to relate with the layer-averaged information detected by a satellite radiometer.

3.3 VAS Sounding Radiances

Five VAS dwell-sounding measurements were acquired in all 12 channels from GOES-5 at 1202, 1502, 1802, 2102, and 2300 GMT on 13 July 1981 through the VAS processing system at NASA's Goddard Space Flight Center. A regional subset covering the central and eastern United States was taken from the original 20° to 50° N and limb-to-limb observations. Similar VAS soundings were also acquired at five times by both the Goddard and University of Wisconsin processing systems on 20 July 1981, of which the

1200 and 2300 GMT datasets are used here to calculate independent regression coefficients. The infrared radiances were averaged by combining five adjacent samples (pixels) to produce a sounding field-of-view (SFOV) of approximately 20 km square. Each SFOV contains 12 infrared radiances (in units of erg cm $^{-2}$ sec $^{-1}$ wavenumber $^{-1}$ steradian $^{-1}$, abbreviated as erg/etc.), which are the principle predictors in the linear regression process. Radiances were also converted to equivalent brightness temperature (Kelvin) using Planck's function with an appropriate set of effective wavenumbers (Table 1). The VAS brightness temperatures are convenient because they have the same units as the basic atmospheric variables and surface predictors.

3.4 Surface Weather Reports

Hourly surface weather reports were obtained through the NWS 604 line. Temperature, dewpoint, sea-level pressure, cloud cover, and the location, elevation, and I.D. of each station were extracted. While cloud information is helpful for making clear radiance selection, only two items, temperature and dewpoint, are incorporated into the retrieval process. In practice, the surface temperature and dewpoint measurements are made separately at the radiosonde and surface stations. Hence, these readings are usually within 2° C, but they can disagree significantly, because of the differences in observing time, location, and particularly the measuring methods employed. For example, we found in the 0000 GMT 14 July dataset that the surface dewpoint discrepancies at 5 of the 40 sites are greater than 4° C and one even exceeds 10° C! Such large discrepancies impose an unexpected limitation upon the accuracy of surface data as statistical predictors of the first radiosonde report in the boundary layer, especially when the number of sites available for statistical training and testing is not large.

The specific times at which the surface data were available and used as supplementary predictors to the VAS radiances are 1200, 1500, 1700, 2100 GMT of 13 July, and 0000 GMT of 14 July 1981. The 1700 and 0000 GMT observations substitute for the 1800 and 2300 GMT data, respectively, which have a large number of missing reports. In addition, surface data of 1200 and 2300 GMT on 20 July were also used in this study (see Table 2).

Gridded surface data were also prepared, using an objective analysis scheme (Cressman, 1959), for the area from 73° to 107° W and 25° to 49° N and with one degree spacing in both directions. When gridded surface data are used instead of the nearest-neighbor surface observations, the retrievals are generally smoother and are only significantly affected in large areas which are devoid of surface reports.

4. CALCULATION OF REGRESSION COEFFICIENTS

Coincident radiance/radiosonde/surface data are essential for statistical regression training and for point-by-point retrieval evaluation. A total of 81 individual coincident points on 13 July and 52 points on 20 July were selected from the database. This database is partitioned into several subsets which will be used to examine different space-time coverages, to validate the sample size and to test for statistical impact. Table 3 is a summary of the attributes of these subsets and is explained below.

4.1 Selection of the Coincident Datasets

For each radiosonde observation time, the data were examined with the aid of an infrared window image (11 or 3.9 μm) which emcompassed the radiosonde sites in the central and eastern United States (from 24° to 49° N and from 73° to 107°W). Many sites were subsequently eliminated because of missing or suspicious reports, or extensive cloud cover. A corresponding VAS dataset was produced which contained relatively clear radiances in all 12 channels for all selected radiosonde sites. A displacement up to 0.5 degree in latitude or longitude was permitted to avoid scattered clouds. The corresponding surface data were obtained by a nearest-neighbor search centered at the SFOV location. A conventional surface report is generally found at or very near the radiosonde site. The mismatches in time were usually less than half of an hour.

Eighty-one coincident data points were selected for 13 July 1981. As listed in Table 3, this main "13 July Continental Day" set contains two time specific subsets: Dawn (1200 GMT) and Dusk (2300 or 0000 GMT). Each subset was further subdivided into a training set (28 sites) and a testing set (12 or 13 sites) at each time. In this sampling process, we tried to maintain a balanced geographical distribution between the two groups (see special symbols on Fig. 3). The training sets were used to calculate the regression coefficients, and the testing sets were used to estimate the retrieval errors. A "Regional" set, which is a subset of the "Continental", was specifically created for field retrievals within the Midwestern region of the United States.

Similarly, 52 coincident observations were obtained from the 20 July data, equally divided between two radiosonde times. The smaller sample size is due to more extensive cloud cover and missing VAS dwell-sounding data to the south of 31°N. The 20 July Regional set is used to calculate regression coefficients for different-day cross-evaluation, so that no further subsets were created.

The establishment of separate training and testing sets made the evaluation of absolute retrieval accuracies possible. However, the paucity of good quality local training sites is the most important limitation in the use of regression retrievals for mesoscale situations. The appropriateness of training selection is as important as the quality and quantity of the matched data samples.

4.2 Standard Procedure and Variations in Controlled Experiments

A standard procedure and a set of control parameters were established for the analyses. The air temperature and dewpoint temperature profiles at 15 levels (100 mb to 1000 mb) are the basic meteorological parameters to be predicted (retrieved). The predictors consist of either all 12 VAS radiances (hereafter referred to as the "VAS only" case), just the surface temperature and dewpoint (the "SFC only" case), or a combination of the 12 VAS radiances plus the corresponding ancillary surface temperature and dewpoint (the "VAS plus SFC" case). Therefore, for each matched dataset, three sets of regression coefficients were calculated. Each case contains two mean data files and a matrix with fixed dimensions of 30 by 14.

Taking advantage of the preconditioning technique discussed in Section 2.1, any predictor can be suppressed by just setting the corresponding conditioning factor to a very large value (e.g., 100.). Thus two or twelve of the fourteen columns will be nearly zero in the matrices of "VAS only" and "SFC only" cases, respectively. For the remaining predictors, the conditioning factor is set equal to 0.1, equivalent to an overall signal-to-noise ratio of 10 to 1, which is close to the expected ratio for VAS sounding brightness temperatures or surface temperature or dewpoint.

The standard matrices were generated for the following four data groups:

1. 13 July Continental Day set, used for regression coefficient examination (in Sec. 4.3) and rms residue statistics (Sec. 5.3).

2. 13 July Continental Training sets, used for the retrievals of independent test sets on the same day (Sec. 5.1).

3. 13 July Regional Day set, used for field retrievals to evaluate the space-time interpolation process on 13 July (Sec. 5.3 and Sec. 6), and

4. 20 July Regional Day set, used for entirely independent training which is tested upon 13 July Regional Day retrievals (Sec. 5.2).

Matrices of several time-specific subsets were also created to test against each other, in order to verify the results from these four basic sets.

Several variations of the standard procedure were also tested. These alternatives included: the replacement of radiances by their brightness temperatures as predictors, the suppression of certain VAS channels, changes in the size of the regression training set, and the use of different values for the conditioning factor. The use of brightness temperature instead of radiance changes the effective sensitivity and somewhat redistributes the weights among predictors in the regression process. However, unless the conditoning factors used are much smaller than 0.1, the differences in retrieval staistics are found to be insignificantly small. The suppression of window channels, particularly the short-wave channel 12 at 3.9 μm, was tried in order to study the impact upon the midday field retrievals, discussed in Section 6.3. Other parameters such as equivalent potential temperature, layer thickness, and total precipitable water were also selectively retrieved. These parameters are retrieved directly, rather than derived from the retrieved temperature and dewpoint profiles, for convenience and greater reliability.

The retrieved results are only moderately sensitive to the variations in the regression procedure. The greatest changes occur when the database used for the coefficient calculation is very small in size (for example, less than 30 training sites). Since the overall sounding results are more or less the same as for the standard sets, the alternative results will only be discussed when they are significantly different.

4.3 Major Contributions Revealed by Regression Matrices

Before the retrieval results are presented, it is worthwhile to inspect the elements of the regression matrices. The linear regression coefficients reveal the empirical sensitivity of the retrieved atmospheric parameters (temperature or dewpoint) with respect to variations in the predictors (radiances or surface data). However, the relative importance of each predictor to a specific parameter cannot be assessed by directly comparing the magnitudes of these coefficients, because not all predictors have variances of similar size. For instance, the VAS window channel at 11 μm has a typical variance of ± 10.0 erg/etc., while the VAS 3.9 μm window has only ± 0.1 erg/etc. for the same scene, due to the shape of the Planck spectrum. Consequently, the products of each regression coefficient and its corresponding predictor's standard deviation are examined together. The product can be regarded as the average contribution to the temperature or dewpoint which is predicted from each component.

Figure 4 shows the major contributions to the low-level temperature retrievals, calculated from the 13 July Continental Day regression coefficients with and without surface data as additional predictors. In both cases, predicted temperature variations between the 500 and 700 mb levels are small because there is little variance in the training at this altitude. Many contribution amplitudes at 850 and 920 mb are large, but no channel dominates. For the 1000 mb (boundary layer) temperature, channels 5, 6, 7, 8 and 12 are the most important contributors for the "VAS only" case, as might be expected from their weighting functions (Fig. 1). In contrast, for the case of "VAS plus SFC", surface temperature almost completely dominates as a predictor of boundary layer temperature, while it only plays a moderate role over the remainder of the lower troposphere. This pattern satisfies our expection that surface temperature is a more efficient predictor of the boundary layer temperature than any combination of the VAS window channels and/or the surface dewpoint.

Figure 5 shows the corresponding contribution functions for dewpoint. The curves in Fig. 5 have been cut off above 700 mb to avoid the large, irregular fluctuations in the middle troposphere, which result from the poor correlation of the radiances with the widely varying radiosonde moisture data at those levels. The prediction of dewpoints below the 700 mb level in the "VAS only" case is dominated by channels 6, 7 and 8, which is consistent with those channels' weighting functions. Virtually no contributions from the upper-level moisture channels 9 and 10 are found to influence dewpoints below the 850 mb level (not shown in the figures because of their small values). Again, in the case of "VAS plus SFC" retrievals, the surface dewpoint obviously dominates at the 1000 mb (boundary layer), and its influence decreases steadily above the 920 mb level. The window channels (8 and 12) and surface temperature do not contribute significantly to the "VAS plus SFC" dewpoint retrievals. Therefore, the surface dewpoint appears to be a more reliable predictor of the boundary layer moisture than several weakly competing VAS channels.

We cannot place much confidence in the small amplitude variations of the contribution functions shown in Figs. 4 and 5 without a substantially larger training set. The conditioning factor in Eq. (3) is known to stabilize the regression coefficients compared with the relatively ill-determined coefficients produced by the least squares approach in Eq. (2). For the least squares approach, the "circle of confusion" (σ_{cf}) between two well-correlated contribution functions is estimated by

$$\sigma_{cf} \leq \sigma \left[\frac{K}{N} f_{K,N-K}(0.95) \right]^{1/2} , \qquad (5)$$

where σ is the residual standard deviation in the predicted variable, K is the number of predictors plus one, N is the number of training cases, and f(0.95) is the Fisher statistic for 95% confidence (Jenkins and Watts, 1968). For the complete 13 July Continental Day set, $\sigma = \pm 1.5$ C for temperature and ±2.0 C for dewpoint (see Table 6), K=15, N=81 and f=1.7, so that $\sigma_{cf} < \pm 0.9$ C for temperature and ±1.2 C for dewpoint. Consequently, the contribution functions of both surface temperature in Fig. 4-b and surface dewpoint in Fig. 5-b appear to be statistically significant in the lower troposphere. We have also verified this pattern empirically by examining the contribution functions for the other "VAS plus SFC" training sets listed in Table 3. Note that the statistical confusion among the less significant channels does not mean that these channels are useless for this impact study. Statistical prediction by multivariate regression is still jointly significant, even when the exact contributions from the separate predictors cannot be determined with confidence, provided that the coefficients are not used to extrapolate far beyond the range of the original training set.

5. RETRIEVAL ACCURACIES AT RADIOSONDE SITES

In this section, regression retrieval errors among the subsets listed in Table 3 are evaluated for the "VAS only", "VAS plus SFC", as well as "SFC only" cases. The impact of including ancillary surface data on retrievals at the radiosonde sites is emphasized. First, the absolute retrieval errors in temperature and dewpoint are estimated by using independent data for training and testing either in the same day or from a different date. Second, all 13 July coincident datasets are used to construct the Continental or Regional Day regression matrices specifically for use in field retrievals. The field retrievals are then re-evaluated at the same radiosonde sites which were used for training. This process measures the goodness-of-fit provided by the regression process, consistent with our use of the VAS and ancillary data to perform space-time interpolations among the synoptic radiosonde observations. In addition to the temperature and dewpoint profiles, some useful integrated or derived meteorological parameters are also retrieved directly and then evaluated.

The retrieval accuracies are measured by the mean errors and standard deviations or alternatively by total rms differences between the actual and the retrieved values. The means and standard deviations within the ground truth data are also calculated, as well as the fractions of the variances recovered by the regression process. This "recovery rate" is a figure-of-merit defined by:

$$r = 1 - S_r^2 / S_t^2, \qquad (6)$$

where S_r^2 is the total variance of the ground truth and S_t is the standard deviation of the retrieved discrepencies. A value of r=1 would indicate a perfect retrieval (except for a possible bias); while a small fraction reflects poor performance. In some instances, the values may even become negative when the retrievals are badly determined by the observations, or when the true variances are too small to be detected within the satellite uncertainties.

5.1 Same-Day Independent Test on Temperature and Dewpoint Profile Retrievals

Temperature and dewpoint profiles are retrieved for the 13 July Continental Day Testing data (25 sites) by using the regression matrices calculated from the independent Training set (56 sites) in the same day and same coverage. Table 4 presents the retrieval statistics of temperature (500 to 1000 mb) and dewpoint (700 to 1000 mb) from the independent testing for the "VAS only", "VAS plus SFC" and "SFC only" cases. The total rms retrieval error curves for these three cases, together with the standard deviation of the original temperature and dewpoint profiles, are also shown in Fig. 6. The ground truth data statistics shown in Table 4 demonstrate that the training and testing sets are compatible.

The "VAS plus SFC" retrievals are better than or about equal to the retrievals of the other two cases. The rms errors in Table 4 are 1.5 to 2 C in temperature from the boundary layer up to the 500 mb level and about 2 C in dewpoint up to the 850 mb level. There are obvious improvements of the "VAS plus SFC" case over the "VAS only" case in both temperature and dewpoint retrievals in the boundary layer, where surface data dominate. The "VAS plus SFC" case shows a modest rms improvement over the "VAS only" retrievals in the lower troposphere. The greatest impact is made upon the 920 mb dewpoint errors. Mixing of surface data with VAS data shows very little effect upon temperature retrievals above 700 mb or dewpoint above 850 mb. The original temperature field in this case has a very low standard deviation above 700 mb, which is very close to the absolute accuracy obtainable by satellite, so that it is impossible to assess the impact in the middle troposphere. The original dewpoint fields in the lower troposphere have enough variance to demonstrate some impact upon the moisture residuals. However, these point-by-point statistics understate the most valuable impact of the surface data upon the VAS retrievals, which is observed from the continuity of the low-level mesoscale fields disscussed in Section 6.

This particular independent test is qualitatively representative of several such experiments with the 13 July subsets. The other experiments sometimes show greater impact for retrievals at certain levels. For instance, the time-specific (Dusk subset) independent test on 13 July shows a significant impact upon dewpoint retrievals at 850 mb, but the test sample size is too small (N=12) for statistical confidence.

5.2 Independent Test with Different Day Training

The retrieval results discussed in Section 5.1 were based on separate training and testing sets from the same day or same time. Statistical validity suffers from the limited number of radiosonde sites which must be subdivided into training and testing subsets. To provide an independent set of larger sample size, the 20 July Regional dataset (52 sites) and the 13 July Regional dataset (51 sites) are used as training and testing counterparts, respectively.

subdivided into training and testing subsets. To provide an independent

The error statistics of the 13 July Regional retrievals using 20 July Regional matrices are shown in Table 5 for "VAS only", "VAS plus SFC" and "SFC only" cases. The characteristics of the retrieval errors are found to be very similar to those of the same-day test on 13 July. The biases are usually smaller than the differences of the means between training and testing sets. Again, the impact of surface data is significant in the boundary layer (920 to 1000 mb), but the improvements made with surface data are more prominant in dewpoint than in temperature, particularly at 850 and 920 mb levels. The potential recovery rates for temperature retrievals above 700 mb remain unresolved with these mid-summer cases.

In summary, the temperature retrieval accuracies found by using the "VAS plus SFC" matrix from an independent day are 1.5° to 2.5° C between the surface and 850 mb, and 1.5° to 2° C above that. The dewpoint accuracy is more uniform at about 2° C below the 850 mb level. The improvement in temperature with ancillary surface data is about 1° C at 1000 mb, but the impact decreases rapidly above the boundary layer. Dewpoint improvements up to 1.5° C are found in the layers below the 850 mb level.

5.3 Re-evaluation of Field Retrievals at All Training Sites

For the purpose of using VAS data as a space-time interpolator within a multi-spectral regression scheme, we should train the retrieval matrix with all available coincident data which encompass the time period and spatial area of interest. The "VAS only", "VAS plus SFC" and "SFC only" retrievals are generated with two 13 July datasets (Continental Day and Regional Day) for low-level temperature, dewpoint, equivalent potential temperature, layer thickness, and total precipitable water content. Retrieval accuracy is evaluated in terms of the rms residuals from the linear regression fits at all training sites. These rms residuals measure the "goodness-of-fit" from the experiregression coefficients, since they overestimate the absolute accuracy of the retrievals. Nevertheless, their relative values indicate the impact of surface data upon retrievals which utilize both VAS and surface data for space-time interpolation.

Estimations of many meteorological parameters such as mixing ratio, equivalent potential temperature, precipitable water amount, layer thickness, etc. could be calculated from the retrieved temperature and dewpoint profiles. However, direct regression retrievals of these parameters are more convenient and reliable, probably due to a lower net sensitivity of the "bulk" or layer retrievals to the many ill-determined moisture coefficients at specific levels of the lower troposphere.

Both the full Continental (N=81) and Regional (N=51) datasets of 13 July are used here for training and re-evaluation process. The Continental set has a comfortable sample size, while the Regional set is more suitable for 13 July field retrievals in the Midwest. The rms residuals of low-level temperature and dewpoint from linear regressions in three cases for the Continental set are listed in Table 6. Figure 7 displays the error statistics of the Regional retrieval residuals in temperature, dewpoint and equivalent potential temperature at the 850 and 920 mb levels, plus two layer thicknesses and the total precipitable water. Standard deviations in the original dataset are displayed in order to indicate the variance across the original field. The bar diagram indicates that the gain from utilizing surface data in the space-time interpolation proccess is significant for both temperature and dewpoint in the layer below 850 mb, and for some bulk parameters which contain this information.

These rms residuals underestimate the absolute error in the VAS regression retrievals. Theoretically, the true error is $\sqrt{N/(N-K-1)}$ times larger than the corresponding rms value, where N and K are the sample size and the number of predictors, respectively. In our studies, the true errors should be about 10% (N=81) or 20% (N=51) larger for "VAS only" and "VAS plus SFC" cases. The theoretical impact from two additional predictors (K=14 versus 12) is marginal, only 2 to 3%. Consequently, the observed relative impact of surface data upon the lower tropospheric retrievals (mostly 10% or more) provides statistical evidence of the information content gleaned from this ancillary data.

The rms residual statistics in Table 6 and Fig. 7 demonstrate that:

1. The "VAS plus SFC" results are always better than or equal to the "VAS only" results. The addition of surface data into the regression process for retrievals at the higher levels may not be very helpful, but at least they are not harmful.

2. By incorporating all available data to perform both the "training" and "testing", the residual errors are significantly smaller compared with those in the independent evaluation (Table 4). Even after accounting for the differences in sample size and degree of independence, part of the improvement appears to be due to the better training when all sites are used.

3. The impact of using ancillary surface data is large at the 920 and 850 mb levels, but is insignificant above the 700 mb level. Consequently, the impact upon the thickness estimates of a deep layer is rather modest.

4. The impact is stronger for those retrieved variables closely associated with the low-level moisture content, namely, dewpoint (or mixing ratio), equivalent potential temperature, and total precipitable water.

These findings reaffirm that the conventional surface data are very useful in retrieving the low-level tropospheric information, especially moisture, which cannot be obtained sufficiently from the VAS radiances within a regression retrieval technique.

Noticeable differences can be found in residual statistics between the Continental and Regional sets (see Table 6). The original temperature and dewpoint variances generally become larger when most southern coastal stations and some distant overcast sites in the Continental set were excluded from the Regional. There are improvements in accuracy up to 0.3° C in temperature and up to 0.5° C in dewpoint for "VAS plus SFC" Regional retrievals, and the over-all recovery rates are better by 0.1 to 0.2 in both temperature and dewpoint.

The results of these experiments show that regression retrievals can produce accurate regional soundings at radiosonde sites in the lower troposphere through the proper selection of a training dataset of moderate sample size. Indeed, Fritz´ regression scheme (1977) forces perfect agreement at the training sites. The real test of VAS is then in the quality of the mesoscale retrievals interpolated between the radiosondes, in both space and time.

6. IMPACT ON MESOSCALE FIELD RETRIEVALS

The previous section provides a quantitative measure of the impact of ancillary surface data upon retrievals at selected radiosonde sites. The point comparisons do not assess the impact upon retrieved fields at the high horizontal and temporal resolution provided by VAS. This section compares mesoscale features which are evident within the retrieved fields generated from "VAS only" and "VAS plus SFC" regression matrices. The impact of the surface data upon the retrieved low-level temperature and moisture fields is evaluated by their space-time continuity. The effect of diurnal skin temperature fluctuations upon the retrievals of the lower troposphere is also investigated.

6.1 Analyzed Temperature and Dewpoint Fields

A mesoscale retrieval grid with one degree spacing in both latitude and longitude (14 by 9 points, about 85 to 110 km apart) is used to produce the temperature and dewpoint temperature fields. The area of the domain extends from 88° to 101°W and from 35° to 43°N. As was stated before, the SFOV at each grid point consists of 12 VAS radiances averaged over 5 instantaneous samples, corresponding to a horizontal radiometric resolution of roughly 20 km. The original grid contains 126 total points, but cloud cover reduces the number of locations selected for retrieval to between 83 and 98 sites. Temperature and dewpoint temperature retrievals are done at the five VAS observation times available on 13 July 1981. Both the "VAS only" and "VAS plus SFC" regression coefficient sets are used with the Continental and Regional training. The selective training of the Regional set, which eliminates some of the distinctly different coastal and fringe stations, provides more specific information for mesoscale retrievals over the study area across the Midwestern United States.

Contour plots of the retrieved fields at the lowest 6 tropospheric levels are generated by applying the Barnes′ objective analysis to produce a regularly spaced grid at one-half degree intervals (Barnes et al., 1973; Koch et al., 1983). The analysis domain is restricted to an area which is one degree within the boundaries of the original retrieval grid. An effective scale length equivalent to 1.0 degree in latitude or longitude is used for the interpolation. In order to provide a comparable field, the radiosonde data, scattered over a much greater area, are analyzed onto a similar one degree grid nested within the VAS fields.

To demonstrate the impact of ancillary surface data upon the space-time continuity of the VAS fields, we examine the spatial structures within the 920 mb dewpoint fields at 2300 GMT, and the temporal development of a five frame time sequence of the 920 mb moisture fields. The 920 mb dewpoint field is selected for this impact study because the ancillary surface data provide a significant contribution to the retrievals at this level. The dewpoint field also displays a high degree of variability on this occasion. The main objective of this exercise is to establish whether the ancillary surface data can help to distinguish between real atmospheric changes and radiometric uncertainties. The effects of the high skin temperature observed by window channels during peak heating are examined by comparing retrieved 920 mb temperature and dewpoint fields at 1800 GMT.

6.2 Comparisons of the Radiosonde and VAS Fields

Figure 8 shows contour charts of the 920 mb dewpoint field at 2300 GMT 13 July ("VAS only" and "VAS plus SFC" for both the Continental and Regional matrices) and 0000 GMT 14 July 1981 (radiosondes). The surface station dewpoint and temperature fields at 0000 GMT 14 July 1981 and the difference field between the "VAS only" and "VAS plus SFC" Regional analyses are also displayed. Inspection of the radiosonde analysis (Fig. 8-f) reveals a general dry-to-wet pattern (from 10° to 20° C) across the region of interest with a dry tongue projecting into northwest Missouri. The moisture gradient at 920 mb is concentrated over central Nebraska and Kansas. The increased resolution available with the dense network of surface data provides several mesoscale features in the boundary layer. The surface dewpoint analysis (Fig. 8-h) shows a region of very moist air (reports of over 24° C) from extreme southeast Minnesota to central Illinois. The surface temperature field (Fig. 8-g) depicts warm temperatures across most of the domain, except for the northeast corner and the south central section. The warmest air (greater than 36°C) is positioned over eastern Nebraska and central Kansas in the region of a large moisture gradient. Thus, in this case the surface dewpoint and surface temperature are not positively correlated as is generally found in climatological statistics. In summary, the conventional analysis of the 920 mb dewpoint radiosonde field only provides a coarse picture of the low-level moisture, while the surface dewpoint field indicates additional mesoscale features which will be reflected in the high-resolution retrievals produced with the VAS radiances.

The VAS 920 mb dewpoint retrieval fields (Figs. 8-a, -b, -c and -d) reproduce the general west-to-east dry-to-wet pattern present in the conventional observations. Mesoscale features which reflect the surface dewpoint analysis are readily identified in the two "VAS plus SFC" retrievals. For instance, an area of moist air (values over 20° C) from central Illinois into central Iowa is present in the "VAS plus SFC" cases and absent in the "VAS only" cases. This moist air at 920 mb appears displaced slightly to the south and west of the moist area depicted in the surface analysis. In addition, the moist air across the southern part of the area extends further west into Oklahoma than is indicated by a mere extrapolation of the surface data. This combination of radiance and surface data also produces a dry tongue which extends from Nebraska into central Missouri. Thus, the "VAS plus SFC" analysis not only reflects the impact of the surface dewpoint data but also reveals the effect of the radiance information.

Several differences occur between the VAS and radiosonde analyses, but these are maximized between the actual radiosonde locations, where they cannot be verified. These differences in the areas between the radiosondes are very important, because the entire character of the overall moisture field and of the gradients is altered. The two "VAS plus SFC" retrievals increase the moisture values across southern Iowa and northern Missouri. The axis of the dry tongue now extends from Nebraska into Missouri, as opposed to the radiosonde analysis which indicates a dry slot from Kansas into northwest Missouri. This disagreement is the result of wetter VAS retrievals near Topeka (16° C versus 19° C), where surface reports are 21° C.

However, the "VAS plus SFC" retrievals are in general agreement with the radiosondes at the radiosonde sites (within 2° C), except at the high elevation stations in the west (Dodge City, Kansas and North Platte, Nebraska). Large differences occur over the western portion of the domain, where surface elevation and warm surface (skin) temperatures in the VAS window channels present a problem (see next section). The differences are generally within 2° to 3° C for "VAS plus SFC", but are much larger for the two "VAS only" cases.

The effect of restricting the training set to a Regional instead of a Continental distribution of radiosonde sites is greatest for the "VAS only" retrievals (Figs. 8-a and -c). Both sets capture the dry tongue across Missouri and the large moisture maximum in Iowa. However, the Regional set is more sensitive in estimating the strength of the gradients and of the local maxima in central Illinois and eastern Kansas. These features are only hinted at by the Continental retrievals. The "VAS plus SFC" retrievals (Figs. 8-b and -d) also indicate a slightly greater sensitivity in the Regional retrievals, but the ancillary surface data appear to dominate the distinction between Regional and Continental training at this time.

A difference field derived from the two Regional VAS analyses is shown in Fig. 8-e. The differences reveal that the main impact of ancillary surface data upon the 920 mb dewpoint retrieval field is to make the eastern two-thirds of the domain wetter, the western portion drier and the entire field smoother (see Section 6.4 for an objective evaluation). These results follow to some extent from the structure of the surface dewpoint data in Fig. 8-h. The point-to-point variability of the "VAS only" cases and the more consistent retrievals of the "VAS plus SFC" cases can be seen in the individual data values displayed at the SFOVs in Fig. 8-a, -b, -c and -d, as well as in the contoured analyses. Note the low dewpoint values (less than 14 C) over northwestern Missouri in the "VAS only" retrievals, which could be due to unresolved clouds or anomalously high surface (skin) brightness temperatures in that area.

The previous observations are consistent with earlier studies (e.g., Chesters et al., 1982a) which have shown that passive remote sounders suffer from reduced resolution in the lower troposphere, especially for moisture. Thus, the "VAS only" retrievals are sensitive to unwanted radiometric influences, which underestimate maxima, minima and gradients of the dewpoint temperature, and which overestimate extremes in the temperature field in areas of high skin temperature.

6.3 Effects of High Skin Temperatures

The influence of high skin temperatures is investigated with Figs. 9 and 10. Figure 9 is a time series of the diurnal variations of the surface temperature and dewpoint and the VAS window channels (7, 8 and 12). These values are generated from an average across a cloud-free 18 SFOV swath through Nebraska (at 41.5°N). The most striking feature of this plot is the prominant diurnal fluctuation of the sensitive window channels 8 and 12, with a smaller change in channel 7. The plot shows that two-thirds of the diurnal variation is captured by the endpoint measurements at 1200 and 2300 GMT for all low-level predictors. As expected, the highest skin temperatures occur near local noon. However, the surface station temperature significantly lags the skin temperature by approximately 3 hours. Consequently, the possibility of encountering a major discrepancy with the VAS retrievals should occur at 1800 GMT.

Figure 10 displays six different VAS retrieval fields of 920 mb dewpoint at 1800 GMT (Figs. 10-a, -b and -e from the Continental matrices; Figs. 10-c, -d and -f from the Regional matrices). The large differences between "VAS only" (Figs. 10-a and -c) and "VAS plus SFC" (Figs. 10-b and -d) retrievals are again evident. Moist air (above 20°C) is present over Iowa, Illinois, southern Missouri and Arkansas for "VAS plus SFC". The Regional field (Fig. 10-d) is generally one degree drier than the Continental case (Fig. 10-b). The two "VAS only" cases (Figs. 10-a and -c) are much drier across Iowa, Illinois and Missouri, while western Kansas is wetter. This pattern does not agree with the surface station field or with the 920 mb dewpoint time series (Fig. 12). Also, very large point-to-point fluctuations are encountered across Iowa and Missouri, which indicate that the "VAS only" matrices are much too sensitive to small variations in the radiances.

To isolate the possible effects of high skin temperatures, the short-wave window channel 12 (3.9 μm) is eliminated from the regression retrieval calculations. This channel is most sensitive to skin temperature variations (Fig. 9), and is sometimes significantly contaminated by reflected sunlight. The major consequence of removing channel 12 is a slightly drier field for both "VAS plus SFC" cases (Fig. 10-e resembles 10-b, and Fig. 10-f resembles 10-d). The Regional field without channel

12 (Fig. 10-f) is quite dry (12°C or less) across western Kansas and southwest Nebraska, which is in close agreement with the surface reports. There are also fewer dewpoint retrievals of 20°C across the moist areas.

The corresponding temperature panels (Fig. 11) reveal a similar situation. The "VAS only" fields (Figs. 11-a and -c) are too warm across Kansas and Nebraska. The two "VAS plus SFC" cases (Figs. 11-b and -d) are similar with slightly warmer retrievals and a steeper gradient over Kansas and Nebraska from the Regional matrix. The removal of channel 12 (Figs. 11-e and -f) only produces minor variations, with an area-wide cooling by 1° C in both the Regional and Continental retrievals.

In summary, the high skin temperatures at 1800 GMT seriously degrade the "VAS only" retrievals, but only cause a marginal over-all bias in the "VAS plus SFC" fields.

6.4 Time Sequence of VAS-Retrieved Fields

The five observations of all 12 VAS infrared channels during the twelve hour period on 13 July 1981 are retrieved with the 13 July Regional Day training to produce contour charts of the "VAS only" and "VAS plus SFC" 920 mb dewpoint fields (Fig. 12). The "VAS plus SFC" retrievals provide a smoother, more consistent pattern at mesoscale resolution which undergoes a more gradual evolution from one time period to another. The general west-to-east dry-to-wet pattern remains throughout the period while a dry tongue develops across Missouri. This dry slot divides two areas of moist air over Iowa and northeastern Oklahoma. Another interesting feature is the evolution of the moist area over southern Iowa. This moist air mass was associated with the rapid development of isolated thunderstorms after 2100 GMT.

The spatial and temporal continuity of the dewpoint fields in Fig. 12 produced by the "VAS plus SFC" analysis is nearly absent from the "VAS only" case. Although some general features in the "VAS only" fields are still recognizable, large and apparently random variations occur from one observation period to another. The absolute magnitude of the fields is underestimated in the wet areas and overestimated in the dry regions, apparently due to the poor low-level vertical resolution of the "VAS only" retrievals. Thus, the temporal impact of the ancillary surface data upon VAS retrievals is to stabilize the magnitude and position of the low-level mesoscale features.

Statistical analyses (Table 7) were done on the objectively analyzed grids produced from the 920 mb dewpoint fields (Fig. 12). The mean dewpoints are 1° to 2°C wetter for the "VAS plus SFC" fields. The standard deviation is approximately the same for the two cases at 1200 and 1500 GMT. However, during the next three times, the standard deviations of the "VAS plus SFC" fields are 0.3° to 0.6°C higher. This larger standard deviation results from the wetter values resolved by the "VAS plus SFC" retrievals across Iowa and Illinois. The standard deviation in the gradient combines both the longitudinal and latitudinal fluctuations about the mean gradient, and is significantly smaller for all the "VAS plus SFC" cases. These statistics reveal that the "VAS plus SFC" retrievals resolve more of the mesoscale variability in the field, while smoothing the point-to-point values to provide better gradients than those of the "VAS only" case. We can define a rms length scale as a measure of the average distance with which the features (patterns) change in the field. This scale is defined by the ratio of the standard deviation in the field to the standard deviation in the gradient. The "VAS plus SFC" rms scale lengths in Table 7 range from 140 to 200 km, while the "VAS only" scale lengths range from 100 to 130 km. The difference in the rms scale lengths indicates the greater smoothness and cohesiveness of the "VAS plus SFC" retrieval fields.

To measure the temporal stability of the fields, the covariances between adjacent frames are shown in Table 7. The "VAS plus SFC" covariances are larger than the "VAS only" (1.5 to 2.4 times higher), with the largest differences occuring later in the day. The temporal continuity of the fields is given by the frame-to-frame correlations. Again, the "VAS plus SFC" fields display a much higher correlation (from 87 to 94%) than the "VAS only" values (from 68 to 81%). Thus, the "VAS plus SFC" fields not only show a higher degree of spatial cohesiveness in the retrieved 920 mb dewpoint but also a much higher temporal correlation.

The "VAS plus SFC" retrievals utilize several sources of information (radiosondes, VAS radiances, surface temperature and dewpoint) to produce fields of dewpoint and temperature at mesoscale resolution and with short time intervals. No ground observation network is available to provide independent data necessary for verification. An independent study using the VAS "split window" technique indicates similar moisture patterns over the same area on this date (Chesters et al., 1982b). Radar summaries (not shown) also reveal a region of rapid convective development across southern Iowa after 2100 GM 13 July 1981. A meteorological case study (in preparation) of the "VAS plus SFC" fields on 13 July 1981 will provide a thorough analysis of the physical validity of the mesoscale features found in these retrievals. Preliminary meteorological case studies of the pre-convective environments on 13 and 20 July 1981, using VAS and ancillary surface data, have already been conducted (Petersen et al., 1982, 1983).

7. Summary and Discussion

The VAS instrument on board the GOES satellites provides the capability of observing subsynoptic and mesoscale phenomena. VAS soundings, with the capacity for frequent observations and high horizontal resolution, have been demonstrated in earlier studies with both simulated and real data. However, passive infrared soundings lack fine vertical resolution and accuracy in the lower layers of the atmosphere. In this retrieval study, conventional surface temperature and dewpoint data at or near the VAS sounding times and areas are incorporated as additional predictors in a conditioned linear regression algorithm to retrieve meteorological parameters in the lower troposphere. The retrievals are evaluated by using a main database of 81 selected coincident radiosonde/VAS/surface samples on 13 July 1981 and a supplementary database of 52 samples on 20 July 1981.

The point-by-point test results show that ancillary surface data dominate satellite infrared data for the prediction of temperature and dewpoint in the boundary layer, as one would anticipate. The impact is also significant at the lowest levels above the boundary, but the effect of conventional surface information decreases upward and becomes insignificant above 700 mb. The absolute moisture retrieval accuracies of "VAS plus SFC" soundings found in this case study are around ± 2° C in dewpoint at all levels below 850 mb. The absolute temperature accuracies are within ± 1.5° C between 500 and 700 mb, about ± 2°C from 850 to 920 mb and ± 1.5°C in the boundary layer. The statistics reveal that the improvements compared with the "VAS only" soundings are at least 1° C in both temperature and dewpoint at the boundary layer. The impact is about 0.5°C for moisture profiles between 850 and 920 mb, but is noticeably smaller for temperature profiles. The inclusion of surface data does not show any adverse effect on VAS regression retrievals above the 700 mb level. Directly retrieved bulk parameters which depend upon the lower tropospheric moisture content, such as equivalent potential temperature and total precipitable water, are likewise improved by the addition of surface data to the VAS radiances.

The "VAS plus SFC" regression technique works better than the "VAS only" below 850 mb, in terms of the fraction of total variance of the meteorological parameters recovered by the retrieval process. For retrievals below 850 mb the recovery rates of "VAS plus SFC" are found to be 0.6 to 0.9, which makes fractional improvements over "VAS only" about 0.1 in temperature and generally between 0.1 and 0.3 in dewpoint. The evaluation of retrieved parameters at higher altitudes are much less reliable, because of the small variances in the actual temperature data for this study, as well as the uncertainties involved in radiosonde humidity reports.

In order to exploit the VAS instrument as a space-time interpolator using a purely statistical retrieval method, all available coincident cloud-free sites were used to stabilize the construction of the regression coefficients. While this procedure sacrifices the ability to independently measure the total absolute retrieval errors, the rms residuals of the goodness-of-fit associated with "VAS only" and "VAS plus SFC" retrievals still measure the relative improvements made with the use of surface data. However, we found that proper selection of appropriate, high-quality coincident data for training was more beneficial than the indiscriminate use of a larger dataset. For the 13 July case of regional mesoscale retrievals, some sample impacts from surface data upon retrievals at 920 mb are 0.15° C in temperature, 0.65° C in dewpoint, or 1.1° C in equivalent potential temperature, and 0.1 g/cm2 for total precipitable water. These apparently small differences are nevertheless quite significant when compared with the retrieval residuals.

The space-time continuity and consistency of temperature and dewpoint patterns on constant pressure surfaces are significantly improved by inclusion of the surface data, and many self-consistent mesoscale features are resolved. The twice-a-day (dawn and dusk) training is able to extrapolate retrievals fairly well into the peak heating period. The problem of over-sensitivity to the skin temperatures observed by the short-wave window channel appears to be small, due to its reduced role in the presence of better correlated predictors such as the surface data and the other less skin-sensitive window channels. However, quantitative assessment of diurnal variation in retrievals cannot be made without ground truth data around local noontime. The quality of the regression retrievals is improved by broadening the database until significantly different training sites are included. There is no "universal" regression coefficient set, and different matrices must be created specifically for each kind of space-time interpolation. Finding enough good quality ground truth data to establish a statistically significant correlation is always a major constraint in applying the regression method to satellite mesoscale retrievals. Quality control on the database, particularly the coincident dataset, is very important for eliminating large individual errors from the small database available for mesoscale training.

The results of this study offer a benchmark for VAS sounding using a minimum-information linear regression retrieval technique. The main sources of error in this purely statistical approach to mesoscale satellite sounding come from the scarcity of upper-air data in space and time, from observation and interpolation error in radiosonde and surface reports, from VAS instrument noise and calibration errors, and from cloud contamination in the observed radiances. Of course, the errors in representing radiation transfer by a linear regression process are not negligible when applied to different air masses within the same scene. While improved VAS soundings from simple regression retrievals using ancillary surface data as input generally satisfy the requirements for mesoscale studies in the lower troposphere, a physically-modelled retrieval scheme should be more suitable for some special situations, such as for areas of high elevation or with an unusual surface, or for weather conditions with large temperature and moisture gradients, especially in the middle and upper troposphere.

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Captions

Table 1 Characteristics and specifications for the VAS sounding channels.

Table 2 Raw database of VAS radiances, conventional surface data, and radiosonde observations.

Table 3 Attributes and sample sizes of the selected coincident data subsets.

Table 4 Retrieval accuracies of the low-level temperature and dewpoint profiles from independent testing on 13 July 1981 Continental dataset. Results of "VAS only", "VAS plus SFC", and "SFC only" cases are presented to demonstrate the relative impact of each input.

Table 5 Retrieval accuracies of low-level temperature and dewpoint from two independent mid-summer days.

Table 6 RMS residuals of goodness-of-fit for temperature and dewpoint regression. Both Continental and Regional datasets of 13 July 1981 are used.

Table 7 Statistics demonstrating the relative spatial and temporal continuity of the retrieved 920 mb dewpoint fields in Fig. 12.

Fig. 1 Radiance weighting functions of the VAS infrared channels for the U. S. Standard Atmosphere. (a) CO_2 band for temperature, (b) H_2O band for moisture and windows for surface soundings. Dashed lines are for the short wave bands, which are potentially affected by reflected sunlight.

Fig. 2 Surface weather maps for the central United States at (a) 1200 GMT 13 July and (b) 0000 GMT 14 July 1981. Temperature (solid line) and dewpoint (dashed) are contoured at every interval of 5°C. Very moist areas are shaded for emphasis.

Fig. 3 VAS image of the central and eastern United States from channel 12 (3.9 μm) at 2300 GMT 13 July 1981. The 40 selected radiosonde stations are identified, of which 12 independent test sites are marked with white squares. Unlabeled plus signs locate where the surface reports are available at this time.

Fig. 4 Average contributions to temperature retrievals by major predictors, derived from 13 July Continental Day regression coefficients for (a) "VAS only" and (b) "VAS plus SFC" cases. The curves are labeled by the VAS channel numbers or ancillary data type.

Fig. 5 Same as Fig. 4 except for low-level dewpoint retrievals.

Fig. 6 Total rms retrieval errors for low-level temperature and dewpoint profiles evaluated at 25 independent radiosonde sites on 13 July 1981. Standard deviations of the original testing data are also shown.

Fig. 7 RMS statistics of regression residuals of some selected meteorological parameters using the 13 July Regional dataset with or without surface data.

Fig. 8 The analyzed 920 mb dewpoint fields at 2300 GMT 13 July or 0000 GMT 14 July 1981 for (a) "VAS only" Continental, (b) "VAS plus SFC" Continental, (c) "VAS only" Regional, (d) "VAS plus SFC" Regional, and (e) the difference between the two VAS Regional retrievals. The corresponding (f) radiosonde, (g) surface dewpoint and (h) surface temperature fields are included to show their impact upon the "VAS plus SFC" retrievals.

Fig. 9 Diurnal behavior of the VAS window channels 7, 8 and 12 and of the ancillary surface temperature (T_s) and dewpoint (D_s) in a cloud-free strip across Nebraska on 13 July 1981.

Fig. 10 Retrieved 920 mb dewpoint fields in the Midwest at 1800 GMT on 13 July 1981, using variously trained regression matrices: (a) "VAS only" Continental, (b) "VAS plus SFC" Continental, (c) "VAS only" Regional, (d) "VAS plus SFC" Regional, (e) "VAS plus SFC" Continental without channel 12, and (f) "VAS plus SFC" Regional without channel 12.

Fig. 11 Retrieved 920 mb temperature fields for the same conditions as Fig. 10.

Fig. 12 Time sequence of retrieved 920 mb dewpoint fields from the regional coefficients of "VAS only" and "VAS plus SFC" at 1200, 1500, 1800, 2100, and 2300 GMT 13 July 1981.

Table 1

VAS Channel Num	Filter Center (μm)	Effective Wave Number (cm^{-1})	Peak Weight level (mb)	Purpose for Sounding	Single Sample Noise (±K)	Required SFOV Accuracy (±K)
1	14.7	679.8	70	temp	5.3	0.3
2	14.5	690.2	125	temp	2.2	0.3
3	14.3	700.2	200	temp	1.8	0.3
4*	14.0	714.5	500	temp	1.2	0.2
5*	13.3	750.3	920	temp	1.0	0.2
6	4.5	2208.1	850	temp+cloud	1.6	0.1
7*	12.7	789.2	1000	moisture	1.0	0.2
8*	11.2	897.4	surf	surface	0.1	0.2
9*	7.3	1374.9	600	moisture	3.4	0.4
10*	6.8	1486.1	400	moisture	1.6	0.5
11	4.4	2252.6	300	temp+cloud	6.7	0.3
12	3.9	2541.1	surf	surface	0.8	0.1

*Available at 7 km (nadir view) resolution, otherwise 15 km.

Table 2

Date(July 1981)	13												14	20		21
Time(GMT)	12*	13	14	15*	16	17	18*	19	20	21*	22	23*	00	12*	23*	00
VAS	US	-	-	US	-	-	US	-	-	US	-	US	-	US	NC	-
SFC	565	-	-	546	-	577	-	-	-	574	-	-	562	564	556	-
RAOB	63	-	-	-	-	-	-	-	-	-	-	-	59	50	-	47

Times marked with an (*) are the nominal event labels. US denotes VAS dwell-sounding data covering the United States east of the Rockies, while NC indicates a smaller coverage of the most northern and central Unites States. The number of SFC and RAOB reports are available within the 20°-55° N and 70°-110° W area.

Table 3

Date	Area	Subgroup	Dawn 1200 GMT	Dusk 2300 GMT	Day
13 July	Continental		41	40	81
		Training	28	28	56
		Testing	13	12	25
13 July	Regional		26	25	51
20 July	Regional		26	26	52

Table 4

Press	Ground Truth				Retrieval Accuracy and Recovery Rate								
Level	Train(N=56)		Test(N=25)		VAS Only			VAS+SFC			SFC Only		
(mb)	mean	stdv	mean	stdv	bias	stdv	r	bias	stdv	r	bias	stdv	r
	Temperature(K)												
1000	300.1	± 5.1	300.3	± 5.1	.2	± 2.5	.8	-.0	± 1.6	.9	-.1	± 1.5	.9
920	297.2	3.7	297.4	3.6	.1	2.0	.7	.0	1.9	.7	-.2	2.0	.7
850	292.8	3.0	292.8	3.1	.3	2.2	.5	.3	1.9	.6	.0	2.4	.4
700	282.9	1.7	282.8	1.9	.3	1.4	.5	.3	1.4	.5	.1	1.7	.2
600	275.5	1.6	276.0	1.2	-.0	1.3	-.2	-.0	1.4	-.4	-.4	1.3	-.2
500	266.9	1.8	267.6	1.4	-.4	1.2	.3	-.3	1.3	.1	-.6	1.3	.1
	Dewpoint (K)												
1000	293.5	± 4.0	293.1	± 3.9	.3	± 3.0	.4	.5	± 1.9	.8	.5	± 1.8	.8
920	290.3	3.4	290.0	2.7	.1	2.3	.3	.1	2.0	.5	.4	1.9	.5
850	286.5	3.1	286.7	2.4	-.7	2.1	.2	-.7	2.1	.2	-.2	2.1	.2
700	272.5	8.0	271.6	7.6	.4	6.4	.3	.4	7.1	.1	1.1	8.6	-.3

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Table 5

Press Level (mb)	13 July Regional Data (N=51)		13 July Retrieval Errors Using 20 July Matrices									20 July Regional Data (N=52)	
			VAS Only			VAS + SFC			SFC Only				
	mean	stdv	bias	stdv	r	bias	stdv	r	bias	stdv	r	mean	stdv
Temperature (K)													
1000	300.2 ±	5.6	-.0 ±	2.6	.8	-.4 ±	1.4	.9	-.5 ±	1.2	1.0	300.9 ±	6.2
920	297.8	4.0	.4	1.7	.8	.5	1.9	.8	-.2	1.9	.8	298.7	5.2
850	293.2	3.4	.7	2.3	.5	.6	2.2	.6	.3	2.6	.4	294.3	4.3
700	283.1	1.8	.5	1.8	.0	.5	1.9	-.1	.3	1.6	.2	283.6	3.1
600	276.0	1.4	-.7	1.4	.0	-.7	1.4	.0	-.8	1.3	.1	275.3	2.5
500	267.5	1.5	-1.4	1.3	.2	-1.4	1.3	.2	-1.4	1.4	.1	266.0	2.6
Dewpoint (K)													
1000	292.6 ±	4.2	-1.0 ±	3.5	.3	-.3 ±	1.6	.9	-.1 ±	1.6	.9	291.7 ±	5.2
920	289.9	3.6	-.6	2.9	.4	-.3	1.9	.7	.1	1.9	.7	289.3	4.2
850	286.5	3.1	-1.7	2.6	.3	-1.5	2.1	.5	-.7	2.2	.5	285.3	3.9
700	271.0	9.4	-1.0	9.4	.0	-.6	9.8	-.1	-1.1	9.2	-.0	270.1	7.2

Table 6

Press	13 July Continental Day Set								13 July Regional Day Set							
Level	Ground truth		Goodness of Fit						Goodness of Fit						Ground truth	
(mb)	(N=81)		VAS		VAS+SFC		SFC		VAS		VAS+SFC		SFC		(N=51)	
	mean	stdv	rms	r	rms	r	rms	r	rms	r	rms	r	rms	r	mean	stdv
	Temperature (K)															
1000	300.1 ±	5.1	2.3	.8	1.3	.9	1.3	.9	1.9	.9	1.1	1.0	1.2	1.0	300.2 ±	5.6
920	297.2	3.7	1.8	.8	1.6	.8	1.9	.7	1.4	.9	1.3	.9	1.8	.8	297.8	4.0
850	292.8	3.0	2.0	.6	1.8	.6	2.3	.4	1.9	.7	1.7	.8	2.5	.5	293.2	3.4
700	282.8	1.7	1.3	.4	1.3	.4	1.6	.1	1.2	.6	1.1	.6	1.6	.2	283.1	1.8
600	275.7	1.5	1.1	.5	1.1	.5	1.3	.3	1.0	.5	.9	.6	1.1	.4	276.0	1.4
500	267.1	1.7	1.2	.5	1.2	.5	1.4	.3	1.1	.5	1.0	.6	1.2	.4	267.5	1.5
	Dewpoint (K)															
1000	293.4 ±	4.0	2.9	.5	1.7	.8	1.9	.8	2.6	.6	1.2	.9	1.4	.9	292.8 ±	4.2
920	290.2	3.2	2.4	.4	1.7	.7	1.8	.7	2.2	.6	1.6	.8	1.9	.7	289.9	3.6
850	286.5	2.9	2.3	.4	2.0	.5	2.3	.4	2.0	.6	1.6	.7	2.1	.5	286.5	3.1
700	272.2	7.9	5.8	.5	5.7	.5	7.7	.0	5.5	.7	5.3	.7	8.7	.1	271.0	9.4

Table 7

Time GMT	Case	Spatial Smoothness: Average Dewpoint (°C)	Spatial Smoothness: Std Dev Dewpoint (±°C)	Spatial Smoothness: Std Dev Gradient (±°C/km)	Spatial Smoothness: RMS Scale Length (km)	Temporal Continuity: Case	Temporal Continuity: Covar (°C²)	Temporal Continuity: Corr (%)
1200	VAS	16.0	1.76	0.018	99.4			
	VAS+SFC	17.6	1.83	0.010	182.7	VAS	2.7	76
1500	VAS	15.4	2.02	0.016	122.6	VAS+SFC	3.2	87
	VAS+SFC	17.8	2.04	0.011	181.4	VAS	3.3	77
1800	VAS	16.2	2.13	0.016	134.5	VAS+SFC	4.6	92
	VAS+SFC	18.1	2.45	0.012	200.0	VAS	2.7	68
2100	VAS	16.3	1.85	0.018	104.3	VAS+SFC	5.1	91
	VAS+SFC	17.8	2.29	0.014	163.0	VAS	3.0	81
2300	VAS	16.8	1.99	0.019	103.1	VAS+SFC	5.3	94
	VAS+SFC	17.7	2.44	0.017	142.5			

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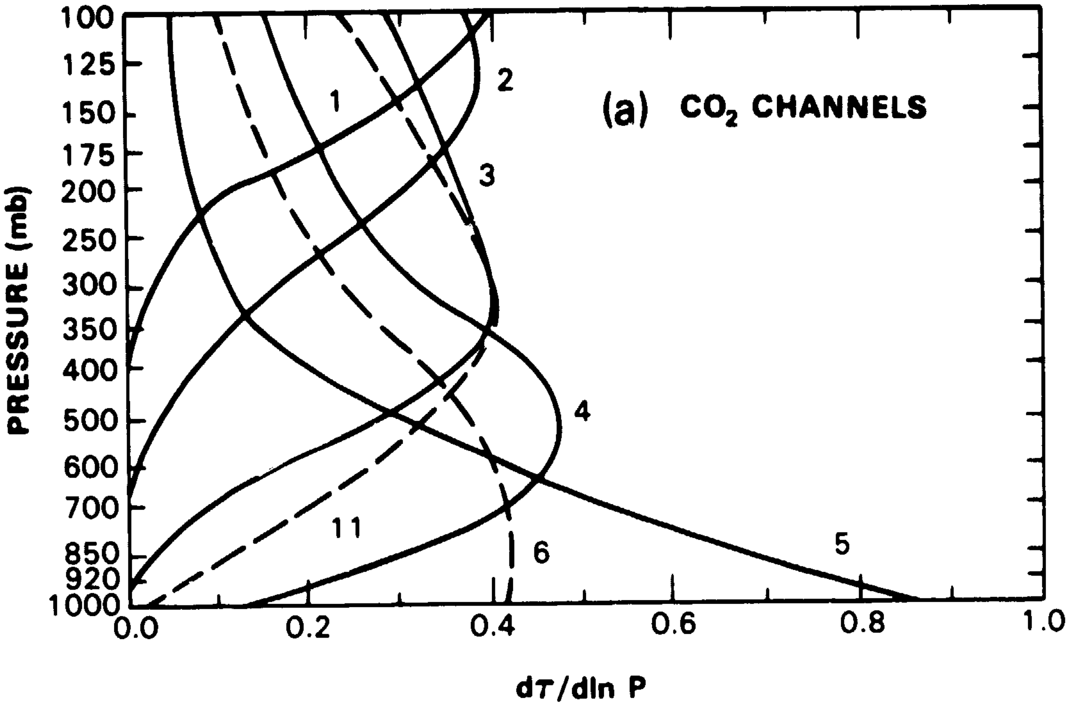

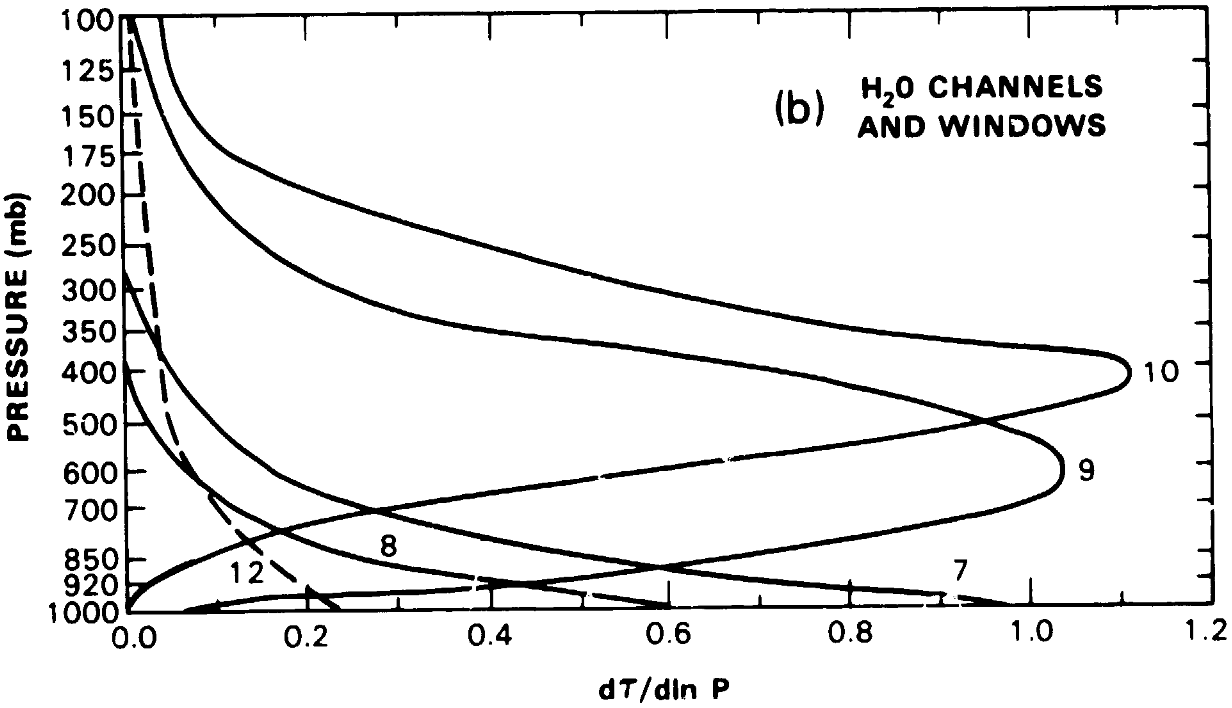

Figure 1

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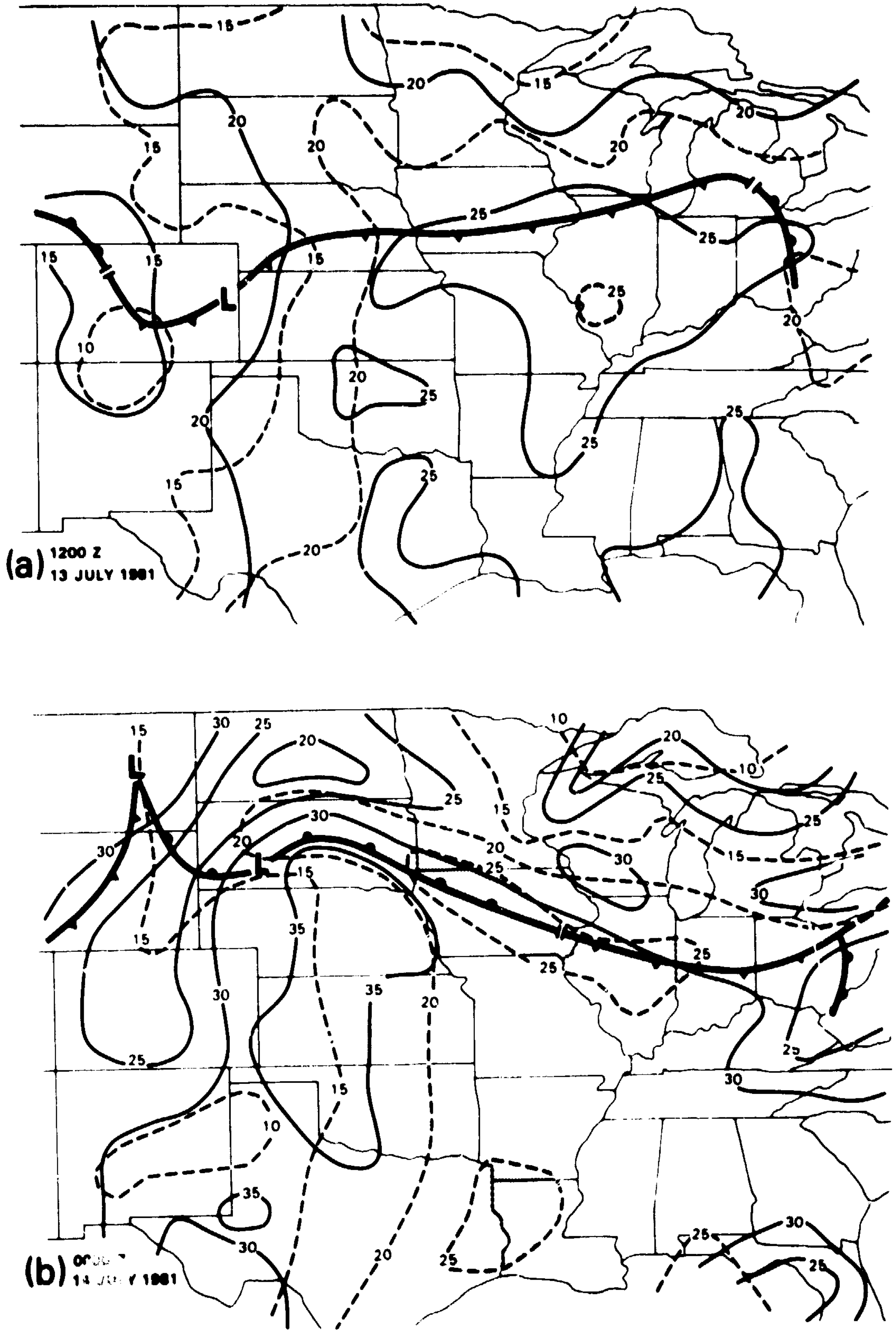

Figure 2

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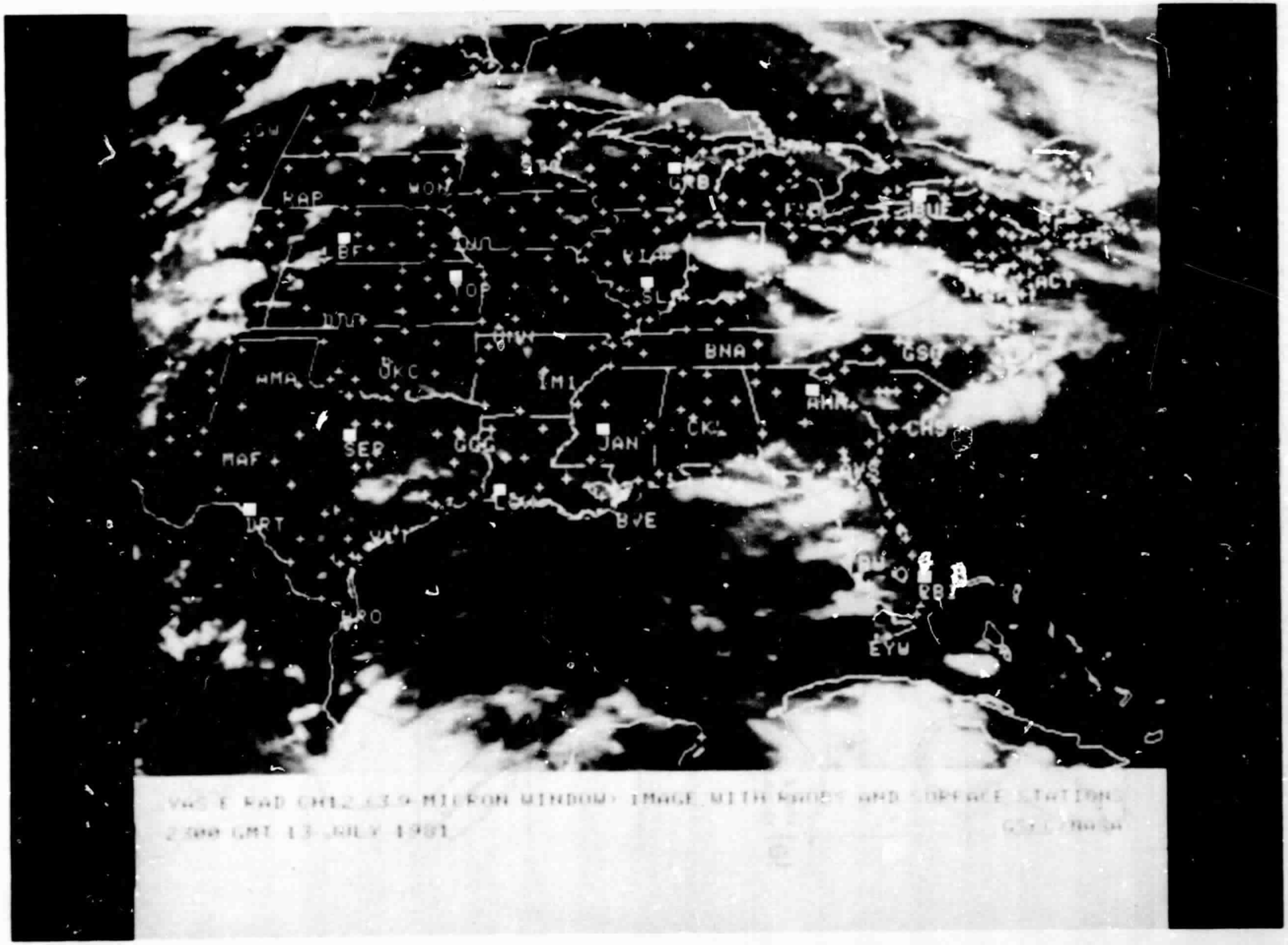
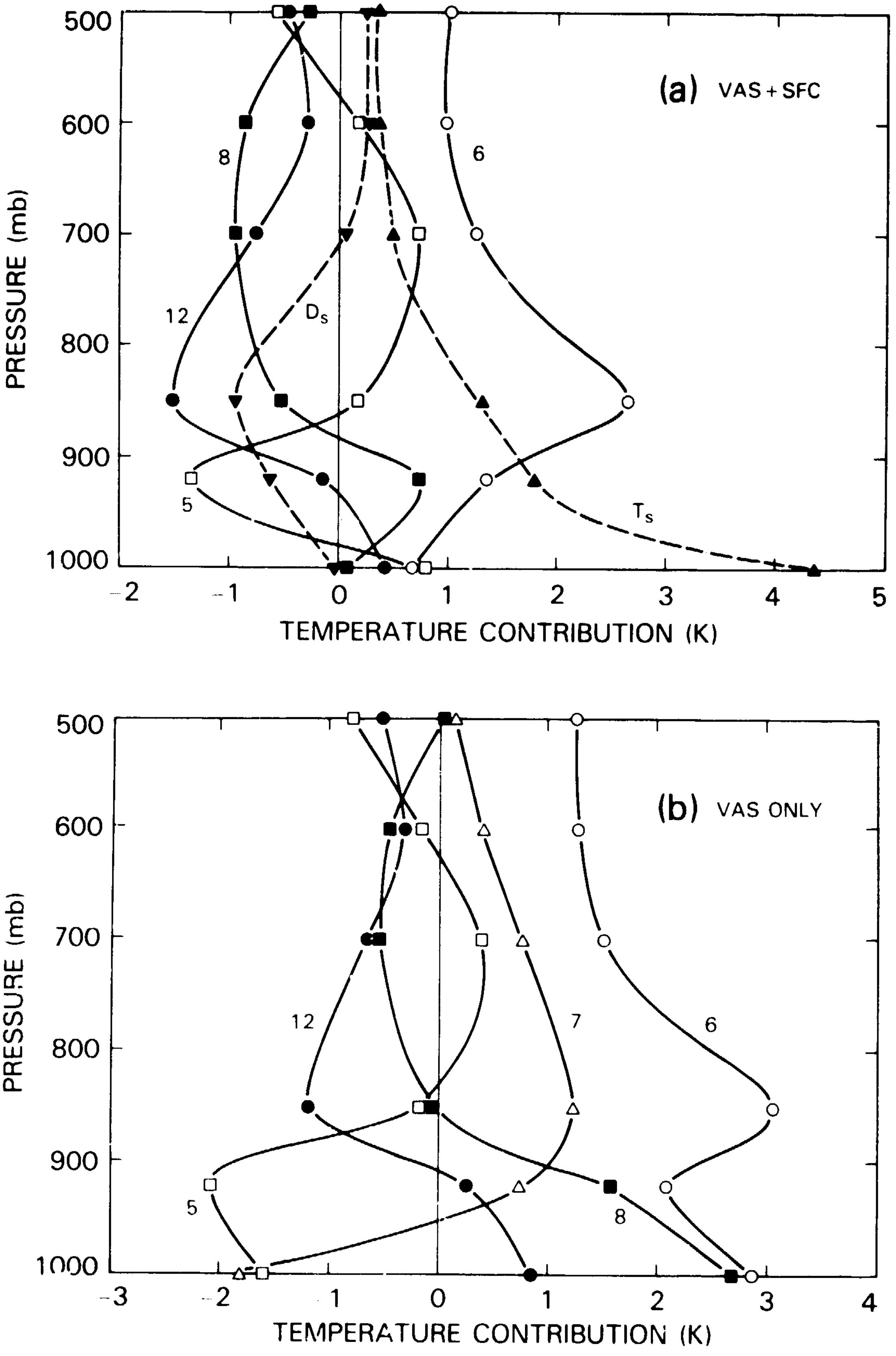


Figure 3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PRESSURE (mb)
500
600
700
800
900
1000
−2
−1
0
1
2
3
4
5
TEMPERATURE CONTRIBUTION (K)
8
6
12
D_s
5
T_s
(b) VAS ONLY
PRESSURE (mb)
500
600
700
800
900
1000
−3
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1
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4
TEMPERATURE CONTRIBUTION (K)
12
7
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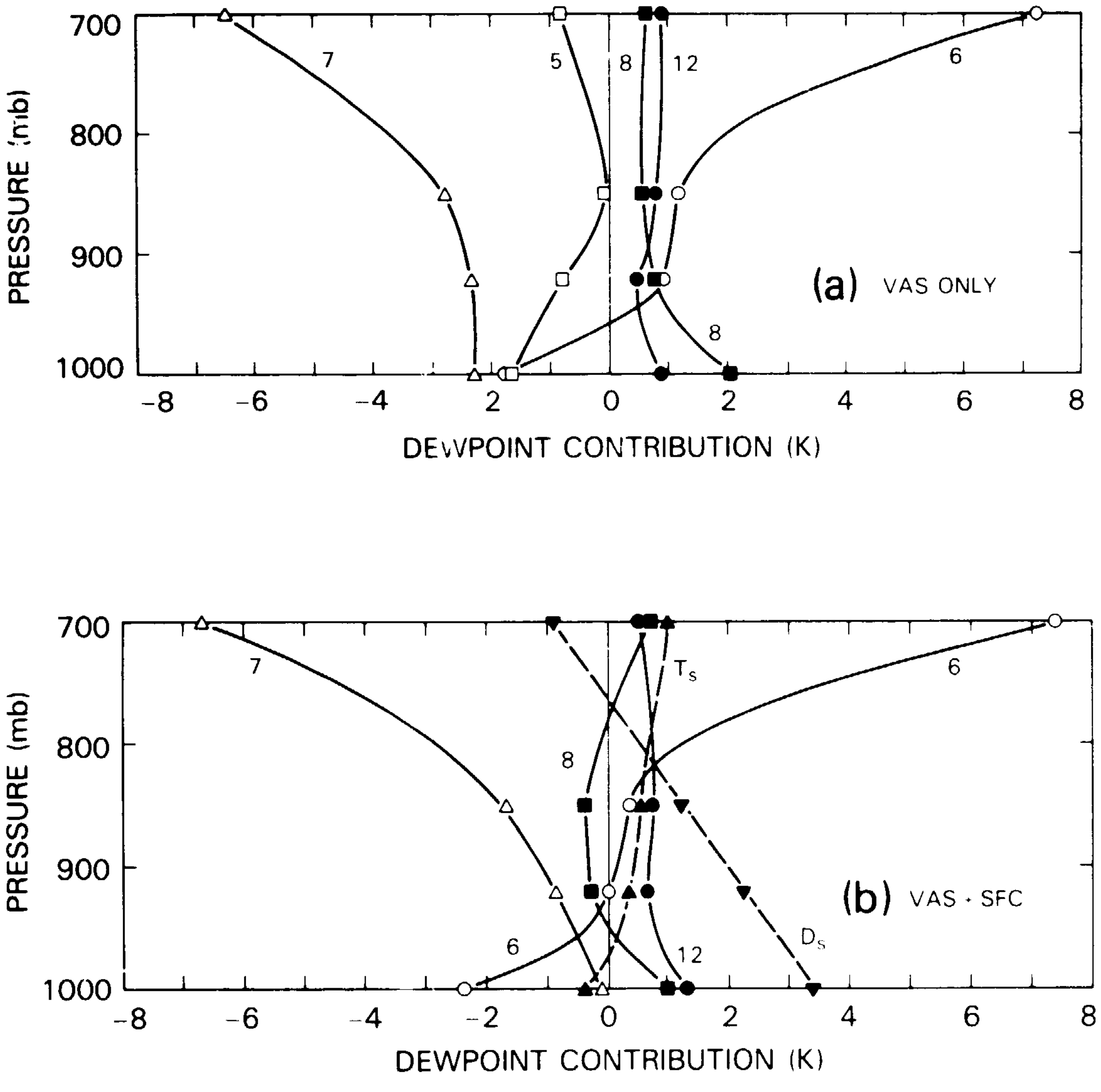
8

Figure 4


PRESSURE (mb)
700
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(a) VAS ONLY
-8
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DEWPOINT CONTRIBUTION (K)
PRESSURE (mb)
700
800
900
1000
7
T_s
6
8
6
12
D_s
(b) VAS + SFC
-8
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DEWPOINT CONTRIBUTION (K)

Figure 5

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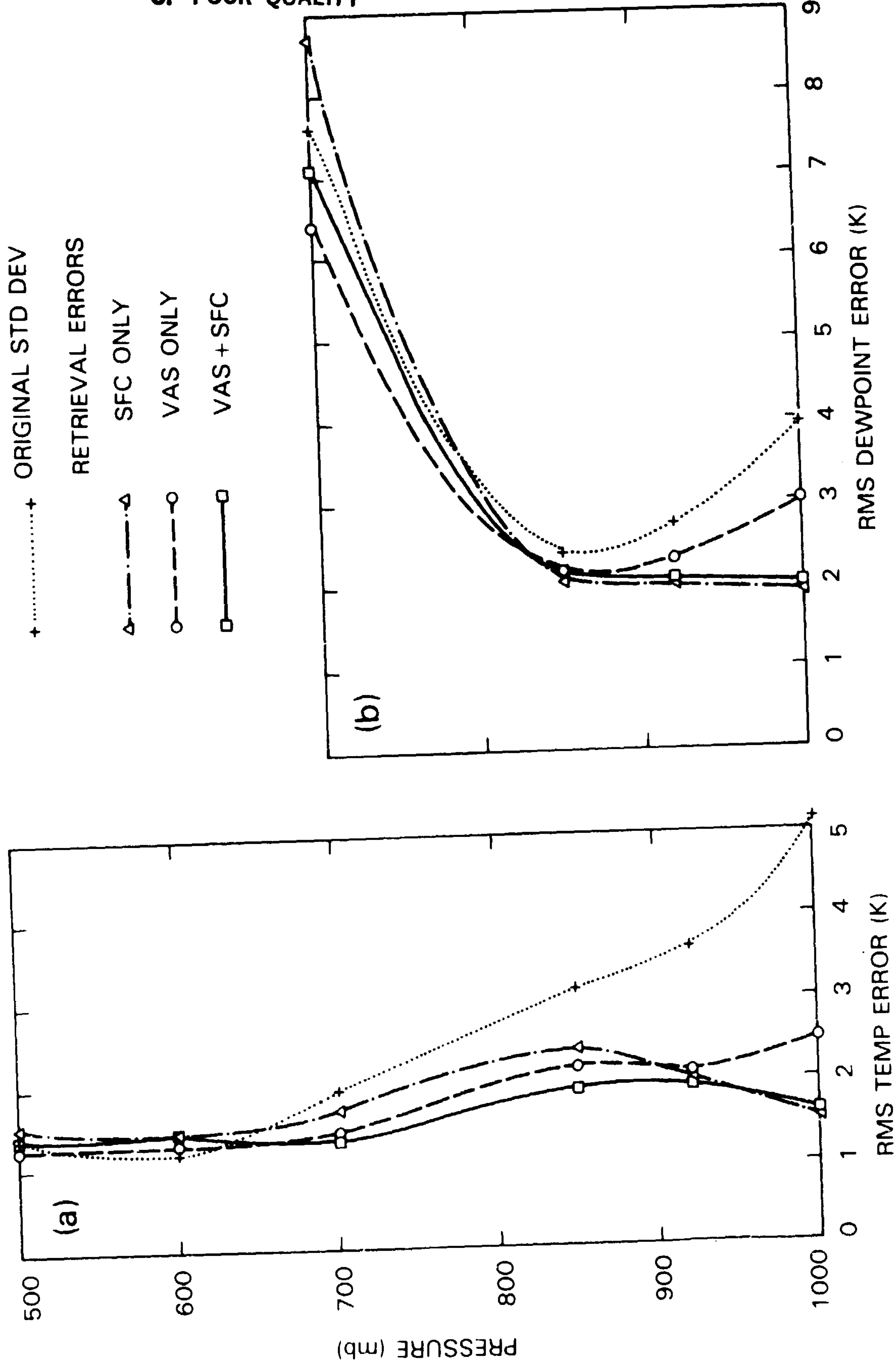
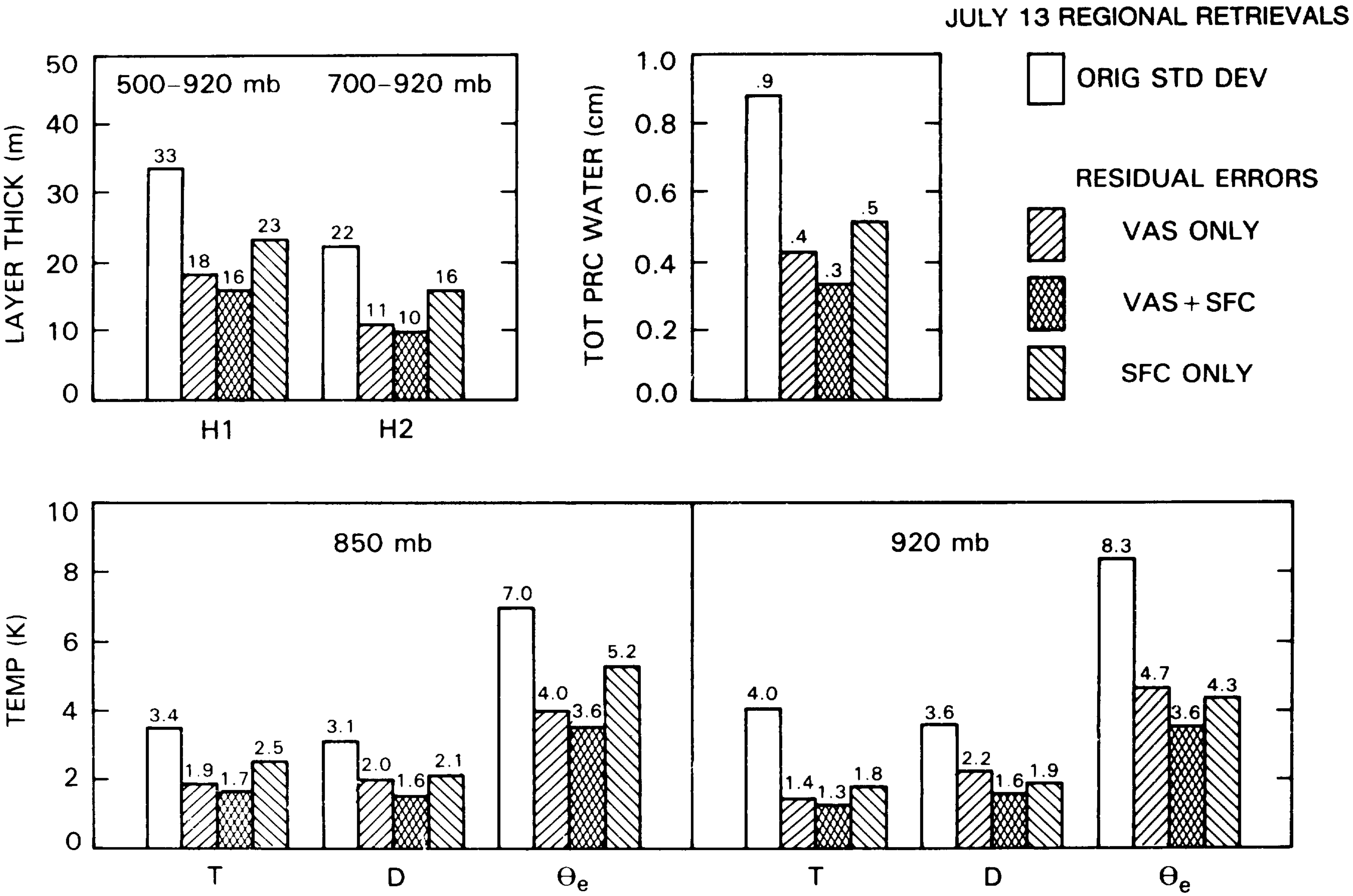


Figure 6


JULY 13 REGIONAL RETRIEVALS
ORIG STD DEV
RESIDUAL ERRORS
VAS ONLY
VAS + SFC
SFC ONLY
LAYER THICK (m)
50
40
30
20
10
0
500–920 mb
700–920 mb
33
18
16
23
22
11
10
16
H1
H2
TOT PRC WATER (cm)
1.0
0.8
0.6
0.4
0.2
0.0
.9
.4
.3
.5
TEMP (K)
10
8
6
4
2
0
850 mb
920 mb
3.4
1.9
1.7
2.5
3.1
2.0
1.6
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7.0
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Figure 7

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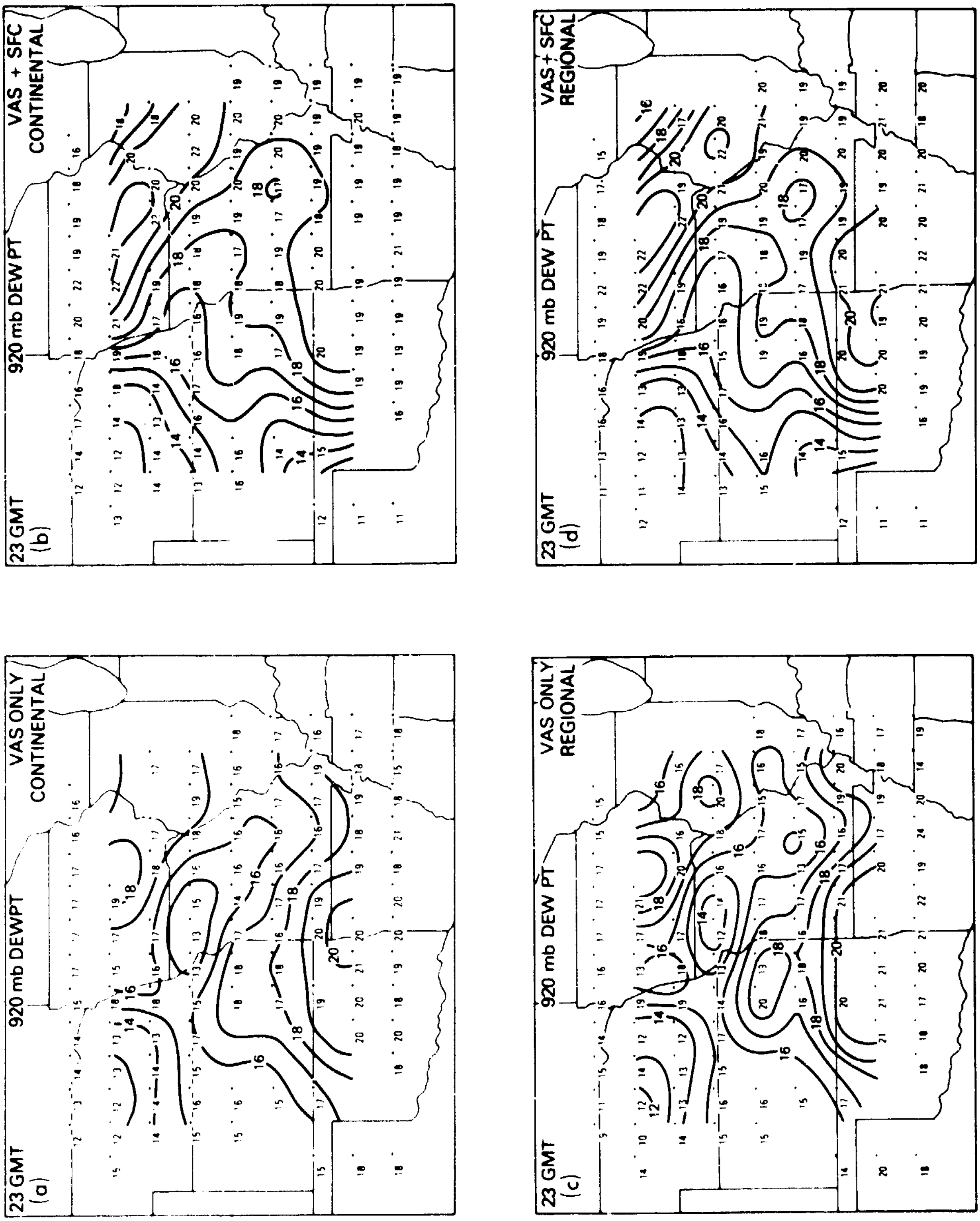


Figure 8 (part 1 of 2)

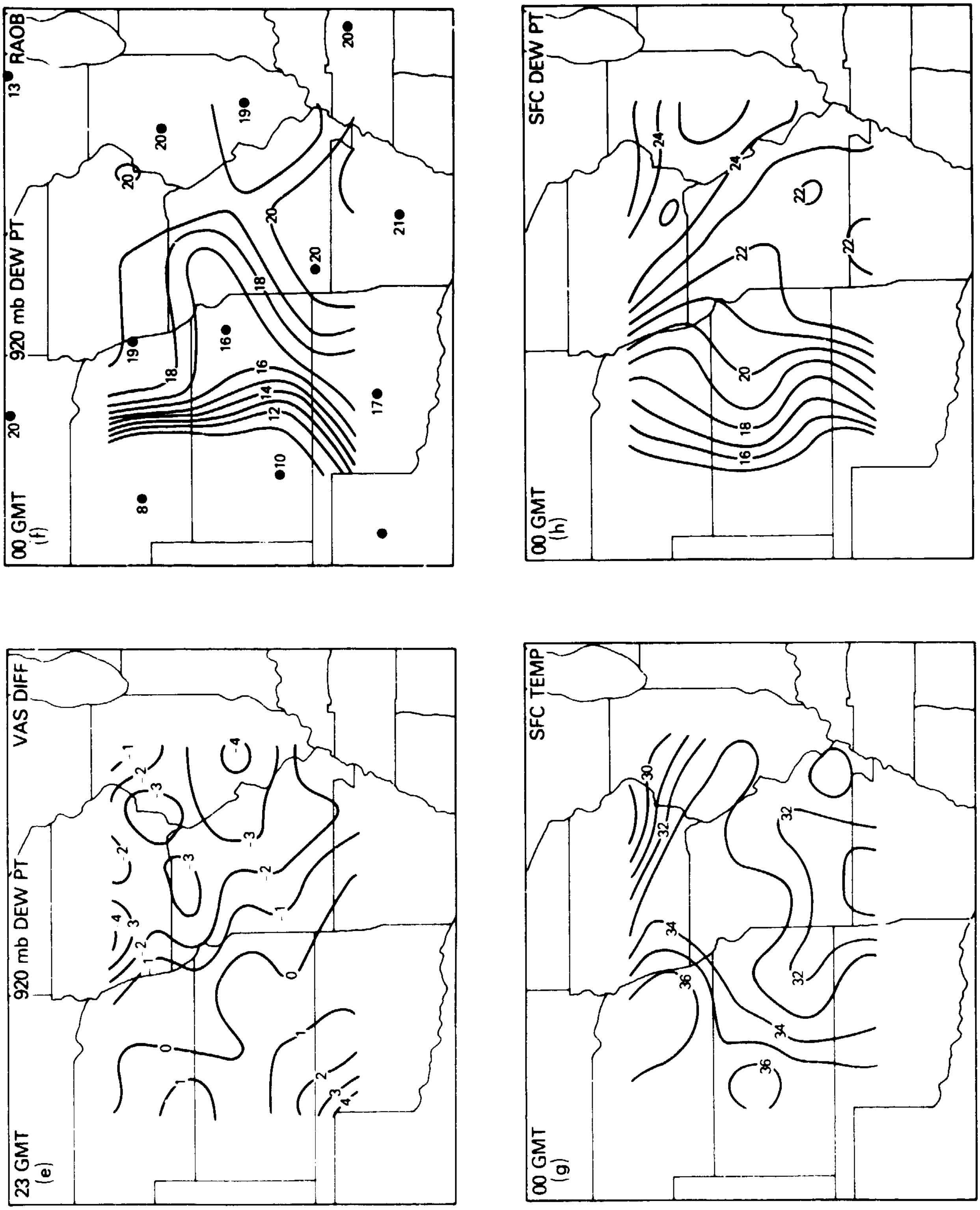


Figure 8 (part 2 of 2)

VAS AND SURFACE DIURNAL VARIATIONS ACROSS 18 SFOV IN NEBRASKA (41.5°N)

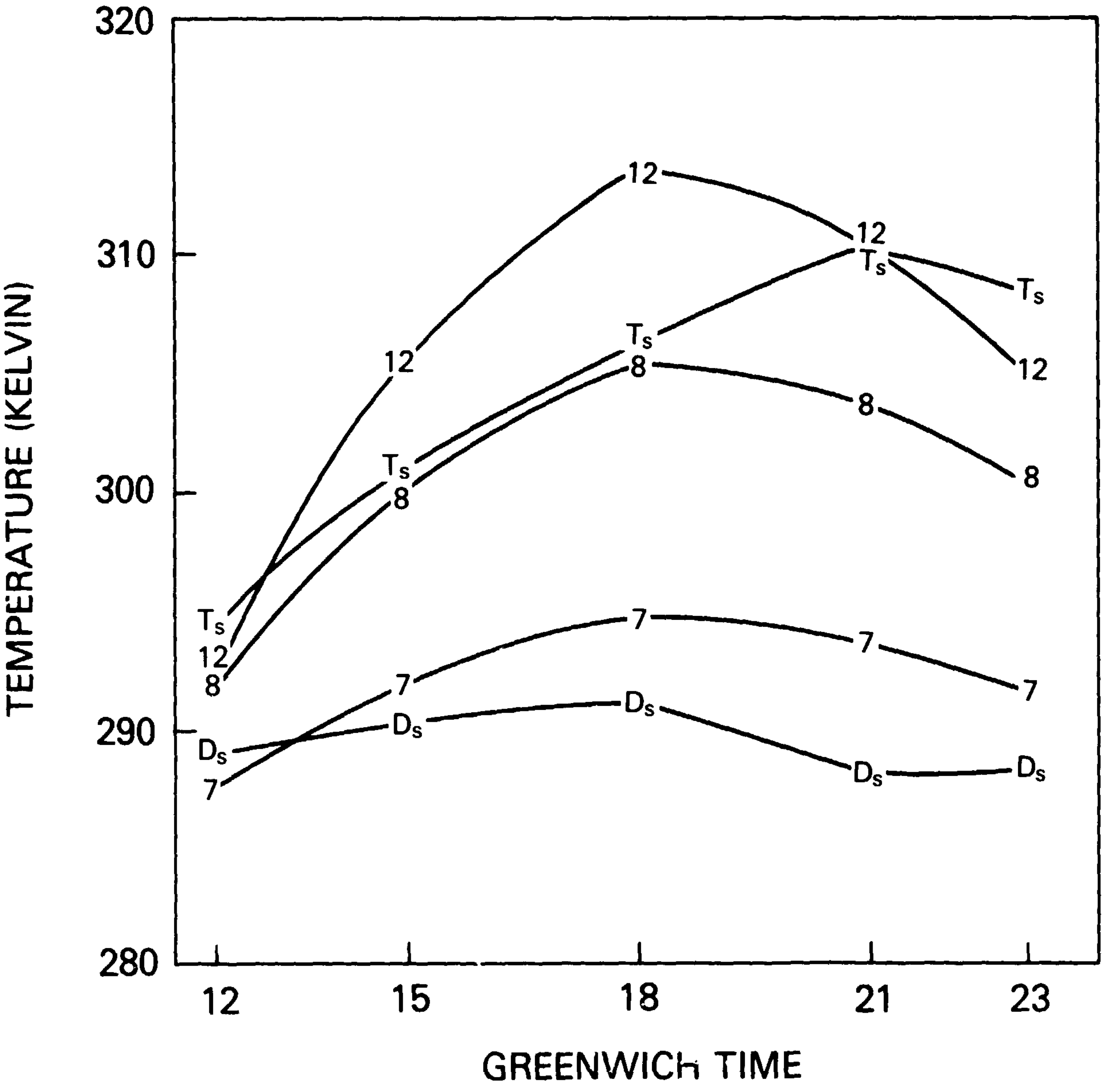
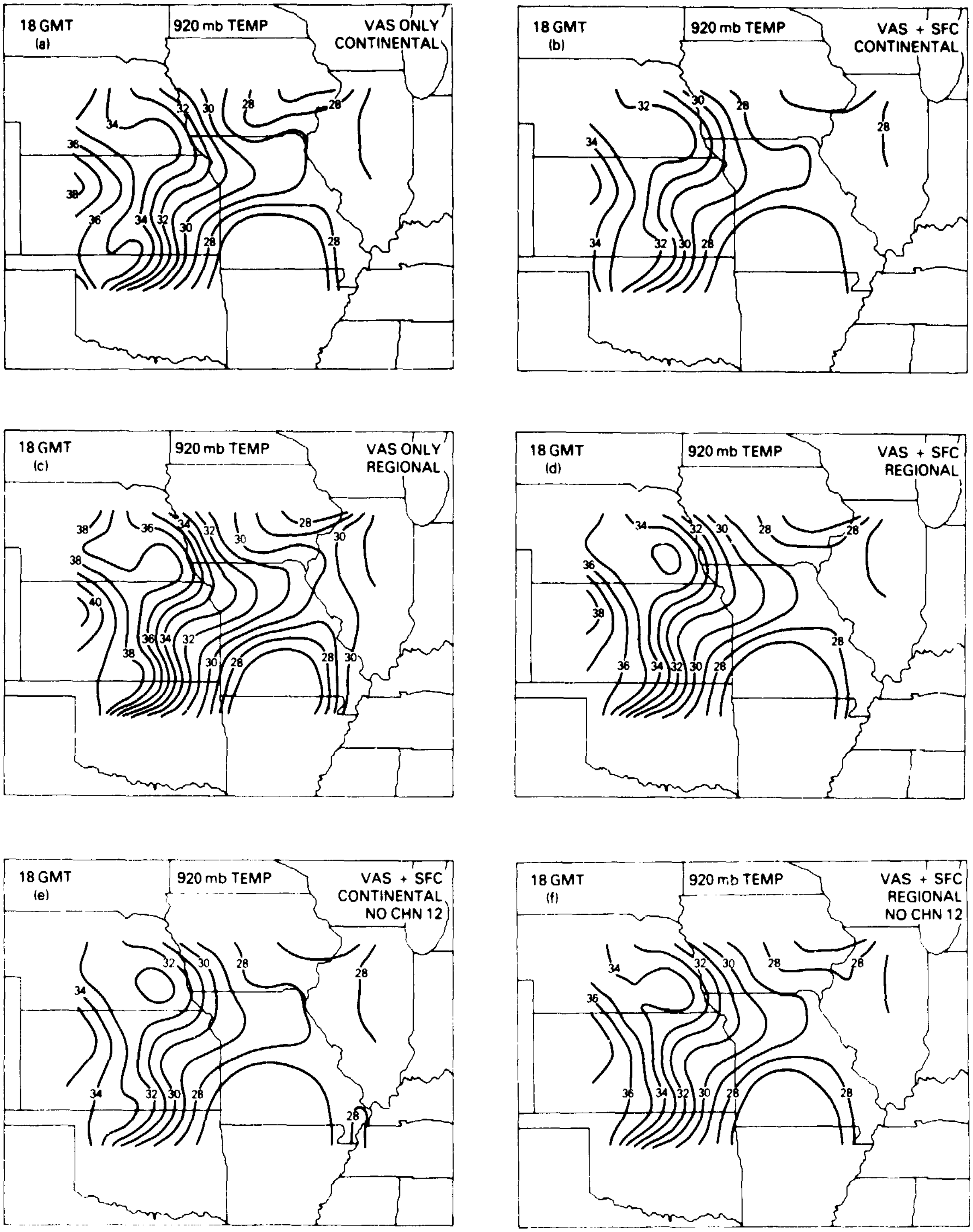


Figure 9


18 GMT
(a)
920 mb TEMP
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CONTINENTAL
18 GMT
(b)
920 mb TEMP
VAS + SFC
CONTINENTAL
18 GMT
(c)
920 mb TEMP
VAS ONLY
REGIONAL
18 GMT
(d)
920 mb TEMP
VAS + SFC
REGIONAL
18 GMT
(e)
920 mb TEMP
VAS + SFC
CONTINENTAL
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(f)
920 mb TEMP
VAS + SFC
REGIONAL
NO CHN 12

Figure 10

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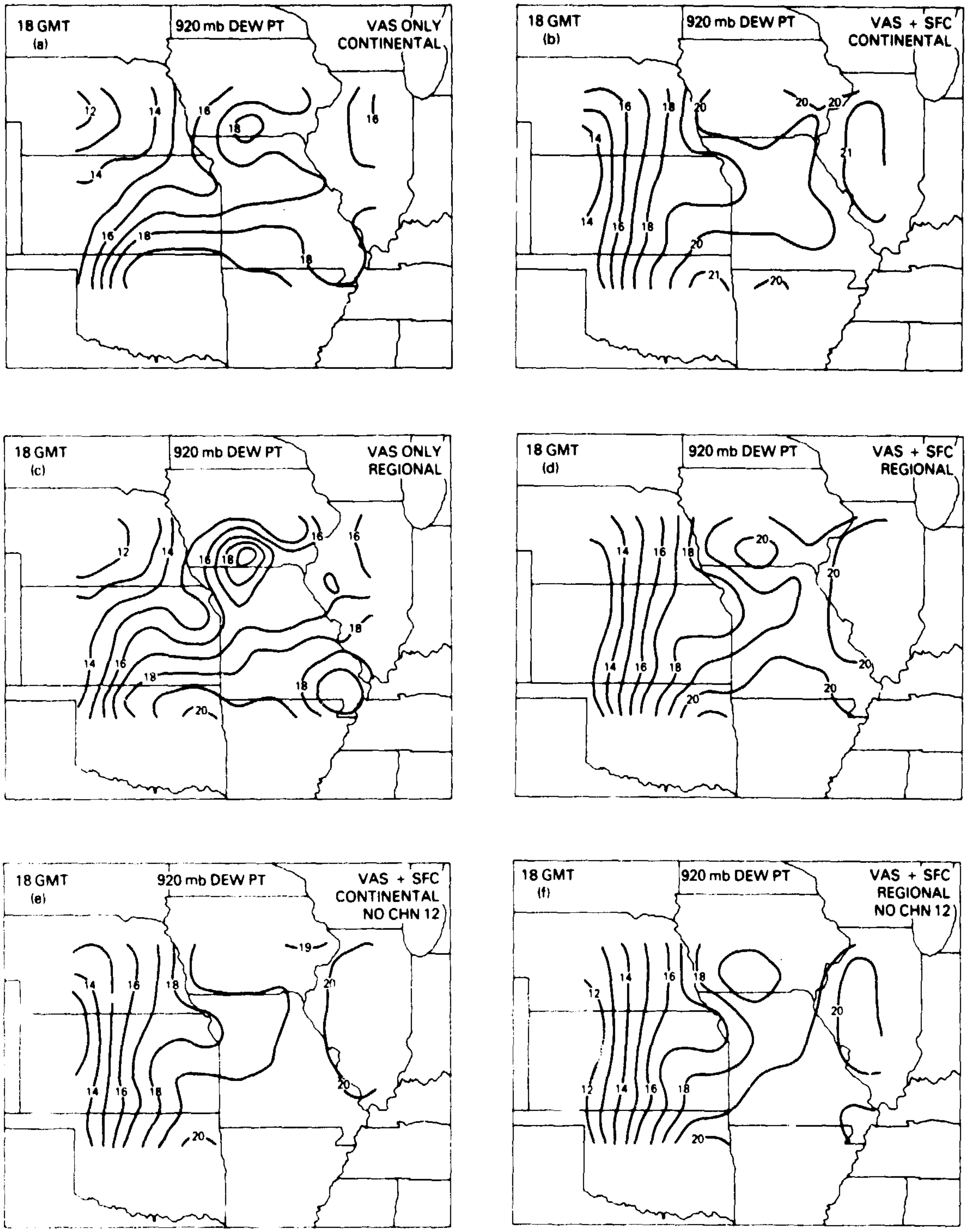

Figure 11

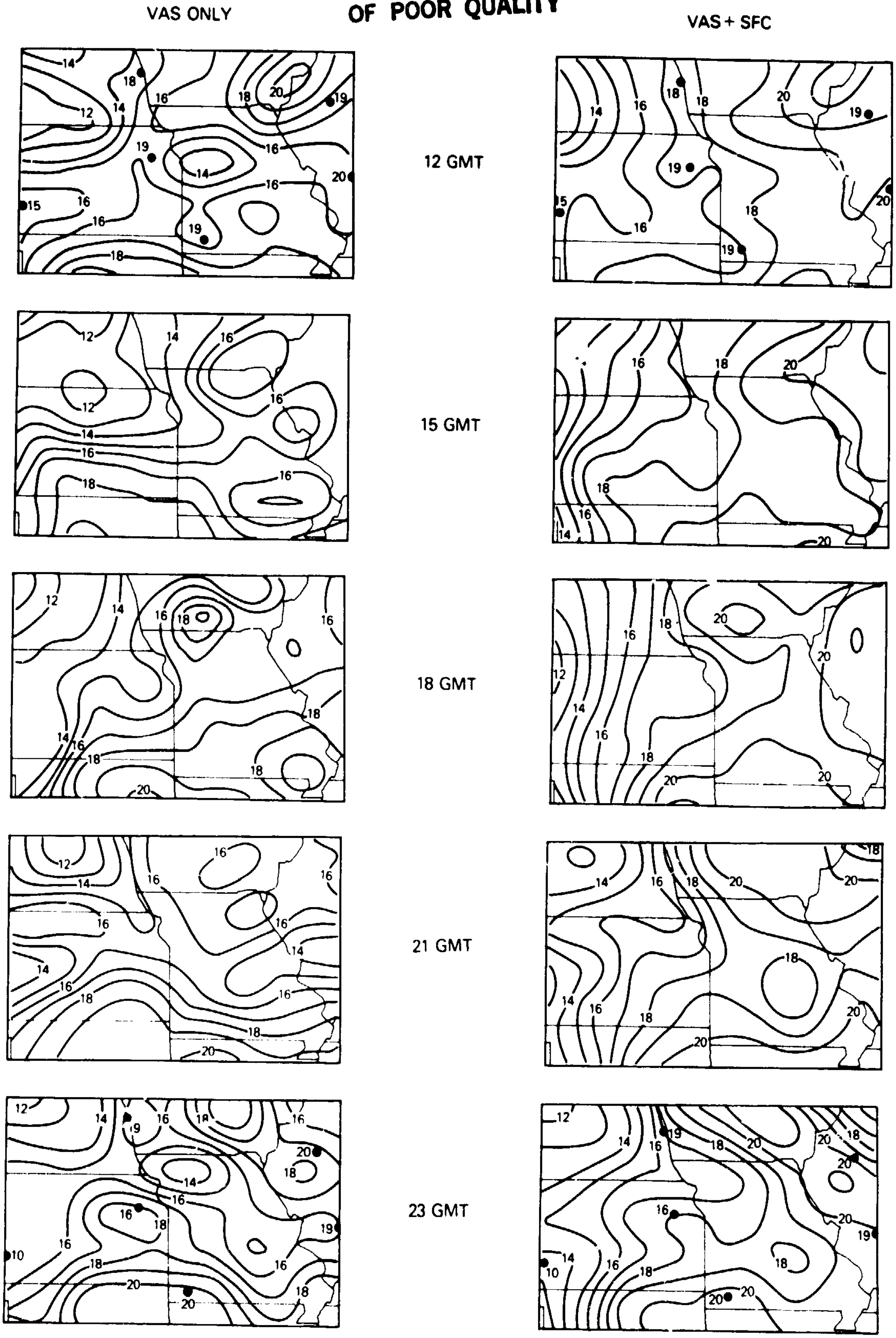

Figure 12