An Objective Isobaric/Isentropic Technique for Upper Air Analysis

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ABSTRACT

An objective meteorological analysis technique has been developed to provide both horizontal and vertical (cross-sectional) upper air analyses. The horizontal analyses are made at grid points that lie on isobaric levels in a conventional manner. However, the interpolation of values other than temperature at a grid point is performed on an isentropic surface that passes through the grid point. The vertical analyses are based on all surrounding radiosonde data and are not confined to a line of stations. They are calculated in an equivalent manner as the horizontal analyses, except that the grid points lie in a vertical plane.

The objective analyses have been evaluated by comparing the computer-generated results of two different versions (A and B) with subjective hand analyses. Comparisons for one test case are presented in this paper. The computer analyses show good agreement with the subjective analyses, and depict the baroclinic features of both the temperature and wind fields. In particular, the B version, which uses a second-order polynomial to interpolate grid-point values, gives very satisfactory results, producing cross-sectional analyses of stability and divergence that are compatible with the frontal surface.

1. Introduction

Analyses of fine-scale atmospheric features are often required to describe the upper air meteorological conditions at various altitude levels of interest as well as to depict the vertical structure of the atmosphere. Objective schemes for automatic horizontal analysis were first developed by fitting polynomials to observations (Panofsky, 1949; Gilchrist and Cressman, 1954). Various other types of objective schemes also have been developed, such as that of optimum interpolation (cf. Schlatter *et al.*, 1976). Horizontal analyses are made conventionally on isobaric (constant-pressure) surfaces. However, the air parcels of the free atmosphere actually tend to move along isentropic (constant potential temperature) surfaces, rather than along the isobaric surfaces. Thus, meteorological variables tend to be more continuous and to vary more linearly on isentropic surfaces than on isobaric surfaces, particularly along frontal discontinuities. The advantage of performing the analyses on isentropic surfaces has been recognized by many investigators (e.g., Rossby *et al.*, 1937; Danielsen, 1959; Reiter, 1972; Bleck, 1975).

Vertical cross-sectional analyses, although less common than horizontal analyses, are useful for depicting the mesostructure of the atmosphere by virtue of the vertical detail contained in the radiosonde data. In addition, they establish a vertical continuity between the horizontal analyses. Recently developed and tested objective cross-sectional analysis schemes have successfully portrayed the baroclinic structure of the atmosphere (Duquet *et al.*, 1966; Shapiro and Hastings, 1973; Cahir *et al.*, 1976; Whittaker and Petersen, 1977; Petersen, 1979). These objective approaches have been designed to be similar to the subjective manual approach, and to take advantage of the quasi-isentropic nature of the atmosphere.

In this study, an objective technique has been developed to produce both horizontal and vertical analyses in a consistent manner. That is, the process used to interpolate grid-point values from the upper-air station data is identical for grid points on both an isobaric surface and a vertical cross-sectional plane. The nearby data that surround each grid point are utilized in the interpolation by means of an anisotropic weighting scheme described later. The interpolation for a grid-point potential temperature is accomplished isobarically. However, wind, mixing-ratio and pressure-height values are then interpolated from data that lie on the isentropic surface that passes through the grid point. This mixed isobaric/isentropic technique tends to take advantage of the fine detail that exists in the vertical sounding data, and justifies the use of finer horizontal grids than would be used otherwise.

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2. Meteorological data and data processing

The sources of upper-air data used in this study were the formatted data on magnetic tape from the National Climatic Center. These formatted upper-air data provide height, temperature, humidity and wind at both significant and standard levels; standard levels are at 50 mb intervals up to 200 mb and at smaller intervals thereafter. The basic processing of the station radiosonde data consists of the following steps:

1) All the pressure or p values (mb) of the radiosonde data are converted to standard-pressure altitude values (m) according to the International Civil Aeronautical Association (ICAO) standard atmosphere, and a new sounding data set is created by interpolating values at points on the sounding spaced at 200 m standard-pressure altitude intervals. (For convenience in operational interpretation, standard-pressure altitude is actually used as the vertical coordinate rather than pressure).

2) Potential-temperature or θ values are calculated and superadiabatic layers are eliminated to produce for each station an essentially monotonic set of potential temperatures for use in the isentropic interpolations.

3) Geostrophic winds and ageostrophic (actual minus geostrophic) winds for each station are calculated at the vertical sounding points spaced at 200 m intervals. The geostrophic and ageostrophic winds for a station at a particular level are calculated by first analyzing height values at this level at four points: one grid interval east, west, north and south of the station. These analyzed height values are then used directly for calculating the geostrophic wind. [This calibration of station geostrophic wind is currently performed on an isobaric surface, however, an analysis on an isentropic surface would probably provide better results (Danielsen, 1964)]. The geostrophic wind is combined with the actual wind (if available) to calculate the ageostrophic wind (ageostrophic winds are later interpolated where wind measurements are missing in the middle of a sounding). This processing procedure provides the basis for the "thermal enhancement" of Whittaker and Petersen (1977), since the geostrophic and ageostrophic winds are analyzed separately and the two results combined to produce the wind analysis.

3. Version A analyses

a. Description of technique

The horizontal analyses are made on a mesh with grid points equally spaced at some selected isobaric level. The vertical analyses are made on a mesh covering the cross-sectional plane with grid points spaced equally along the horizontal coordinate and equally along the vertical (pressure-altitude) coordinate. In either the horizontal or vertical analyses, a potential-temperature value for a given grid point, θ_g, is first interpolated from the surrounding measured values on the same isobaric level. The value for any other parameter (such as wind) at the grid point is then derived from values that are located in adjacent radiosonde reports at levels where this potential-temperature value occurs, as illustrated in Fig. 1. A value for the parameter at a particular sounding is obtained by interpolating, by proportional parts, between the two θ values between which the θ_g falls. The analysis procedure has been designed principally for upper-air investigations; however, if a θ_g surface extends into the boundary mixing layer, a value at the top of the mixing layer (set at 1 km) is used. This mixed isobaric/isentropic approach combines the convenience of having the final analysis on an isobaric level with the continuity and accuracy associated with an isentropic analysis. The resulting analyses reflect more closely the actual conditions inherent in the vertical variations in the atmosphere than would a simple isobaric analysis.

The technique used for interpolating a set of values at regularly spaced grid points from irregularly spaced observed values is the same for both the horizontal and vertical analyses. A grid-point value for a quantity is determined by fitting a polynomial surface by least squares to N nearby observations ($N = 6$). That is, an optimum fit is obtained by minimizing

$$Q = \sum_{n=1}^{N} w(q - \hat{q})^2,$$

where w is a weighting factor, q is an observed value at some location (x, y), and $\hat{q}$ is the polynomial estimate for the same location. In version A, a first-degree polynomial or plane surface is used ($\hat{q} = a + bx + cy$). An initial guess value provided at a grid point is treated as the first observational value ($n = 1$) and is given a fixed weight ($w_1 = 0.05$). This initial-guess value is generated by computing a simple weighted average of nearby observations. The remaining $N - 1$ observations are those nearest the grid point; however, it is required that at least one observation (if possible) be selected from each of the four angular quadrants about the grid point.

The weighting for an observation is given by

$$w = C^2/[C^2 + R^2 + (\alpha S)^2],$$

$$S \equiv (\mathbf{k}\cdot\mathbf{R} \times \mathbf{V})/|\mathbf{V}|.$$

The R in the above equation represents the magnitude of the horizontal distance vector ($\mathbf{R}$) between the grid point and the observation. Thus, the closer an observation is to the grid point, the greater the weighting. The degree of this effect is dependent

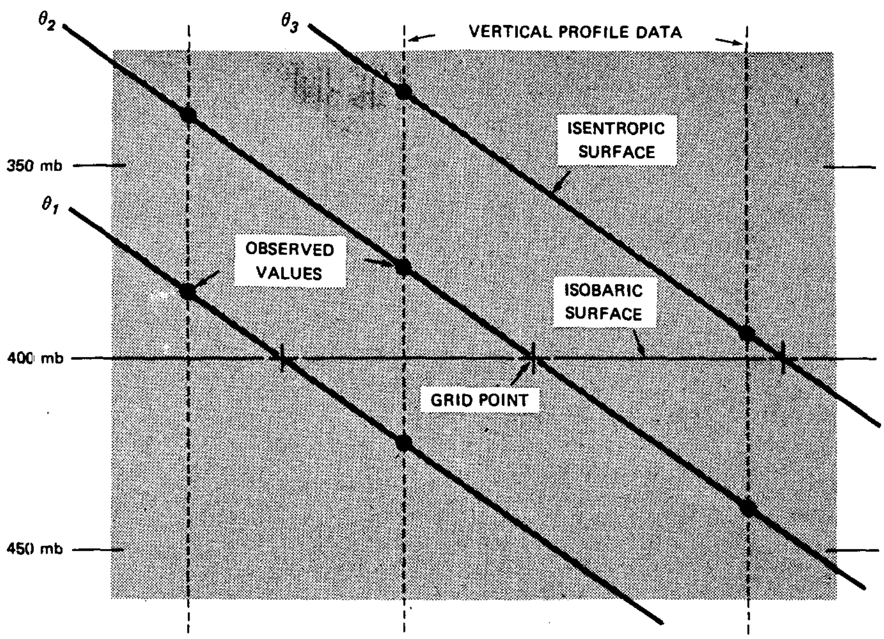

FIG. 1. Two-dimensional schematic of isentropic analysis on an isobaric surface. Values at grid points (+) on an isobaric surface are interpolated from observed values (●) that lie on isentropic surfaces that pass through the grid points.

on the value assigned to the constant C. The S in the above equation is dependent on the orientation of the **R** vector and the wind vector (**V**), and is included to give a greater weighting to upstream and downstream observations than to cross-stream observations. This anisotropic type of weighting is generally followed in subjective analysis, and it is theoretically consistent with the advection terms in the equation of motion (Sasaki, 1971). The above technique was developed in a previous study (Endlich and Mancuso, 1968), and has been modified in this application to perform the interpolation on isentropic surfaces that pass through the grid points of either the horizontal or cross-sectional mesh. Values used for N, C, and

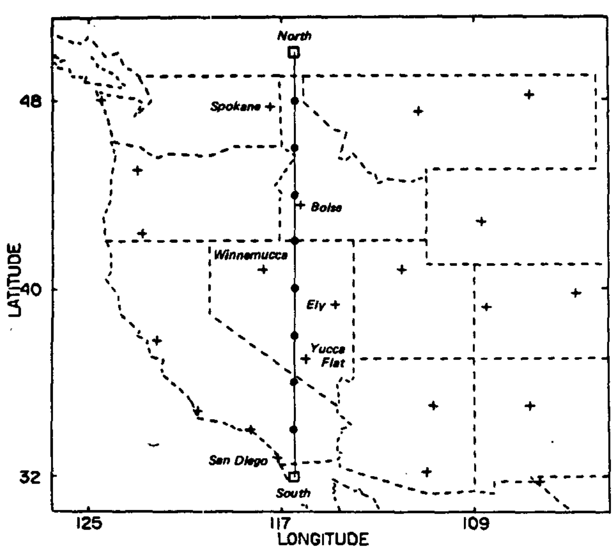

FIG. 2. Map of region of analysis showing radiosonde sites and cross-sectional path. The dots along the path show the location of the mesh's vertical columns of grid points at which values are calculated in the objective cross-sectional analysis. All of the sites shown were used in the objective cross-sectional analysis, but only those named were used in the subjective analysis.

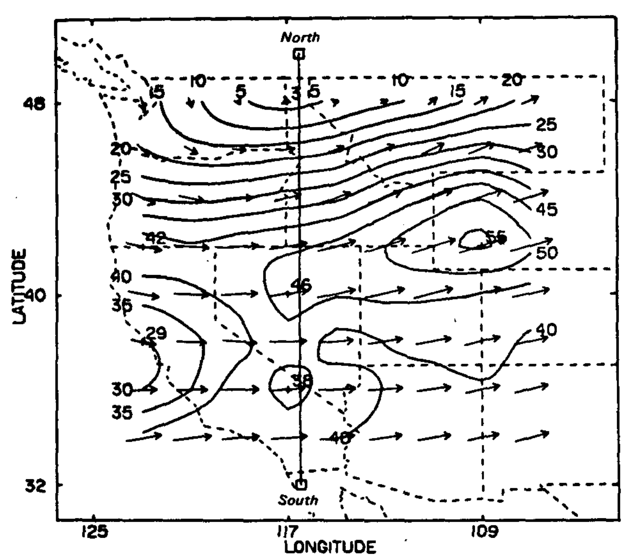

FIG. 3. Computer-analyzed wind speeds (m s^{-1}) and wind vectors for the 9200 m level and 0000 GMT 19 November 1977, based on version A.

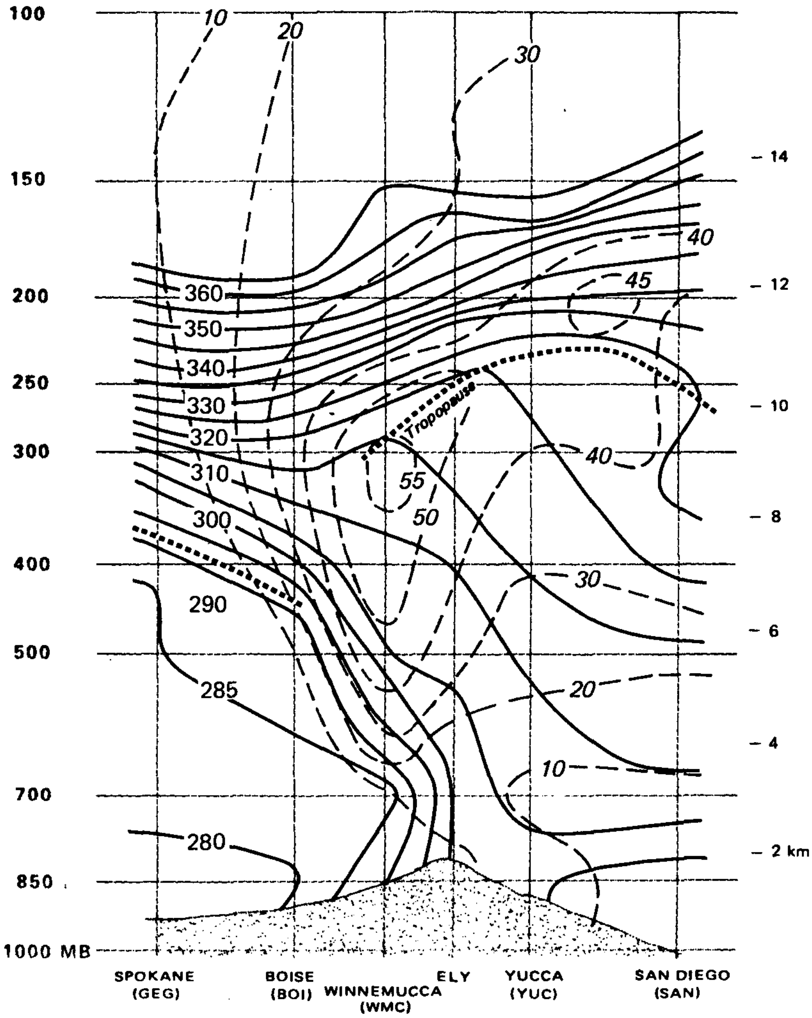

FIG. 4. Subjective cross-sectional analyses for 0000 GMT 19 November 1977. Potential temperatures (K) are shown by solid lines and wind speeds (m s^{-1}) by dashed lines.

α are 6, 157 km, and $\sqrt{2}$ based on previous optimization experiments (e.g., Mancuso and Wolf, 1974).

In the objective cross-sectional analysis studies that were previously referenced, only those stations very close to the selected cross-sectional path have been used. Thus, outlying data that can often aid significantly in depicting the mesoscale features are neglected. In this study, all nearby sounding data are used in constructing a cross-sectional analysis. The method used is identical to that used in a horizontal analysis, except that the analysis is performed at a number of points along the cross-sectional path and at a number of discrete levels; an example of points at one level along a path is shown in Fig. 2.

b. Results

The objective technique described above (version A) was evaluated by qualitatively comparing the computer analyses with subjective hand-drawn analyses. Three test cases, each covering a 24 h period, were used. In this paper, results are shown for the midtime of one of these test-case periods, 0000 GMT 19 November 1977 (results for other test cases are given by Mancuso and Endlich, 1979). The cross section was aligned along the north/south path previously shown in Fig. 2—the cross section is viewed from a western position. At this time, a pronounced trough was passing over western Canada and the United States. The southern part of this trough is revealed by the 9200 m level (~300 mb) version A objective wind analysis shown in Fig. 3. At this altitude, the wind speed varies along the cross-sectional path from a value of less than 5 m s^{-1} over northern Idaho to more than 45 m s^{-1} over northern Nevada, and then decreases southward. The isotach pattern shown is very similar to that shown by the

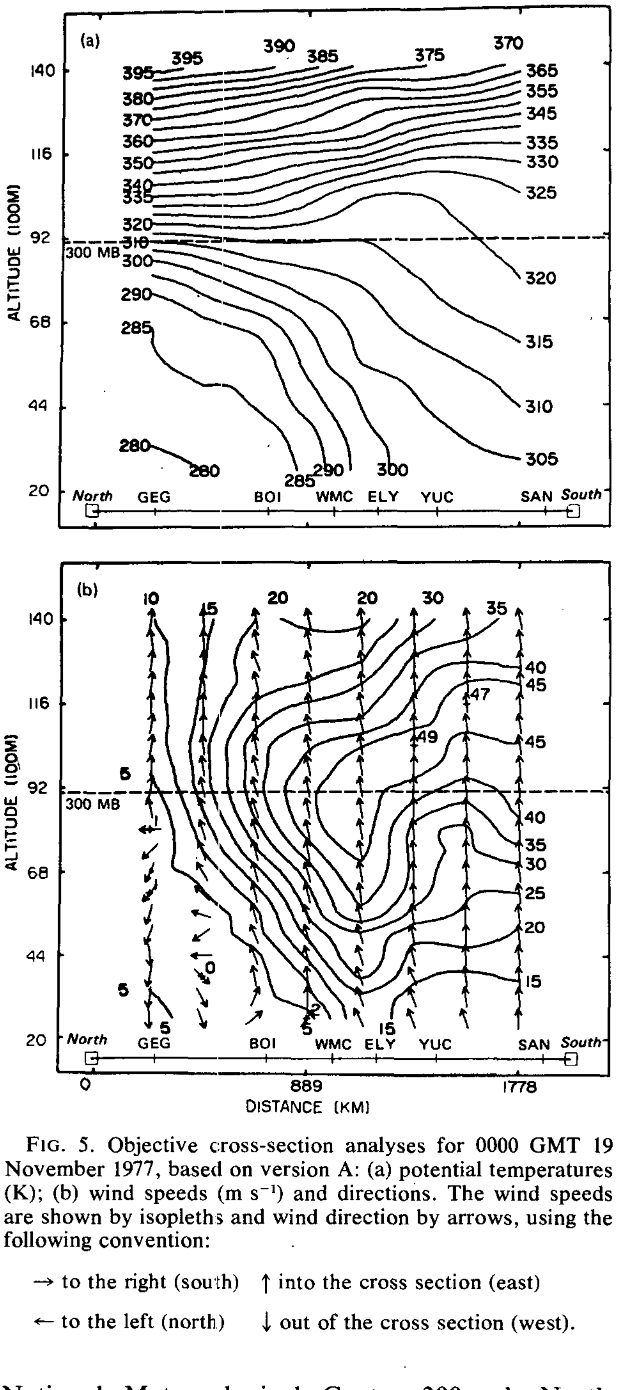

FIG. 5. Objective cross-section analyses for 0000 GMT 19 November 1977, based on version A: (a) potential temperatures (K); (b) wind speeds (m s^{-1}) and directions. The wind speeds are shown by isopleths and wind direction by arrows, using the following convention:

→ to the right (south) ↑ into the cross section (east)

← to the left (north) ↓ out of the cross section (west).

National Meteorological Center 300 mb North American analysis for the same time.

Subjective cross-sectional analyses for both the potential temperature (θ) values and wind speeds are shown in Fig. 4. The θ cross section clearly depicts a lower tropopause in the north where θ values start increasing rapidly with height, and a higher tropopause in the south. Also, a distinct frontal zone of tightly packed θ isentropes extends downward from the northern tropopause into the troposphere, separating a cold northern air mass from a warm southern one. The wind-speed pattern shows a relatively wide jet core lying along the southern tropopause with speeds up to ~55 m s^{-1}. Also, it shows a strong speed shear across the frontal zone.

The objective cross sections of potential temperature and wind based on version A are shown in Figs. 5a and 5b. To obtain the wind vectors of Fig. 5b, which are drawn at each of the grid points of the cross-sectional mesh, the geostrophic and ageostrophic winds were first analyzed separately, and then added together. The detail in these objective cross-sectional analyses is produced entirely by the detail in the sounding data. Different vertical and horizontal scales were used in preparing the subjective and objective analyses (Figs. 4 and 5); however, the 300 mb pressure level and station locations are indicated in both the objective and subjective cross sections to aid the reader in comparing them.

The cross-sectional θ analysis based on version A (Fig. 5a) is similar to the subjective (Fig. 4), but the subjective analysis appear to show a tighter packing of the θ isopleths in the frontal zone and a greater peaking in the isolines above the jet core. These types of differences are caused by

1) The analyst's insertion of mesoscale features that are characteristic of frontal and tropopause zones into the subjective analysis.

2) Smoothing inherent in the version A objective analysis.

3) Displacement of sounding data onto the cross-sectional path for the construction of the subjective analyses. This can introduce critical distortions, particularly of mesoscale features; for example, by increasing or decreasing the packing of the θ isopleths.

The objective cross-sectional wind analysis (Fig. 5b) depicts wind speeds ~ 10% lower than the subjective analysis (Fig. 4); this difference results from the smoothing inherent in the adopted objective technique. The subjective wind-speed analysis of Fig. 4 was difficult to construct, because winds were missing in the Yucca sounding above 400 mb and over Winnemucca between 300 and 175 mb. In these areas of missing winds, the objective wind analysis was influenced by the thermal enhancement, which appears to have been slightly beneficial.

Comparison of the objective and subjective horizontal analyses for all the three test cases showed that the elimination of superadiabatic lapse rates frequently resulted in significantly different horizontal temperature fields. However, the elimination of the superadiabatic lapse rates seemed to have improved the temporal and spatial continuity of the temperature fields.

4. Version B analyses

a. Description of technique

The evaluation of version A had indicated that various refinements might improve the analyses. This led to version B, which has the following modifications:

1) Use of a second-order polynomial (quadratic surface) fitting scheme for calculating grid-point values ($\hat{q} = a + bx + cy + dx^2 + ey^2 + fxy$, with $N = 8$).

2) Analysis of wind directions and wind speeds rather than the wind components (this tends to simulate more closely what is done in a subjective analysis).

3) Deletion of thermal enhancement from the analysis (the thermal enhancement was not found to be very significant in the cases studied, and its deletion reduces the complexity of the procedure).

b. Results

The version B cross-sectional analyses of potential temperature and winds are shown in Figs. 6a and 6b.

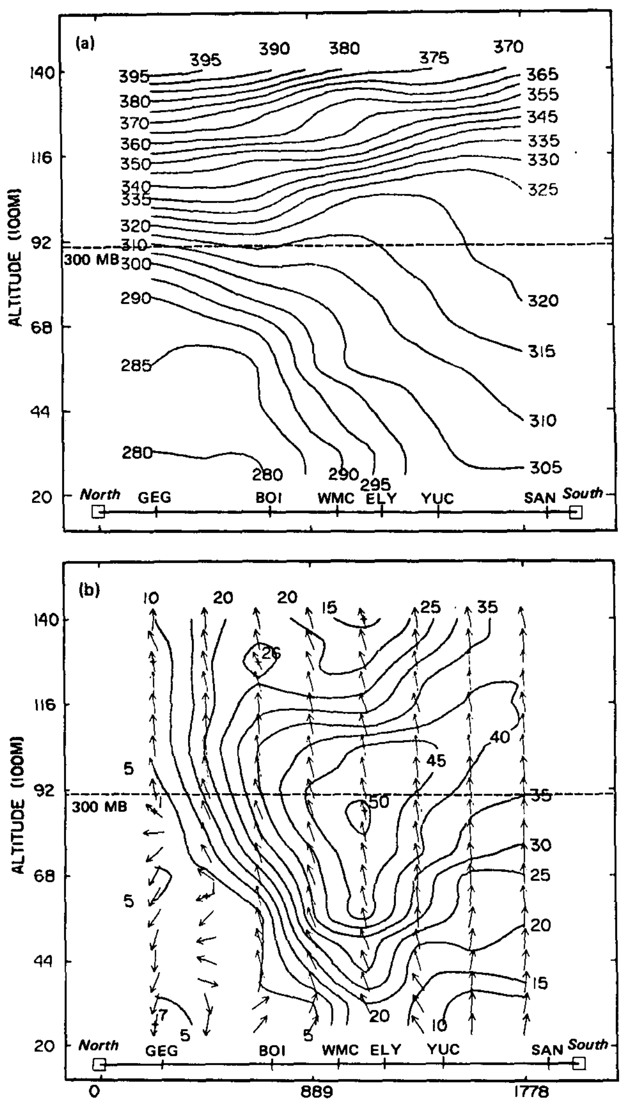

FIG. 6. Objective cross-section analyses for 0000 GMT 19 November 1977, based on version B: (a) potential temperatures (K); (b) wind speeds (m s^{-1}) and directions.

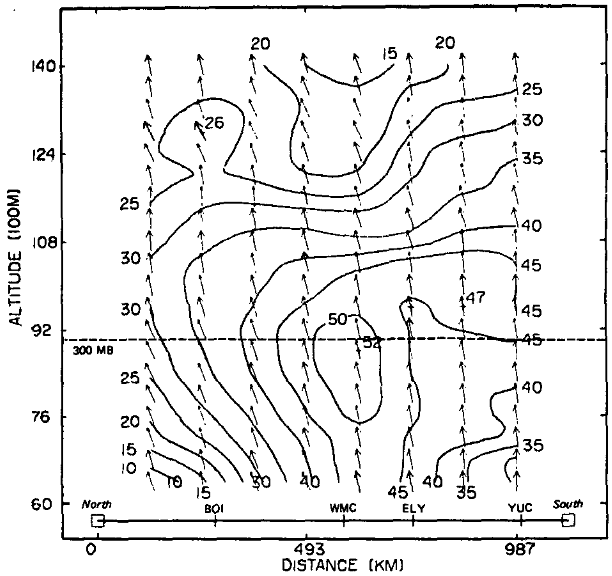

FIG. 7. Zoom-in wind analysis based on version B that shows more detailed features of the jet-core center in Fig. 6.

Compared to version A (Fig. 5a), the θ pattern shows a much tighter packing along the front and is more consistent with the subjectively drawn pattern (Fig. 4). Also, the objectively generated wind vectors of Fig. 6b show a significantly stronger speed shear across the front than did those of Fig. 5b. However, the wind-speed maximum is still slightly lower than shown in the subjective analysis. This results principally from the grid-point locations in the objective analysis.

By performing an analysis that effectively zooms in on the jet core, an enlarged depiction of the jet-core section is obtained as shown in Fig. 7. In this figure the same number of grid points are used, but they cover a smaller cross-sectional area centered over the core. The speed maximum agrees closely with the maximum observed value over Winnemucca (55 m s^{-1}).

With version B, it is possible to produce cross sections with slightly unstable (superadiabatic) layers (see Fig. 6a). For most applications this is unimportant; however, in applications, such as the computation of potential vorticity, where superadiabatic layers are unacceptable, an additional check for this condition would be required.

5. Advantages of isentropic interpolation

Several experiments were made to determine the significance of performing the grid-point interpolations on isentropic surfaces that pass through the grid points, in contrast to a strictly isobaric analysis. The experiments consisted of generating cross-sectional analyses of lapse rates, vorticity and divergence. These results were produced using version B of the analysis technique, first by interpolating grid-

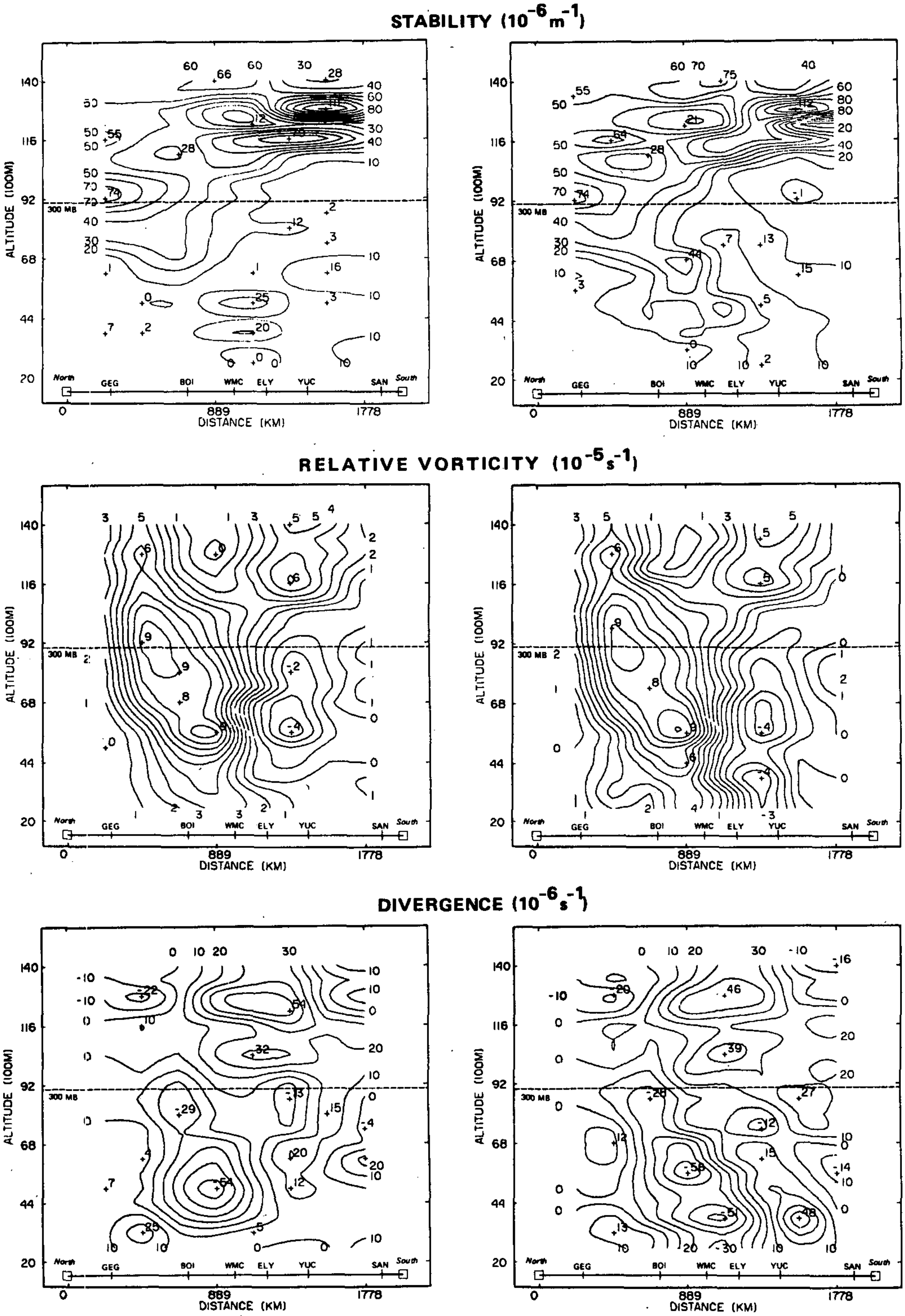

FIG. 8. Comparison of isobaric (left column) and isentropic (right column) analyses of stability, vorticity and divergence for 0000 GMT 19 November 1977, using version B of the analysis technique.

point values from data that lie on isentropic surfaces that pass through the grid points, and then by interpolating grid-point values from data that lie on the isobaric levels of the grid points. The results of these experiments are shown in Fig. 8, which includes cross sections of stability, vorticity and divergence.

a. Stability

These results are based on a direct analysis of stability values [i.e., $(1/\theta)(\partial\theta/\partial z)$] that were derived for each of the radiosonde profiles at every 200 m interval, using centered differences over 400 m. There are noticeable differences between the two different types of stability analysis. The analysis based on isentropic interpolations tends to depict a continuous zone of high positive stabilities extending along the upper frontal zone, whereas the one based on isobaric interpolations does not. This is because frontal characteristics (e.g., frontal temperature inversions) lie between observations on many pressure surfaces and are not directly detectable with a conventional isobaric analysis.

b. Vorticity and divergence

Cross sections of vorticity and divergence are obtained by the following procedure: wind values are analyzed for the main cross section and for two additional cross sections parallel to the first one, but located one grid interval away in opposite directions. This permits calculations of vorticity and divergence using standard formulas.

The vorticity fields that were calculated from both the isobarically and the isentropically interpolated grid-point winds are generally quite similar, except at low altitudes over Yucca Flat. The similarity is not unreasonable because vorticity is the major kinetic component of the wind field, and most likely it would not depict mesoscale features very distinctly. (This would not be true for potential vorticity which contains the stability term $\partial p/\partial\theta$.)

In contrast, the divergence fields that were calculated from the isobarically and the isentropically interpolated winds show some distinct differences. The isentropic result depicts a more definite alignment of a convergence zone with the front, and a sharp gradient between this convergence and the divergence that lies above the front. This result, which is based on an isentropic technique, appears to be more consistent with classical concepts of frontal structure.

6. Concluding remarks

Two versions (A and B) of an objective analysis technique were evaluated by comparing computer-generated analyses with subjective analyses for selected test cases. The comparisons showed as follows:

- The objective products of version A generally had fair correspondence with the subjective analyses and with the station data, and gave a reasonably satisfactory depiction of the structure of the upper fronts, tropopauses and jet streams. The objective analysis did tend to smooth out the high wind speeds in the jet-core centers and some of the mesoscale structure of both the wind and temperature fields.
- The objective products of version B corresponded more closely to the subjective analyses, showing the same strong gradients across the upper front with only minor smoothing. Using version B, it was shown that the isentropic interpolation produced results significantly different from those that would be obtained with an isobaric interpolation. The stability and divergence patterns that were obtained with the isentropic interpolation tended to align more consistently with an upper frontal zone.

The evaluation and comparisons in this study were based on standard reported data, and should be extended to more complete data sources such as AVE/SESAME-type data (Hill *et al.*, 1979). Such data would provide radiosonde observations at 3 h intervals, and permit a more conclusive testing and evaluation of the analysis procedures based on time continuity considerations.

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