VOL. 105, NO. 9 MONTHLY WEATHER REVIEW SEPTEMBER 1977

A Comparison of Several Meteorological Analysis Schemes over a Data-Rich Region

BETTE OTTO-BLIESNER,[1] DAVID P. BAUMHEFNER AND THOMAS W. SCHLATTER

National Center for Atmospheric Research,[2] Boulder, Colo. 80307

RAINER BLECK

University of Miami, Coral Gables, Fla. 33124

(Manuscript received 14 March 1977, in revised form 27 May 1977)

ABSTRACT

Among the many ways of comparing meteorological analyses, two are considered in this paper: their ability to fit the contours to observed data and to portray accurately the amplitude and position of synoptic-scale waves. Four analysis methods are investigated in a data-rich area: the National Meteorological Center (NMC) operational successive-correction objective analysis, a global statistical multivariate analysis, an isentropic analysis and a hand-analyzed subjective analysis. Analyses of wind and height for 11–14 December 1967 are compared on mandatory pressure surfaces. The individual analyses show minor differences in the positions and intensities of synoptic-scale meteorological features, in gradients, and in the smoothing of the data. Most differences are explained in terms of the computational methods employed by each analysis scheme. The NMC, isentropic and multivariate schemes fit the station data more closely than the subjective analyses. On the basis of these comparisons, we are unable to distinguish among the performances of the three objective analyses in a data-rich area.

1. Introduction

The primary purpose of a meteorological objective analysis scheme is to produce, on a regular grid mesh, an internally consistent field of values from irregularly spaced observations of differing quality and type. The gridded information can be used in numerical prediction models or for diagnostic studies. Development of accurate and computationally efficient objective analysis schemes has received considerable attention in recent years. For reviews of this subject, see Kasahara (1972), McPherson (1975) and Bengtsson (1975). With the advent of the First GARP[3] Global Experiment (FGGE), which is expected to yield unprecedented volumes of meteorological data in the late 1970's, it becomes increasingly important to examine the behavior of various analysis schemes.

The utility of analysis schemes may be judged in several ways: 1) ability to distinguish between accurate and erroneous data, 2) ability to fit data to within the accuracy of observations, 3) ability to define accurately the amplitude and phase of synoptic-scale waves, and 4) ability to provide initial conditions for numerical models of the atmosphere such that forecast error is minimized. In this paper, we shall concentrate on items 2) and 3) by comparing different analysis schemes with each other and with observed data. We hope to include studies of item 4) in future work.

Several analysis schemes have been compared in previous studies. Petersen (1973) compared weighting coefficients used in the National Meteorological Center (NMC) operational 300 mb height analysis scheme and in an "optimal" objective analysis based on verification error covariance for operational 12 h forecasts. Stuart (1974) found that similar magnitudes and patterns of vertical motion over North America were computed from three subjective and two objective analysis techniques. Schlatter *et al.* (1976) compared multivariate statistical analyses, NMC Cressman analyses and subjective analyses over the Northern Hemisphere. They found little difference in data-fitting ability. They also tested the multivariate scheme with different initial guesses and two different covariance models.

This study examines the ability of three quite different objective analysis schemes to fit the data and to define the amplitude and phase of synoptic-scale waves

---

[1] Present affiliation: Department of Meteorology, University of Wisconsin, Madison 53706.

[2] The National Center for Atmospheric Research is sponsored by the National Science Foundation.

[3] GARP is an acronym for the Global Atmospheric Research Program.

in a region of uniform, high-density data coverage similar to that expected during FGGE. Wind and height analyses on constant pressure surfaces are compared on four consecutive days in mid-December 1967. The three schemes are the Cressman scheme formerly operational at NMC, a multivariate statistical scheme developed at the National Center for Atmospheric Research (NCAR) and an isentropic scheme by Bleck (1975). These three are, in turn, compared to subjective hand analyses of the same data set.

The remainder of this paper is organized as follows. Section 2 summarizes the operation of each analysis scheme. Section 3 explains how the analyses were compared. Detailed comparisons of analyses including difference maps are in Section 4, and Section 5 shows how well each scheme fits the data.

2. Description of the analysis scheme

The analysis methods under study are 1) purely subjective, 2) successive-correction (Cressman scheme), 3) multivariate statistical and 4) isentropic. A brief description of each method follows.

The subjective analyses used here were prepared by D. Baumhefner at NCAR and are part of a series of analyses developed for global forecast experiments with the NCAR general circulation model. All available meteorological information is used, including extra surface ship reports, aircraft reports, satellite pictures, and other analyses such as the NMC operational product. Supplemental information is carefully blended with the conventional observing network data.

Specialized techniques enhance the high quality of the analyses. The analyzed geopotential heights are subjectively adjusted to the observed winds so that the geostrophic wind relation is approximately satisfied, particularly in regions where height observations are scarce. Satellite cloud pictures are used to specify sea level pressure patterns over data-sparse areas according to several empirical techniques. Adjusted sea level analyses are then used to alter the upper layer geopotential analyses subjectively. Finally, the analyses are scrutinized for two-way temporal continuity of all transient features and for vertical consistency. The final results are compared with other analyses and the differences justified in terms of previous decisions.

The successive-correction analysis scheme (Cressman, 1959), operational at NMC during 1967, produces gridded data for the Northern Hemisphere poleward of about 15°N. A height analysis is computed as follows. A 12 h NMC forecast provides the "first-guess" or trial height field, which is corrected during repeated "scans" through the data. Only observations within a specified radius N of the grid point can influence the corrections. N is reduced on successive scans in order to emphasize progressively shorter scales in the analysis. The result of each scan becomes the first guess for the succeeding scan.

The geopotential height correction at a grid point depends upon both wind and height observations nearby. The correction due to a single height observation is the difference between observed and trial values of height at the observing point multiplied by a weight which depends upon the distance d_i between the grid point and observation i. If both height and wind are reported, a different procedure is followed. The observed height and the gradient implied by the wind field permit extrapolation of the height to the grid point. The difference between the extrapolated and trial values, multiplied by a distance-dependent weight, is the grid-point correction in this case. The distance-dependent part of the weight is given by

$$W_i=\begin{cases}\dfrac{N^2-d_i^2}{N^2+d_i^2}, & d_i\leqslant N\\[2ex] 0, & d_i>N\end{cases}\qquad(1)$$

The total correction at a grid point is a linear combination of the individual corrections in which the sum of the coefficients is 1, and provision exists for adjusting the relative emphasis given to wind and height observations.

The multivariate statistical analysis scheme (Schlatter, 1975; Schlatter *et al.*, 1976) is based on the concept of optimal interpolation (Gandin, 1963). As in the successive-correction scheme, the first-guess field, a forecast, is modified by a linear combination of differences between observed and forecast values; but there is only one pass through the data. Geopotential height (h) and the horizontal components of the wind (u, v) are estimated simultaneously; height observations influence the wind analysis and vice versa. Since the scheme is multivariate, the weighting coefficients are 3×3 matrices instead of scalars. These depend upon correlations among the forecast errors in h, u and v.

A damped cosine curve models the height-height correlation

$$\mathrm{Cor}(h_i,h_j)=(c_1+c_2\cos c_3 s_{ij})(1+c_4^2 s_{ij}^2)^{-c_5},\qquad(2)$$

where s_{ij} is the great circle distance between points i and j, and c_1–c_5 are empirical constants generated by a curve-fitting routine from raw correlation data. Eq. (2) gives the distance-dependence of those weights which determine the contribution of height observations to the height analysis; it is the analog of (1). Other correlations involving wind components (there are eight in all) are derived from (2) under the assumption of geostrophy. This amounts to a weak constraint discernible on analyzed maps primarily in data-sparse areas; the wind speed analyzed between two isolated height observations is proportional to the implied height gradient.

The multivariate statistical analysis has two desirable features: it is based on linear regression, i.e., past atmospheric behavior determines the weight coefficients; and the analysis error in all variables is minimized in the long run. One drawback is the amount of computing time required to invert matrices in calculating the weights.

As the name implies, the isentropic analysis scheme generates grid-point data of meteorological fields on isentropic surfaces. Aside from this choice of vertical coordinate, the scheme is a compromise between the iterative Cressmen technique and the multivariate optimal interpolation method. It borrows from the Cressman scheme the idea of carrying out several analysis scans with successively reduced radii of influence; however, the weights in each scan are computed using the optimal interpolation regression technique. Since optimal interpolation reduces the spatial autocorrelations of analysis error to nearly zero after one scan through the data, the autocorrelation curve for the second (and final) scan has to be posed artificially. Therefore, the final analysis generated by the program is not an "optimal" one.

In isentropic coordinates, the so-called Montgomery potential $M=\phi+c_pT$ takes the place of the familiar geopotential in isobaric coordinates. Construction of the first-guess M field, which is based on current radiosonde data only, and the first analysis scan, which is multivariate on the input side (i.e., uses both M and wind observations), are described in detail by Bleck (1975). The autocorrelation curves used in this part of the code are based on historical data.

The rationale for performing a second analysis scan is as follows. The first scan uses an autocorrelation curve derived under the assumption of spatial homogeneity in the data. This assumption turns out to be particularly damaging in the case of short-wave disturbances which remain "underanalyzed" after one scan, i.e., lead to clusters of positively correlated residual analysis errors. To improve the representation of those short-wave features, one clearly would have to adhere more closely to the data than the optimal interpolation scheme allows. This is the purpose of the second scan. Even though any further modification of an optimally interpolated field is likely to make it noisier, the dynamic significance of short-wave disturbances makes this a reasonable price to pay.

The autocorrelation curve used in the second scan is a parabola with its apex at zero distance. The original intent was to let this curve fit the residual correlations. However, those are only slightly greater than zero after the first scan, even after some light smoothing of the grid-point data; therefore, before the curve fit, the correlation values in the distance classes 0.5, 1.0 and 1.5 are raised arbitrarily to values of 0.3, 0.2 and 0.1, respectively (distance expressed in terms of NMC grid units).

To assure vertical consistency, the analysis of the M field is backed by independent analyses of $\partial M/\partial\theta$ (which is proportional to the 2/7-th power of pressure) and $\partial^2M/\partial\theta^2$ (related to static stability). Once all three fields are known at a number of isentropic levels, a final M field is generated by means of a least-squares fit in the vertical at every grid point. The two auxiliary fields $\partial M/\partial\theta$ and $\partial^2M/\partial\theta^2$ are analyzed separately, i.e., no attempt is made to improve their definition by using first and second vertical derivatives of the observed wind vector.

The u and v components of the wind are analyzed independently in this program, based on geostrophic first-guess values obtained from the preceding Montgomery potential analysis. Again, two passes are carried out, both based on parabolic fits to observed correlations. The curve for the second pass is modified in the same manner as that described above.

3. Method of comparison

All four analyses are compared with radiosonde reports from a data-rich region centered over the United States and bounded by latitudes 25° and 50°N and longitudes 125° and 70°W (Fig. 1). Seventy reports are normally available within this area. Identical data, from the daily NMC archives, are used within another prescribed area as input to the isentropic and multivariate analyses. This second prescribed area, termed the analysis area, is larger than the comparison area in order to allow for an influence radius of 1500 km (Fig. 1). No automatic data error detection and removal are in these two analyses. Data used in the NMC analyses are identical except for those reports rejected operationally. The subjective analyses incorporate available reports according to the judgment of the synoptician.

The multivariate and subjective analyses are produced on mandatory pressure surfaces on a 2.5° latitude-longitude grid. The NMC analyses are converted from the NMC octagonal grid to a 2.5° grid with a 16-point Bessel interpolation (Whittaker and Robinson, 1944). The isentropic analyses are computed for the NMC octagonal grid on θ surfaces 10 K apart and then interpolated to the mandatory pressure surfaces and a 2.5° grid for comparison.

The period 11–14 December 1967 was chosen because

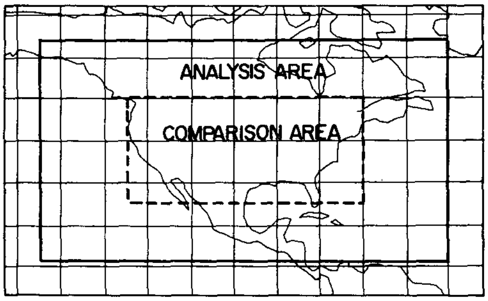

FIG. 1. Geographical locations of analysis and comparison areas.

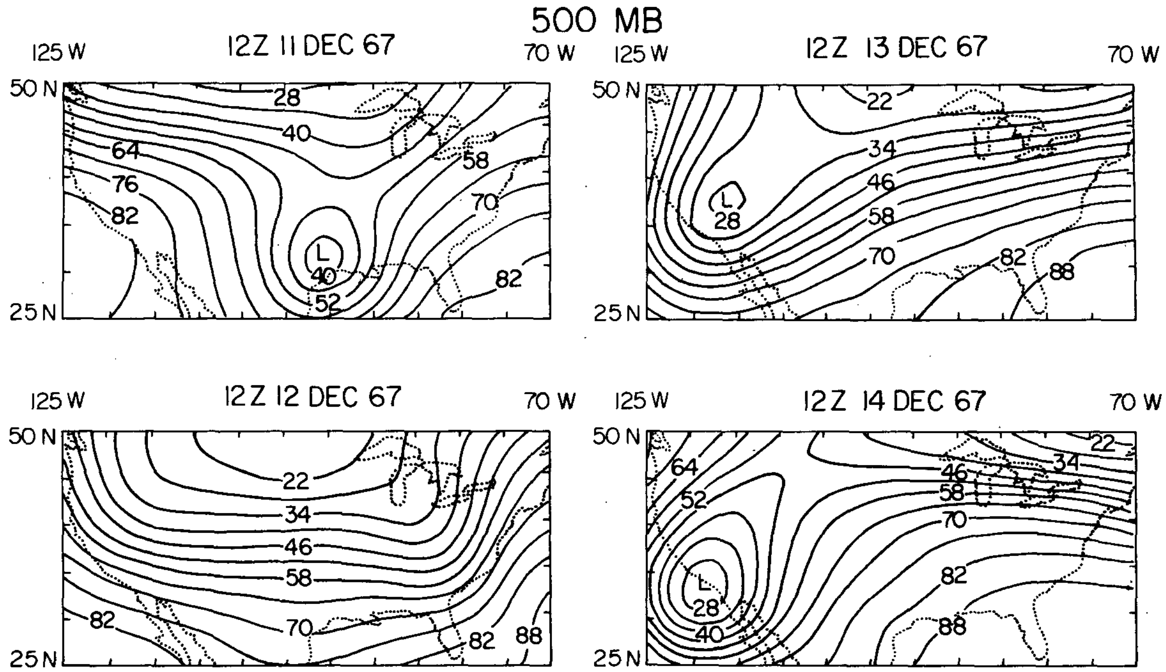

FIG. 2. 500 mb height over comparison area for 1200 GMT 11–14 December 1967 as analyzed by NMC. Contours in decameters at 6 dam intervals with leading digit omitted (70=570 dam).

subjective analyses are available. The 500 mb synoptic features are illustrated in Fig. 2. On 11 December, there was a cutoff low in the south-central United States, with strong ridging on both coasts. By 1200 GMT 12 December, the cutoff low had opened into a short-wave trough, moved rapidly to the northeast and weakened, while a new trough developed over the western United States. This feature amplified rapidly, retrograded to the southwest and became stationary on 14 December. A strong ridge developed over the eastern United States late in the period.

The analyses at 1200 GMT each day are compared by means of difference maps and root-mean-square (rms) differences between observed station data and

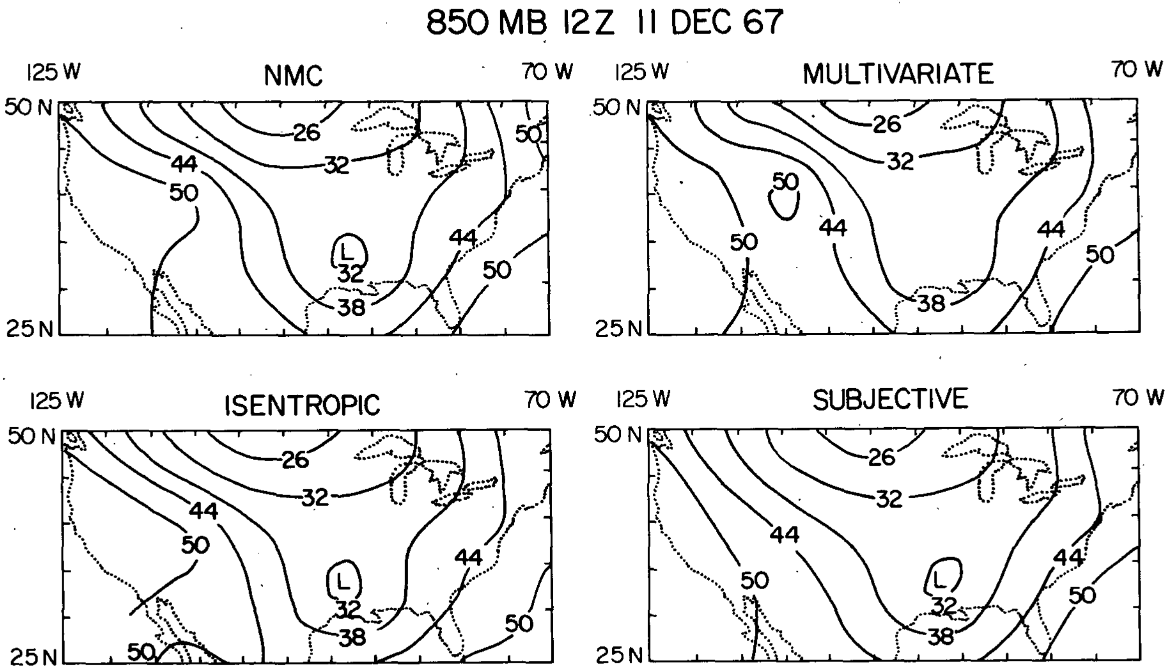

FIG. 3. 850 mb height analyzed by each scheme for 1200 GMT 11 December 1967. Contours at 60 dam intervals.

analyses. Comparisons of height analyses are made for all four schemes, but wind analyses are available for only the isentropic and multivariate schemes.

4. Analysis intercomparisons

The four analysis schemes are compared at 1200 GMT 11 December 1967 for 850, 500 and 200 mb. All four 850 mb analyses in Fig. 3 show a trough over the central United States and the short wave extending from Lake Superior to New York; all but the multivariate scheme have a closed low centered over Arkansas and Louisiana. The largest differences occur in the gradient over the northern Rocky Mountains and are associated with the degree of smoothing and the analysis of mountain station reports.

Difference maps (NMC analysis versus the other three) are shown in Fig. 4. The difference values over the eastern United States are on the order of 10 m; however, differences over the western mountains approach 40–60 m. The NMC-multivariate difference shows the trough to be less intense in the multivariate scheme. Part of the NMC-isentropic difference map has been blocked out in Fig. 4 and in subsequent figures because a portion of the comparison area lies outside the isentropic analysis area. In addition, a crude first guess remained unmodified by data in the blocked-out area; this would have resulted in unfair comparison between the isentropic scheme and the other three.

The 500 mb height analyses for 1200 GMT 11 December 1967 and the differences from the NMC analysis are given in Figs. 5 and 6, respectively. In general, the large-scale features are similar, with the intensity and southward extent of the main trough varying slightly among analyses. The isentropic and NMC analyses differ only slightly, by 20 m to the south and west of the trough and in the intensity of the ridge east of Florida. These two schemes differ most over the data-poor oceans and parts of Canada. Heights in the center of the closed low analyzed by the multivariate scheme are more than 40 m higher than in the NMC analysis. The gradients associated with the low are also weaker in the multivariate scheme. The subjective analysis locates the trough farther north than the NMC, more in agreement with the multivariate scheme, accounting for the 40 m difference just north of the Gulf of Mexico. A 60 m difference between the NMC and subjective analyses over the northern Rocky Mountains is due to the stronger short-wave ridge present in the subjective analysis.

The four analyses of 200 mb heights and related difference maps are given in Figs. 7 and 8, respectively. The tendency for the differences among analyses to increase with height is clearly illustrated. The trough over the central United States is analyzed differently by each scheme. The subjective analysis displays the deepest trough, and the multivariate method produces the weakest system. Only the NMC analysis has a cutoff low.

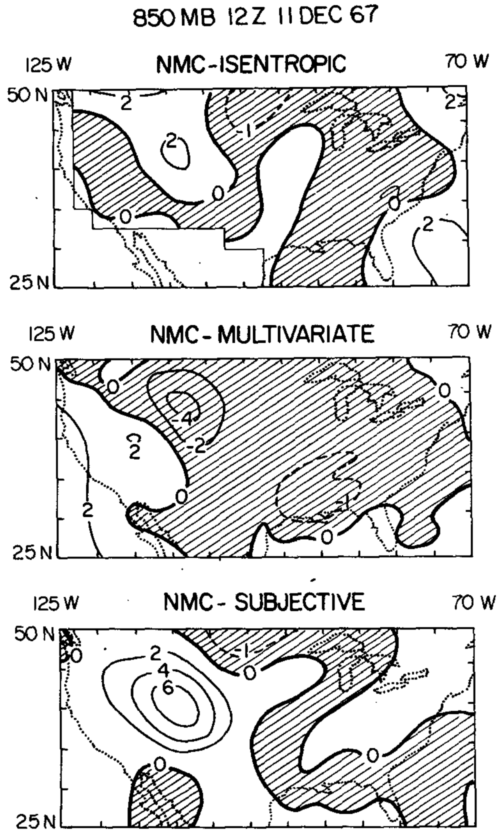

Fig. 4. Maps of differences between NMC analysis and isentropic, multivariate or subjective analyses of 850 mb height for 1200 GMT 11 December 1967. Contours at 10 m intervals with negative values shaded.

The most prominent difference between the NMC and isentropic analyses is again the ridge east of Florida, over a data-sparse area; heights are 80 m higher in the NMC analysis. In data-rich areas, the two analyses are still quite similar, with differences of less than 30 m. In the multivariate analysis, the central trough does not extend as far south as in the NMC analysis, which results in differences of 40 m. The subjective analysis is the most dissimilar. Differences as large as 60 m in the data-rich region are common. These are associated with higher geopotential height values and tighter gradients on the southern side of the trough in the subjective analysis and more amplitude in the ridge over the eastern Great Lakes.

Similar relationships among analyses also exist at other times in the period of interest. For example, at 1200 GMT 12 December 1967 the 500 mb flow over the United States is predominantly zonal in contrast to the flow of 11 December. We do not show analyses for this time, but the isentropic and NMC analyses are again in close agreement, with differences generally less than 20 m. In data-sparse regions, such as the Atlantic

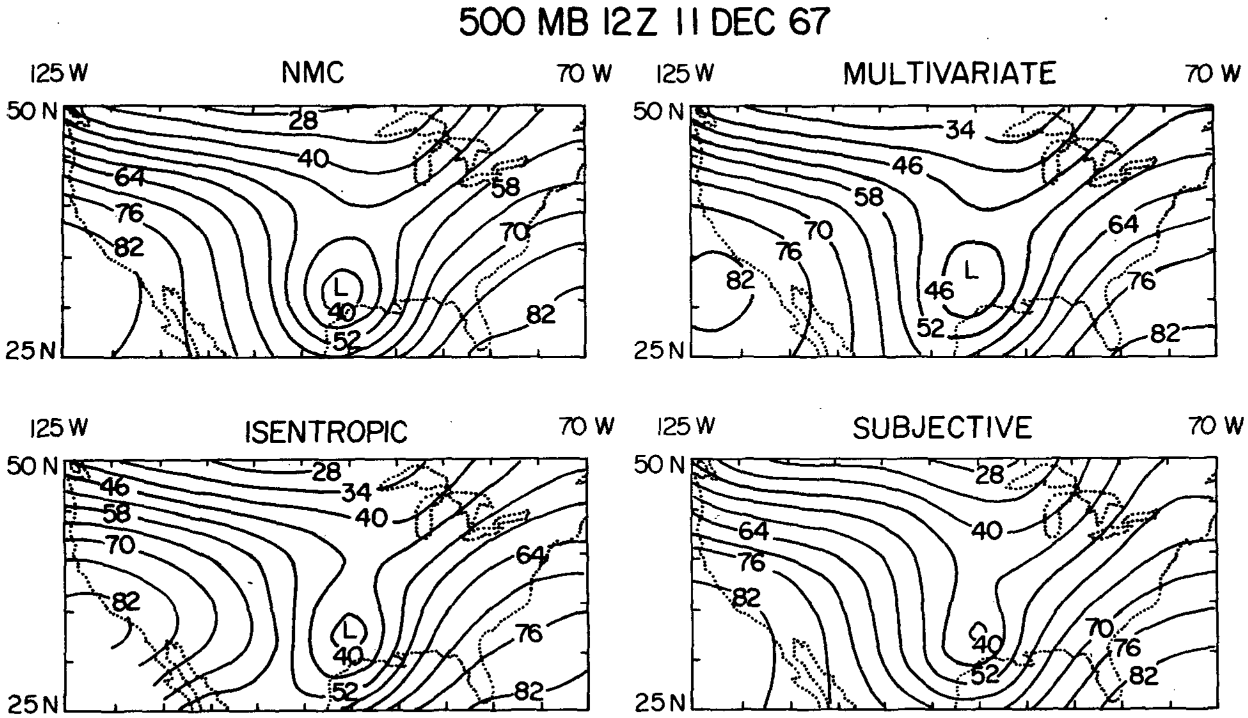

FIG. 5. As in Fig. 3 except at 500 mb.

Ocean, height differences up to 40 m exist. There are differences of 30 m over the northwestern United States because differing gradients are analyzed in the intensifying trough.

The largest differences between the NMC and multivariate analyses occur off the east and west coasts and may be explained by differences in the first guess. In the multivariate analysis, heights are 60 m lower in the Atlantic and 100 m lower in the Pacific than those in the NMC analysis. Heights in the short-wave troughs differ by nearly 30 m.

Differences between the NMC and subjective analyses are largest over the eastern United States; in the NMC analysis, the amplitudes of the ridge and the short-wave trough are 40 m greater. The ridge in the Pacific is also stronger in the NMC analysis.

It is clear from these examples and further comparison of analyses at other times that the large-scale synoptic features of the weather are faithfully reproduced by all analysis schemes. However, the positions and intensities of synoptic-scale troughs and ridges and the contour gradients differ from one analysis to another. With the NMC analysis as a standard, reasons for these differences may be postulated.

The isentropic and NMC schemes produce similar analyses, even though the former is on surfaces of constant potential temperature and the latter on constant pressure surfaces. This similarity is related to the use of successive corrections in both schemes. The largest differences between them occur in data-sparse areas, because the first guess is derived from actual

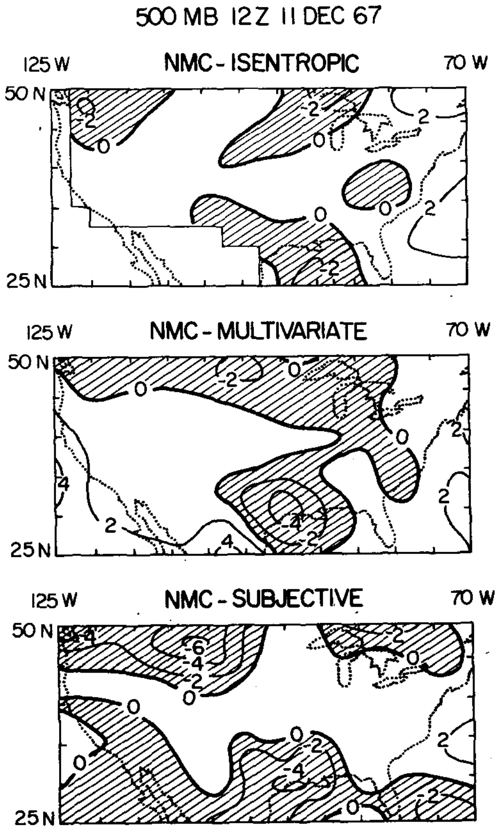

FIG. 6. As in Fig. 4 except at 500 mb.

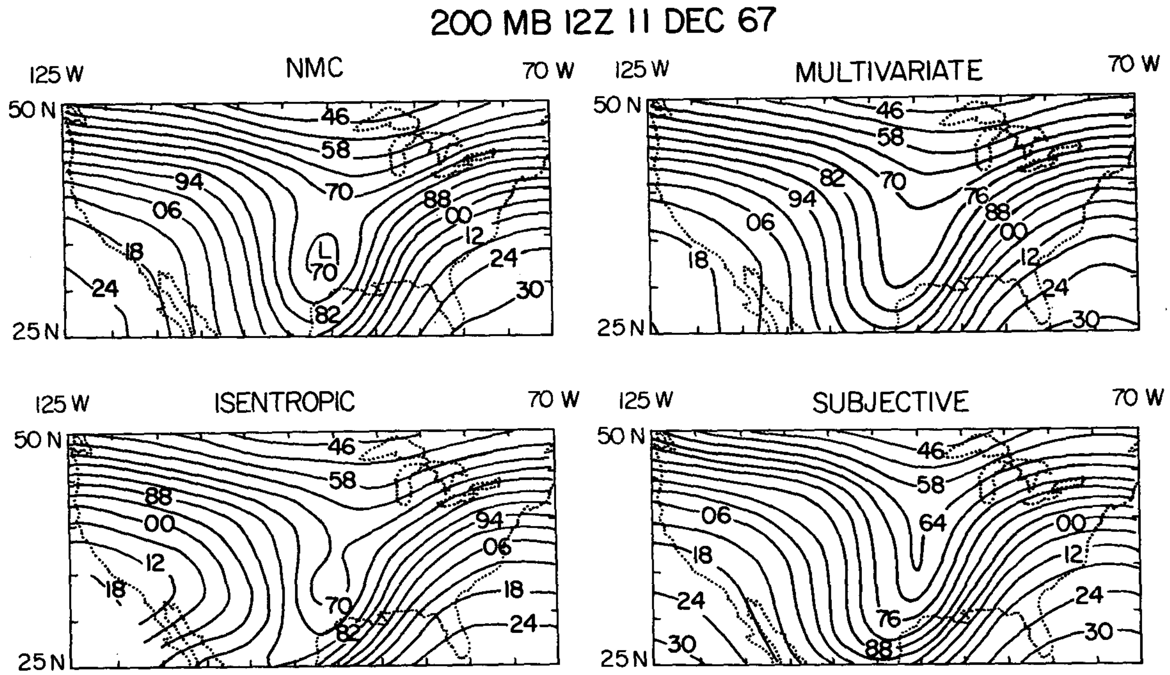

FIG. 7. As in Fig. 3 except at 200 mb.

station data in the isentropic scheme but from a forecast in the NMC scheme.

The failure of the multivariate scheme to analyze for the lowest or highest reported values should not be interpreted as an inherent shortcoming of the scheme but merely as a peculiarity of the cases examined here. Two examples suggested by Bengtsson (1976) illustrate that the statistical scheme is capable of analyzing values higher or lower than any observed.

The differences between the subjective and NMC analyses, largest at upper levels, are ascribed to the synoptician's confidence (or lack of it) in the observed data and his emphasis on maintaining the vertical and temporal continuity of the transient systems.

5. The fit of analyses to data

The analyses were interpolated bilinearly to station locations; then rms differences between analyzed and observed values were computed. Absolute differences in each 4 m band were calculated for 1200 GMT 11 December 1967.

At 850 mb the NMC and isentropic analyses fit the station data best, with rms values of 7.7 and 8.1 m, respectively. The NMC scheme achieves this skill by fitting the great majority of stations within 8 m of their reported values, but the isentropic analysis has a more uniform distribution of differences between 0 and 12 m. The majority of differences in the multivariate analysis, which has a larger rms of 11.5 m, falls in the range 4–8 m, indicating the increased smoothing of the method. Some of this smoothing results from interpolation error, and some from our assumption that 4% of the variance of observed-minus-predicted differences arises from observational error. If perfectly accurate measurements were available at each grid point, the multivariate scheme would fit the data exactly. The

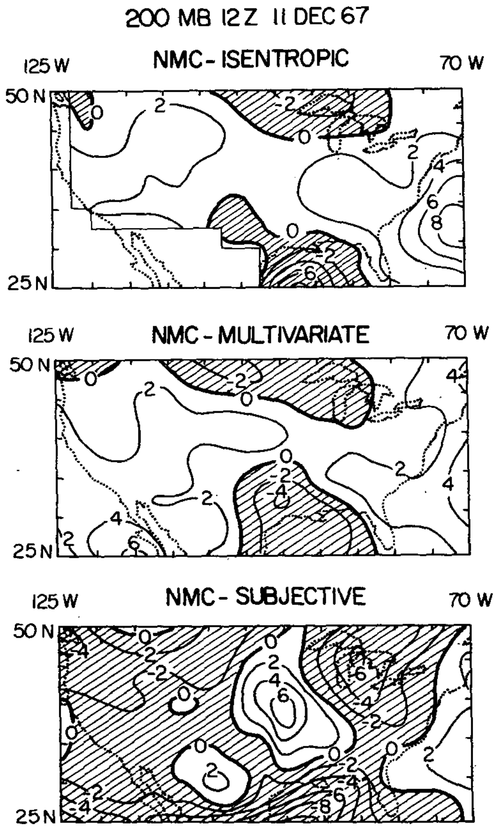

FIG. 8. As in Fig. 4 except at 200 mb.

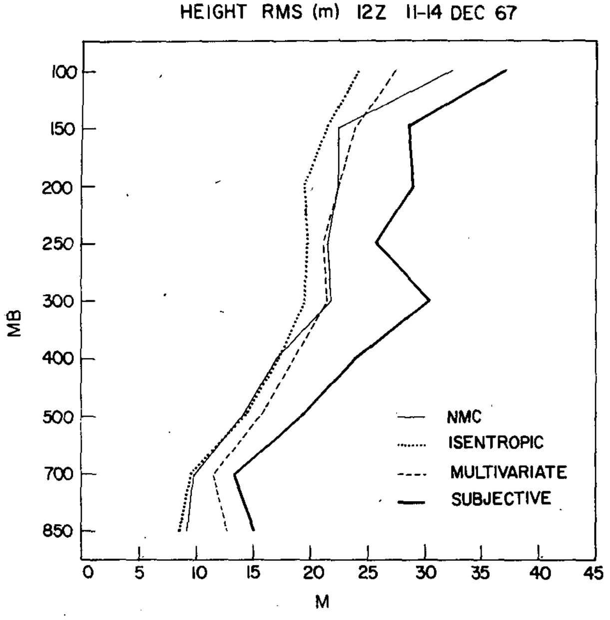

FIG. 9. Root-mean-square height difference between each analysis and station data, averaged for 1200 GMT 11–14 December 1967.

subjective analysis has the largest rms difference (17.1 m). Although about as many values fall within 4 m of the station values as in the NMC analysis, differences as large as 88 m are found. These large discrepancies exist because the subjective analysis is compared with data initially rejected by the synoptician.

Features similar to those at 850 mb are found at the 500 mb level, but the errors spread toward higher values. The NMC analysis again produces the smallest rms difference (12.3 m), having over half the analyzed values within 8 m of the station values. The isentropic, multivariate and subjective analyses have rms values of 13.5, 15.3 and 20.8 m, respectively.

The 200 mb differences exhibit the most spread of all analyses. The isentropic analysis has the smallest rms difference (21.5 m) and lacks any differences >48 m; note, however, that the second scan, described in Section 2, is designed to prevent large differences. The NMC and multivariate schemes have similar rms differences (23.7 and 23.3 m, respectively) and similar difference distributions at this level. The subjective analysis has a flat distribution of differences out to 48 m, with a maximum difference of 104 m between the analysis and station data. The subjective analysis is less faithful to the 200 mb observations than the objective analyses; the heavy smoothing employed by the synoptician results in a sizable rms value of 34.6 m.

The average rms height differences between the station data and each analysis are plotted in Fig. 9 for the entire analysis period. These differences increase with height, reflecting the characteristic increase of radiosonde errors with height. Below 400 mb, the NMC and isentropic schemes fit the station data equally well and more closely than the other schemes. Above 400 mb, the isentropic scheme fits the data most closely. The multivariate scheme fits the station data less precisely (rms values 10% greater) than the NMC and isentropic schemes—an insignificant difference, considering the small sample size and lack of independent samples. The subjective analyses depart most from the data because the analyst was free to smooth or reject selected data. The standard deviation about the mean is largest for the subjective analyses and smallest for the isentropic scheme. Independent analysis periods are needed, though, to substantiate these findings.

The mean rms differences for the u and v components of the wind, as analyzed by the isentropic and multivariate methods, are presented in Fig. 10. In general, the rms differences are largest at the level of maximum u and v, and the rms for u is less than the rms for v. The mean rms differences for the two schemes do not differ significantly at any level.

6. Conclusions

For the limited data sample considered, which did, however, include a rapidly changing synoptic situation, we conclude that the three objective analysis schemes tested reproduce the same overall patterns with considerable fidelity to observed data. There are minor differences in the positions, intensities and gradients of the synoptic-scale features. Differences among height analyses average 20–40 m, increase upward, and are greatest between the objective and subjective analyses. The largest differences, nearly 60 m at 200 mb over the data-rich United States, reflect personal judgments of the analyst regarding data accuracy. Most differences among the objective analyses are explained by the separate algorithms employed by each scheme.

When the analyses are compared with actual station data, differences between schemes generally fall within

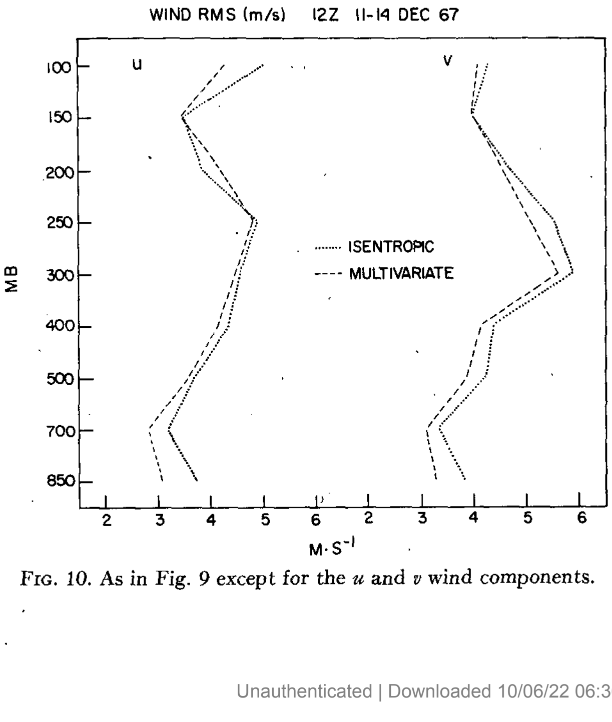

FIG. 10. As in Fig. 9 except for the u and v wind components.

the observational error at most levels, except for the subjective analysis. The accuracy of the "data fit" decreases with height for all methods.

On the basis of fitting the data or accurately portraying the amplitude and position of synoptic-scale waves, we find no significant differences among the three objective analysis schemes considered. Since another important aspect of an analysis scheme is its ability to maximize the skill of a forecast model, as mentioned in the Introduction, future work will include comparison of limited-area forecasts at different resolutions generated from each analysis scheme.

Acknowledgments. The authors thank W. Washington and L. Bengtsson for helpful suggestions on the manuscript, G. Branstator and R. Berglin for programming assistance and E. Rosenberg for drafting the figures.

REFERENCES

Bengtsson, L., 1975: Four-dimensional assimilation of meteorological observations. GARP Publ. Ser. No. 15 (January), Global Atmospheric Research Programme, WMO-ICSU Joint Organizing Committee, 76 pp.

——, 1976: Initial data and some practical aspects of forecasting. *Weather Forecasting and Weather Forecasts: Models, Systems, and Users*, Notes from a colloquium, Summer 1976, NCAR, 254–419.

Bleck, R., 1975: An economical approach to the use of wind data in the optimum interpolation of geo- and Montgomery potential fields. *Mon. Wea. Rev.*, **103**, 807–816.

Cressman, G. P., 1959: An operational objective analysis system. *Mon. Wea. Rev.*, **87**, 367–374.

Gandin, L. S., 1963: *Objective Analysis of Meteorological Fields.* Gidrometeor. Izdatel'stvo, Leningrad. [Israel Program for Scientific Translations, Jerusalem, 1965, 63–86 and 147–157].

Kasahara, A., 1972: Simulation experiments for meteorological observing systems for GARP. *Bull. Amer. Meteor. Soc.*, **53**, 252–264.

McPherson, R. D., 1975: Progress, problems and prospects in meteorological data assimilation. *Bull. Amer. Meteor. Soc.*, **56**, 1154–1166.

Petersen, D. P., 1973: A comparison of the performance of quasi-optimal and conventional objective analysis schemes. *J. Appl. Meteor.*, **12**, 1093–1101.

Schlatter, T. W., 1975: Some experiments with a multivariate statistical objective analysis scheme. *Mon. Wea. Rev.*, **103**, 246–257.

——, G. W. Branstator and L. G. Thiel, 1976: Testing a global multivariate statistical objective analysis scheme with observed data. *Mon. Wea. Rev.*, **104**, 765–783.

Stuart, D. W., 1974: A comparison of quasi-geostrophic vertical motion using various analyses. *Mon. Wea. Rev.*, **102**, 363–374.

Whittaker, E., and G. Robinson, 1944: *The Calculus of Observations*, 4th ed. Blackie and Son, Ltd., 395 pp. (see p. 39).