SOME PROBLEMS OF NUMERICAL OBJECTIVE ANALYSIS OF STRATOSPHERIC CONSTANT PRESSURE SURFACES

SIDNEY TEWELES and MIRCO SNIDERO
U.S. Weather Bureau, Washington, D. C.

[Manuscript received November 17, 1961; revised January 10, 1962]

ABSTRACT

A method of numerical objective analysis, developed by Cressman, is adapted for application to stratospheric constant pressure surfaces by giving greater weight to wind observations, correcting heights for radiation error, and building up the pressure pattern statistically over ocean areas. The temperature pattern is analyzed by a similar method.

Specimens of regression and temperature correction diagrams are shown, and the array of wind, temperature, and height errors engendered by a radiosonde pressure error is discussed.

1. INTRODUCTION

At the present time, analysis of hemispheric constant pressure surfaces in the troposphere is routinely carried out by electronic computer. When the technique, described by Cressman [1], was applied by Snidero and Teweles [2] to the analysis of stratospheric constant pressure surfaces at 100 mb. and 50 mb., difficulties arose that required special treatment. The most necessary modifications for application at high levels were: (1) Increase of weight given to wind observations vs. height observations; (2) correction of height and temperature to eliminate effect of solar radiation on the radiosonde; (3) use of regression equations to build up analysis from one level to the next over oceans and other areas of sparse data. The purpose of this paper is to describe the problems of numerical analysis of stratospheric constant pressure charts.

2. ANALYSIS PROCEDURES

An outline of the process of analysis is given in table 1 (see Cressman [1] for additional details). Initially, an estimated analysis or first guess must be provided for input to the computer. In the lower stratosphere up to the 100-mb. surface, statistical vertical extrapolation of a numerical prognosis of the 500-mb. chart promises to provide a satisfactory first guess. At 100 mb. and higher surfaces, the final analysis for 24 hours earlier appears to

TABLE 1.—*Outline of Cressman's [1] adaptation of Bergthórsson-Döös method [3]*

I. OCTAGONAL GRID OF 1977 POINTS
Covers hemisphere north of 16°N.
Grid size about 200 nautical miles.

II. ESTIMATED ANALYSIS
Climatological normal.
Hand drawn.
Last previous.
Numerically computed prognostic.
Extrapolated or interpolated from analysis of other surfaces.
Combined prognostic and extrapolated.

TABLE 1.—*Outline of Cressman's [1] adaptation of Bergthórsson-Döös method [3]*—Continued

III. AUTOMATICALLY PROCESSED DATA
(Bedient and Cressman [4])
Recognition of codes and location of stations.
Recomputation of radiosonde reports.
Elimination of gross errors.

IV. MODIFICATION OF ESTIMATED ANALYSIS
Successive correction of grid point values.
Application of observed heights (temperatures) and winds (thermal winds) within scan area.
Observed data weighted for distance from grid point.
Height (temperature) data weighted relative to wind (thermal wind) data. At 100 mb. winds are weighted 32 times as much as height (at 500 mb. this weighting factor is 4).

Smoothing of field by applying the formula $\overline{D}=\frac{1}{2}D+\frac{1}{8}\sum_{i=1}^{4}D_i$

where D=height (temperature) at central grid point
D_i=values at nearest surrounding grid points
$\overline{D}$=adjusted value at central grid point

Repetition of process using successively smaller scan areas as tabulated below. Result of previous scan becomes estimated analysis.

Scan no.	*Scan area (grid lengths)*	*Gross error (ft.)*	*Gross error (kt.)*	*Followed by smoothing*
		100-mb. Height and Wind		
1	4.75	700	90	None
2	3.60	600	70	Three *
3	2.20	500	70	None
4	1.80	350	60	Three *
Print-out	----------	200	40	
		100-mb. Temperature and Thermal Wind		
		(°C.)	(kt/km)	
1	4.75	20	----------	None
2	3.60	12	----------	One
3	2.20	8	----------	None
4	1.80	5	----------	One*
Print-out	----------	3		

* followed by—
removal of negative vorticity $\zeta_g > -(f/2)$

boundary smoothing $\overline{D}=\frac{1}{2}D+\frac{1}{4}\sum_{i=1}^{2}D_i$

short wave removal $\overline{D}=\frac{1}{2}D+\frac{1}{16}\sum_{i=1}^{8}D_i$

V. PRINT-OUT
List of data in gross error
Plot of coded data on grid
Estimated analysis
Final computed analysis
Difference between estimated and computed analysis

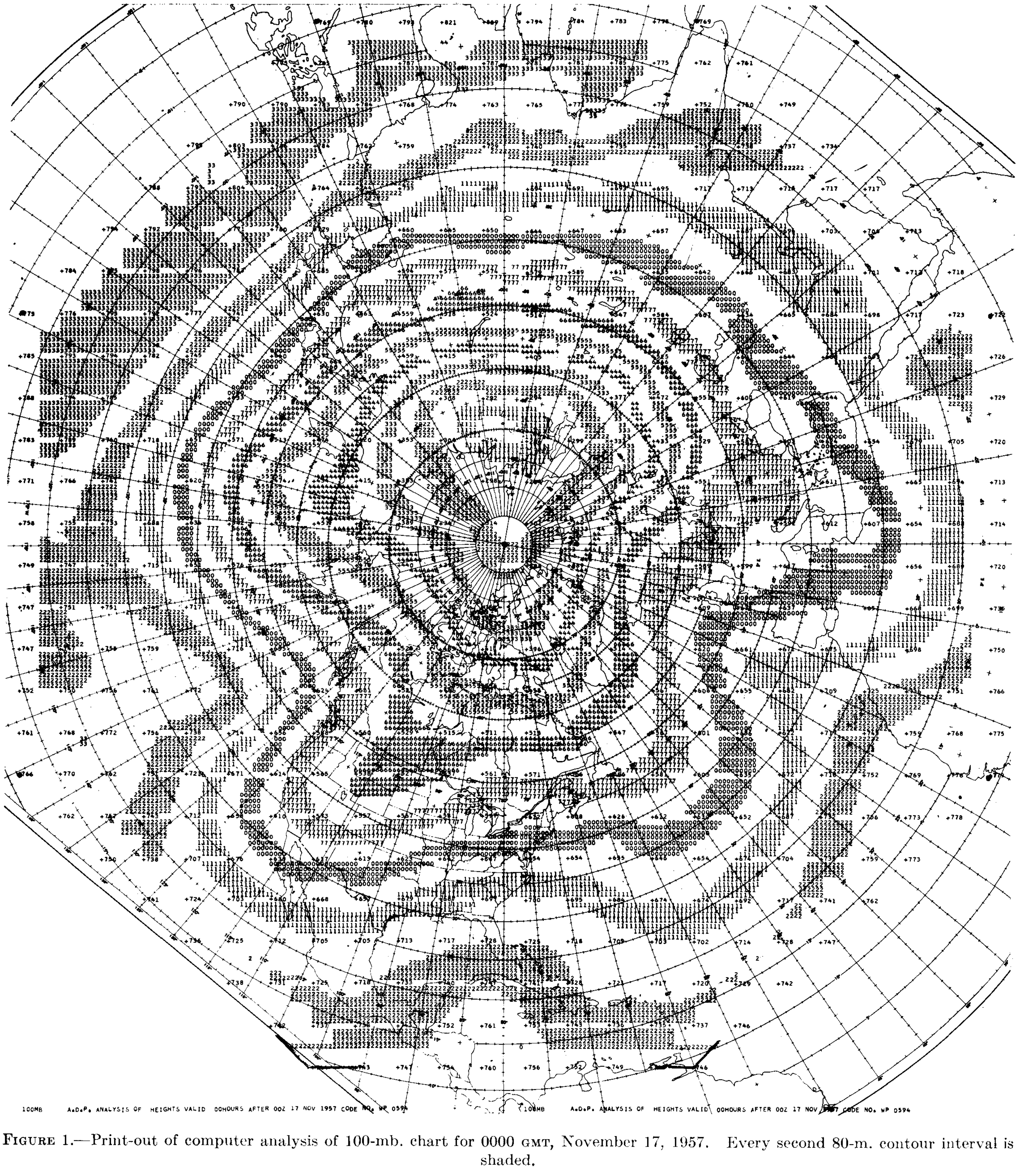

FIGURE 1.—Print-out of computer analysis of 100-mb. chart for 0000 GMT, November 17, 1957. Every second 80-m. contour interval is shaded.

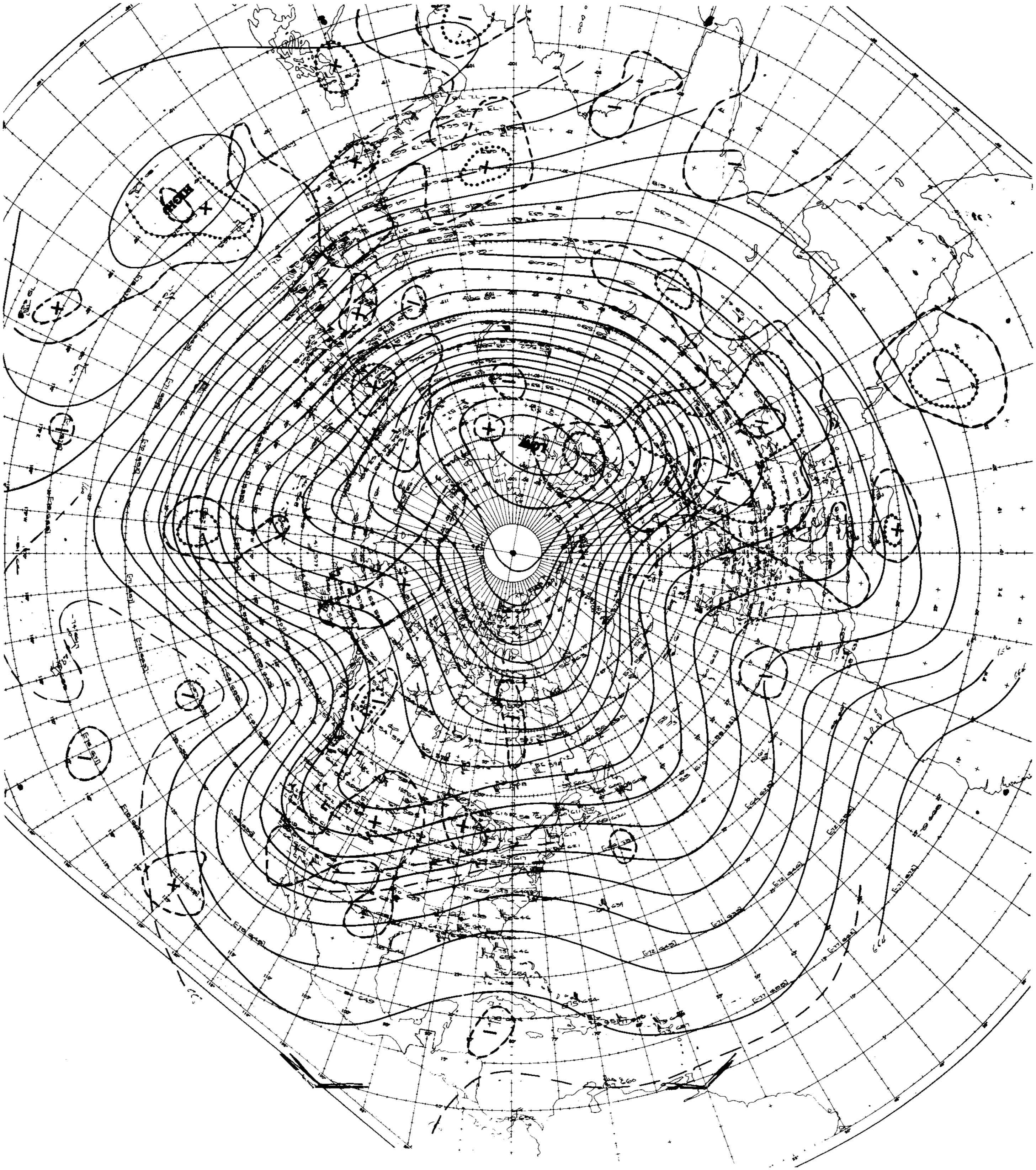

Figure 2.—Hand analysis of 100-mb. chart for 0000 gmt, November 17, 1957. Contours (solid lines) are drawn at 80-m. intervals; lines of difference between hand and computer analysis (heavy dashed lines) at 10-m. intervals are superimposed, but the line of zero difference is omitted.

REGRESSION EQUATIONS

PRIMARY PREDICTORS

H_{100}; T_{100}

SECONDARY PREDICTORS

$(H_{100})^2$; $(T_{100})^2$; $H_{100}T_{100}$; $T_{100}T_{200}$; $(T_{200})^2$; $H_{100}T_{200}$; $T_{100}-T_{200}$

$$H_{50} = A_0 + A_1 H_{100} + A_2 T_{100} + A_3 (T_{100} - T_{200})$$

$$T_{50} = A'_0 + A'_1 H_{100} + A'_2 T_{100} + A'_3 (T_{100} - T_{200})$$

AT 45 N. IN NOVEMBER

$$H_{50} = 3848 + 1.09 H_{100} + 16.7 T_{100}$$

$$T_{50} = -176.8 + .010 H_{100} + .73 T_{100}$$

WHERE:

T_{200} — TEMPERATURE AT 200 MB SURFACE

H_{100} — HEIGHT OF 100 MB SURFACE

T_{100} — TEMPERATURE AT 100-MB SURFACE

H_{50} — HEIGHT OF 50-MB SURFACE

T_{50} — TEMPERATURE AT 50-MB SURFACE

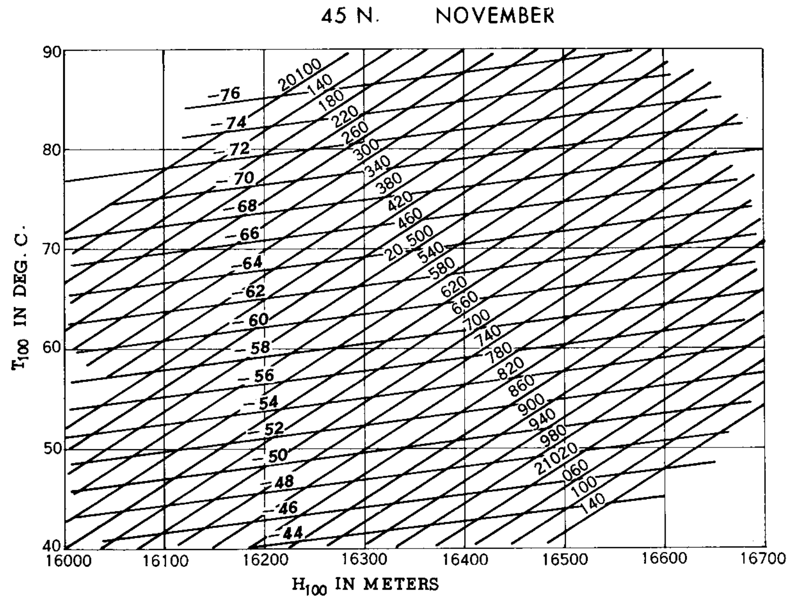

Figure 3.—Sample regression equations and graph giving 50-mb. height and temperature as functions of 100-mb. height and temperature in November at 45°N. (used for locations in the band 42.5°N. to 47.5°N.).

be adequate for use as a first guess, but the 12-hour previous analysis should prove superior provided that the 12-hour diurnal variation is removed from the data.

Synoptic information is applied to adjust the estimate to current conditions. The resulting analysis is then substituted for the first guess, and the data reapplied to this second guess, with the option of using a smaller scan area and smaller gross error criteria. Although the influence of the first guess is rapidly reduced to insignificance in areas of ample data, it aids in achieving meaningful analysis at the grid boundaries and over areas of sparse data.

The elimination of spurious diurnal variation in reported data becomes important at 100 mb. and is of increased importance at higher surfaces. Radiational temperature and height corrections for the radiosonde instruments used during the IGY have been determined by Teweles and Finger [5] and Rothenberg and Teweles [6]. It is a simple matter for monthly sets of such corrections to be incorporated into the data processing system. A necessary improvement on this procedure in actual practice is the adjustment of these correction values on a continuing basis with the aid of a program for computing monthly average 12-hour differences in reported station data.

In areas of sparse data on a constant pressure surface the system of regression equations described by Lea [7] does an adequate job of supplying reasonable values of height and temperature based on those of a surface not too far below. The analysis process at each surface allows data at distant points to influence the analysis in sparse data areas. This then provides values for use in regression equations to obtain values at the next higher surface. Thus the oceanic analysis remains stable and realistic from surface to surface.

Regression coefficients for finding stratospheric heights or temperatures at one surface from those at a lower one have been computed for several latitude belts and for each month of the year. Since a long period of record is not available for this purpose, the final computer program should include provisions for continuous adjustment of the regression coefficients from current data as in the case of the radiation corrections. Alternatively it has been suggested that the vertical extrapolation be accomplished by building up the analysis layer by layer with layer thicknesses based on the previous analysis adjusted for the available current data. This latter system has the advantage of being founded on relatively current, local conditions; its weakness lies in the difficulty of accounting for the effects of rapid movement of systems.

The wind information, brought into the analysis through the geostrophic wind equation, is a much more sensitive determinant of height gradient, i.e., contour spacing, than the height information itself. Excessive cross-contour flow continued to be apparent in the 100-mb. analyses until the weighting factor by which wind information was favored over height information was raised to 32:1 Indications are that the factor will have to be even larger, perhaps 64:1, at 50 mb.

Poor data must be eliminated at some point in the process. Cressman's data processing system makes a hydrostatic check of individual reports. In addition, as data are applied to the analysis in scan areas of decreasing size, any datum differing from the average value over the scan area by more than an arbitrarily fixed amount is withheld, but listed for further consideration by an analyst. The same criteria recommended by Cressman for casting out height and wind data in the troposphere were found

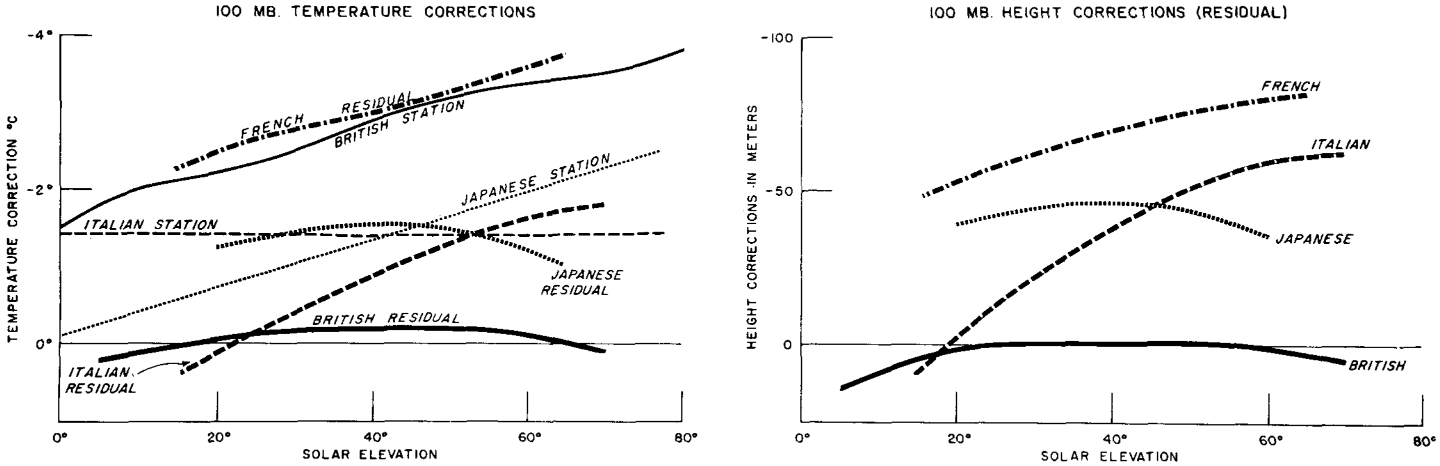

FIGURE 4.—Temperature and height corrections for use in eliminating false diurnal variation in 100-mb. data reported from several countries. The temperature correction made during evaluation of the sounding is shown by the thin lines on the left. (No on-station correction was made at French stations.) Wide lines indicate the remaining correction to be made to eliminate the day-night difference.

satisfactory for use at 100 mb. (see gross error limits in section IV of table 1).

Similar temperature criteria, also listed in the table, were determined by Snidero and Teweles [2] to adapt Cressman's scheme to 100-mb. isotherm analysis. An additional necessary step, not yet taken, is the calculation of thermal winds for use in orienting isotherms. Criteria for casting out erratic thermal winds will then have to be established.

Smoothing is applied to intermediate analyses both between the scans and as a final step of the overall analysis procedure. This artificial process removes certain kinds of unwanted small-scale roughness within the analysis and at the boundaries. In stratospheric analysis, the latter effect is particularly severe in the case of boundaries near the equator where data are sparse and the control exerted by the Coriolis force is weak. A possible solution to this problem is to extend the analysis over a larger area and then discard a peripheral strip. In this way there would be a regulatory influence from stations beyond the final boundary.

The analysis program also includes a means for modifying contour gradients to eliminate negative absolute vorticity. Ultimately, there should be other modifications, such as cognizance of the effect of air trajectory curvature upon contour gradient, filtered smoothing of the vorticity field as a means of preserving extreme values in high and low centers, and a layer-to-layer check to eliminate static instability. More sophisticated restrictions can be applied as necessary and desirable. Shuman [8] has discussed some methods and objectives of smoothing and filtering.

3. COMPARISON OF COMPUTER AND HAND ANALYSES

Charts for November 17, 1957 (figs. 1 and 2) permit a comparison of analyses made by computer and by hand. The computer print-out (fig. 1) is in the form of grid-point values with shading provided by printed digits in every second contour interval. These grid-point values were subtracted from corresponding values interpolated from the hand analysis. Isopleths of these differences are superimposed upon the contour analysis of figure 2. Positive centers show where the contour values of the hand analysis were high compared to those of the computer analysis. The areas of difference were studied as one means of determining the relative excellence of the two methods. Where the computer analysis was judged inferior, a general rule was sought which would eliminate the trouble once and for all and the computer program was changed accordingly. Most remaining differences represented inconsistencies in the hand analysis; the analyst changes his rules from map to map and even from one area of a map to another. Cures for some remaining deficiencies of the computer analysis have been mentioned earlier in this text as work yet to be done.

4. REGRESSION EQUATIONS AND TEMPERATURE CORRECTIONS

The form of regression equations employed is shown in figure 3 along with a sample nomogram made up for use in extrapolating from 100 mb. to 50 mb. in November at 45° N. Double-entry tables have also been made up for this purpose and are generally preferred in practice. The complete set of coefficients and information on their use are obtainable from the Navy Weather Research Facility and from the Weather Bureau National Weather Records Center, Asheville, N.C.

Sample curves for making corrections for radiational errors in 100-mb. radiosonde data of several countries during the IGY are shown in figure 4. This information is now being refined by the Weather Bureau Stratospheric Meteorology Research Project. The value of the solar elevation at a station is given by a chart such as figure 5.

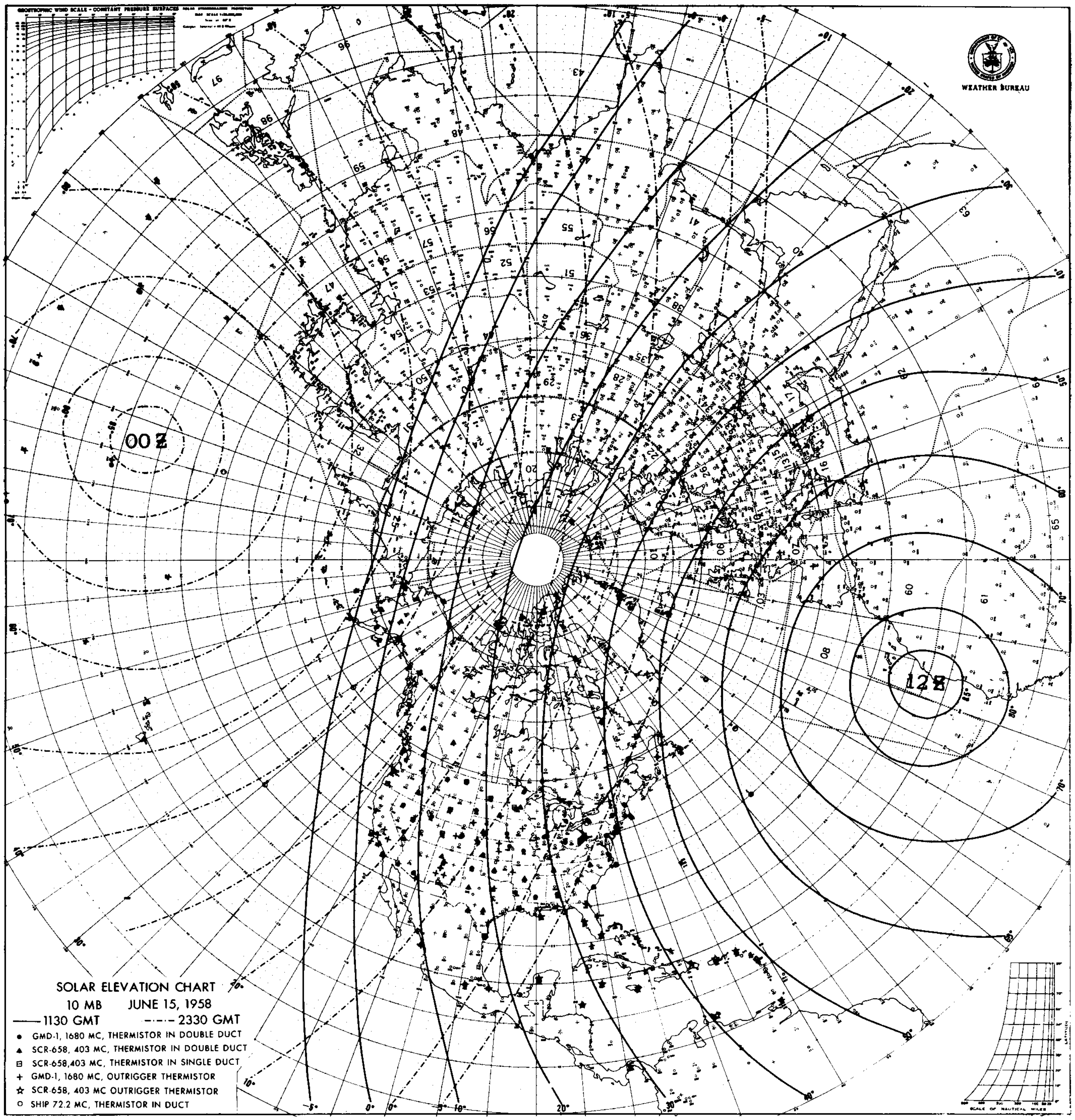

Figure 5.—Solar elevation chart for use at 10-mb. level on June 15. Station code shows type of instrument in use on that date in 1958 at stations supplied by United States services. Separate sets of isopleths are given for 0000 GMT and 1200 GMT. Balloons are assumed to be released one-half hour early and to rise about 300 m./min.

For each time of observation there is a family of isopleths of solar elevation angle. The isopleths shown are for the 15th day of June and for the time during an observation when the balloon is estimated to be at the 100-mb. surface. Simple adjustments can be made for other days of the month, other constant pressure surfaces, other times of release, or other rates of ascent of the instrument train.

The effect of solar radiation on the 10-mb. temperatures, as measured by four U.S. Air Force radiosonde stations between 30° N. and 40° N. using the externally-mounted, white-coated thermistor with the 1680-mc./sec. transmitter, is illustrated in figure 6. For each station, the seasonal average value for each observation time was subtracted from the combined average of all four observation times. The deviations for winter months and summer months are plotted according to local solar time. Superimposed on the same graph is the diurnal variation of air temperature near the 10-mb. level as calculated from radiation theory by Pressman [9] and verified more recently by calculation from diurnal wind variations by Harris, Finger, and Teweles [10].

The necessity for making radiation corrections is demonstrated by the large discrepancy between the observed and theoretical diurnal variation. Correction for the false diurnal height variation is particularly important. This variation, which is the cumulative effect of all the false temperature variation from the ground up to 10 mb. amounts to 150 m. at noon for the stations and instruments shown in figure 6. For other stations in the world the required correction ranges from zero, at stations where proper corrections have been made by the observer, to 150 m. at 100 mb. or 1500 m. at 10 mb., at stations using unshielded duct-type instruments without on-station correction procedures.

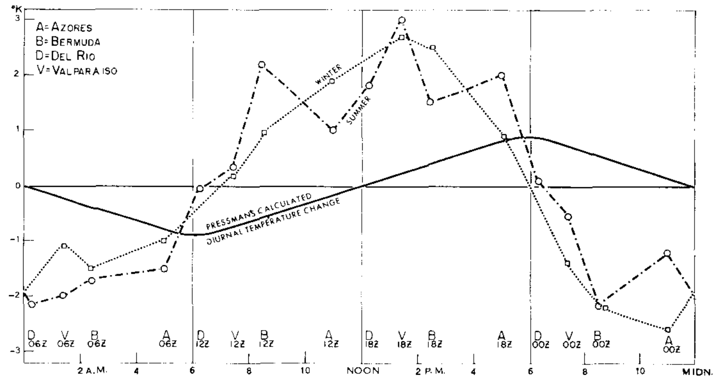

FIGURE 6.—Theoretical and observed diurnal temperature change at 10 mb. Deviations from the daily mean are plotted according to local time at each station.

5. ERRORS PRODUCED BY RADIOSONDE PRESSURE ERROR

An investigation of Russian stratospheric data by Kochanski [11] showed interesting deviations from hemispheric mean values for the season and levels studied. The matter is of such vital importance to stratospheric analysis and research that a further study of the data has been made to find whether this could be a real phenomenon or a manifestation of instrument error. Results of this study, patently based on indirect evidence, are that errors in pressure reported by the radiosonde provide a sufficient explanation for many of the reported anomalies. In July and August, the lower stratosphere in middle and high latitudes is reputed to be isothermal or else to have a slight increase of temperature with height, particularly above the 50-mb. level. In figure 7, the vertical temperature distribution at night is in accordance with this consideration. On the other hand, daytime temperatures, which incidentally are reported to greater

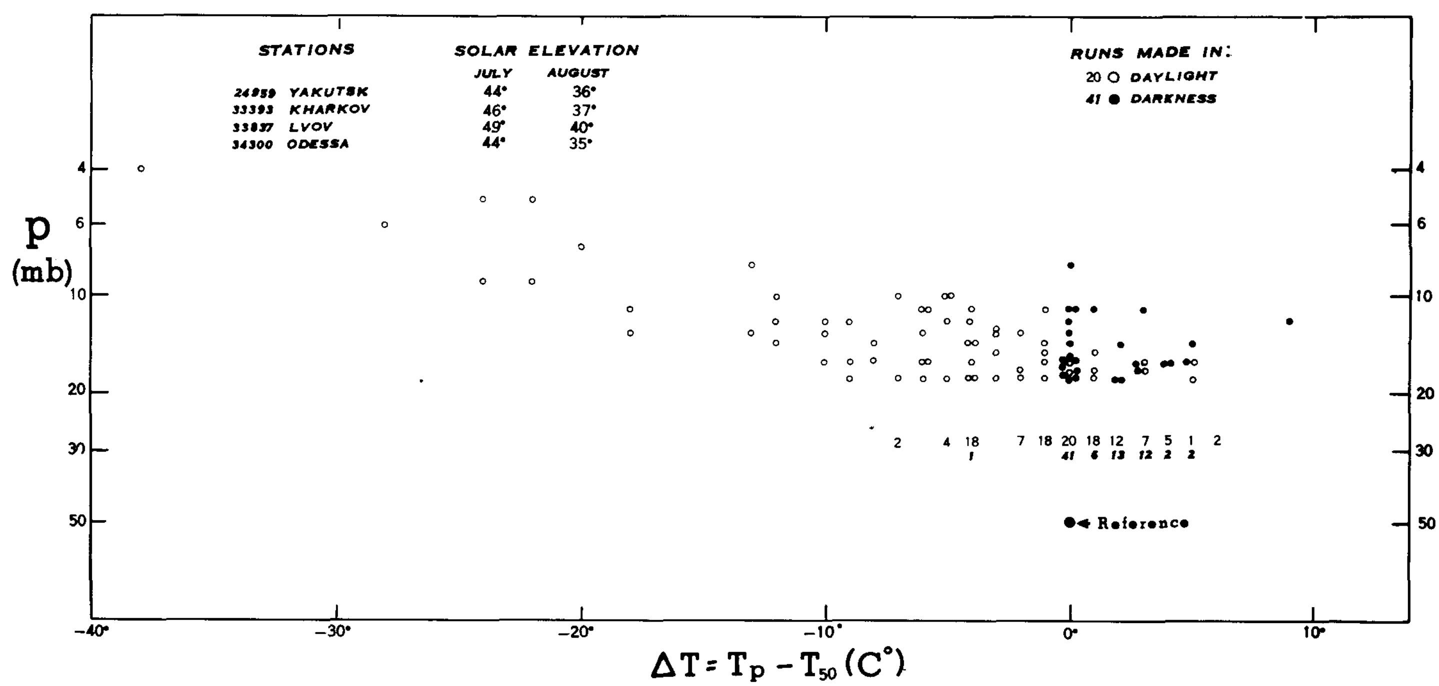

FIGURE 7.—Difference in temperature at p mb. from that at 50 mb. for runs taken in July and August 1957 at a group of Russian radiosonde stations. The 50-mb. temperature is used as a zero reference.

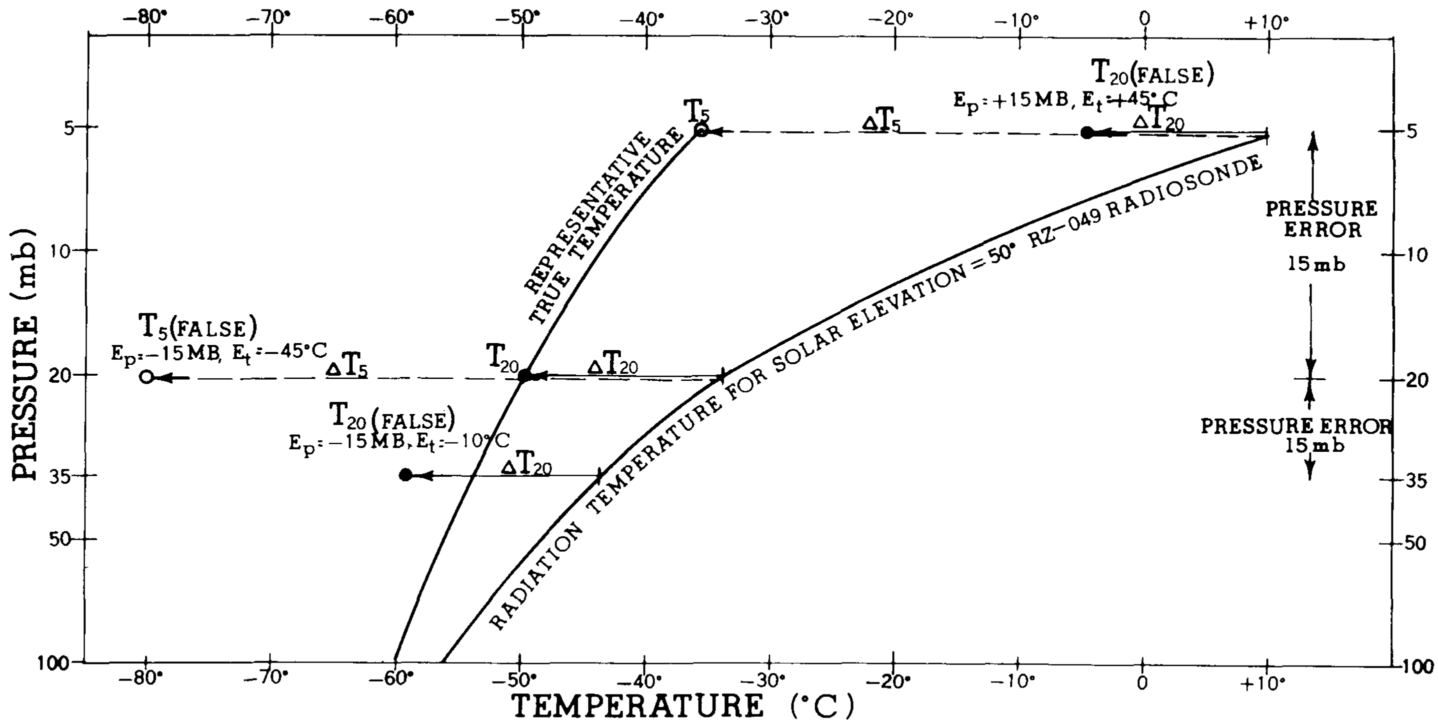

Figure 8.—Representative temperature curves for a summertime sounding in middle or high latitudes. The curve on the left is true temperature; the curve on the right is temperature reported by a radiosonde having radiation error equal to the correction applied to the RZ–049 radiosonde at solar elevation of 50°. The horizontal distance between these curves is the correction to be applied at the indicated pressure. Thus the effect of a pressure error is to cause the wrong correction to be applied and for assignment of the resulting incorrect temperature to the incorrect pressure level.

heights, tend to show a large lapse rate. No known natural effect accounts for such a diurnal change in lapse rate. However, the radiational temperature correction system could account for the change since the system is only applied in daytime and would give temperature values progressively colder than the actual temperature if the reported pressure is incorrect. Positive pressure errors would not indicate a high-reaching sounding; only negative pressure errors would do so and at the same time would result in overcorrection of the temperature (fig. 8) and thus also of the height.

If the rate of ascent of the balloon is calculated level by level from the reported pressure, a negative pressure error would also result in an error in calculating the velocity of the wind computed by following the balloon. Sample calculations (table 2) have been made for typical conditions in October, August, and July, respectively. With assumed winds of west–10.7 m./sec., calm, and east–10.0 m./sec., in the 25- to 20-mb. layer, a negative pressure error of 15 mb. would result in reported winds of W–33.3 m./sec., W–19 m./sec., and W–5.7 m./sec., respectively in the 10- to 5-mb. layer. Such excessive westerly components would tend to be reported in the same observations

Table 2.—*Wind and temperature error caused by a −15 mb. pressure error in radiosonde*

(a) Wind error

	Pressure (mb.)	Balloon Elevation Angle E	Cot E	Height H (m.)	Distance D (m.)	ΔD (m.)	$V=\frac{\Delta D}{285}$	Direction
Case I (Oct.)	20	25°	2.1445	26570	56979	3056	10.7 m.p.s.	W
	25	25°	2.1445	25145	53923		20.8 kt.	
	5	25°	2.1445	35430	75980	9502	33.3 m.p.s.	W
	10	25°	2.1445	31000	66478		64.8 kt.	
Case II (Aug.)	20	26°14′	2.0294	26570	53923	0	Calm	-------
	25	25°	2.1445	25145	53923			
	5	26°14′	2.0294	35430	71902	5424	19.0 m.p.s.	W
	10	25°	2.1445	31000	66478		36.9 kt.	
Case III (July)	20	27°29′	1.9222	26570	51073	2850	10.0 m.p.s.	E
	25	25°	2.1445	25145	53923		19.4 kt.	
	5	27°29′	1.9222	35430	68104	1626	5.7 m.p.s.	W
	10	25°	2.1445	31000	66478		11.1 kt.	

(b) Temperature error

Pressure (mb.)	True temperature (°C.)	Measured temperature (°C.)	Radiational temp. correction for RZ–049 radiosonde (°C.)	Reported temperature (°C.)	Error (°C).
20	−49.6	−34.6	−15.0	−49.6	0
25	−51.5	−38.6	−12.9	−51.5	0
5	−35.6	−34.6	−46.2	−80.8	−45.2
10	−43.6	−38.6	−29.1	−67.7	−24.1

having excessively low temperatures in unusually high radiosonde runs. It is of interest to note that if the area of low temperature were real, the wind anomalies to be expected with it would be nearly the same as those attributable to a negative pressure error. However, inspection of a series of 30-mb. charts for the summer of 1957 [12] shows no systematic relationship between anomalous winds and anomalous temperatures reported over Russia or other areas. Thus, it seems advisable that such anomalous values be discarded in the process of numerical objective analysis.

REFERENCES

1. G. P. Cressman, "An Operational Objective Analysis System," *Monthly Weather Review*, vol. 87, No. 10, Oct. 1959, pp. 367–374.
2. M. P. Snidero and S. Teweles, "Numerical Objective Analysis of Stratospheric Constant Pressure Charts," (abstract) *Bulletin of the American Meteorological Society*, vol. 40, No. 12, Dec. 1959, p. 630.
3. P. Bergthórsson and B. R. Döös, "Numerical Weather Map Analysis," *Tellus*, vol. 7, No. 3, Aug. 1955, pp. 329–340.
4. H. A. Bedient and G. P. Cressman, "An Experiment in Automatic Data Processing," *Monthly Weather Review*, vol. 85, No. 10, Oct. 1957, pp. 333–340.
5. S. Teweles and F. G. Finger, "Reduction of Diurnal Variation in the Reported Temperature and Height of Stratospheric Constant Pressure Surfaces," *Journal of Meteorology*, vol. 17, No. 2, Apr. 1960, pp. 177–194.
6. L. Rothenberg and S. Teweles, "Diurnal Variation in Stratospheric Temperatures and Pressure-Heights Reported by Other Countries," (manuscript) U.S. Weather Bureau, 1960.
7. D. A. Lea, "Regression Equations for Vertical Extrapolation of Constant-Pressure-Surface Heights and Temperatures between 200 mb. and 30 mb." (abstract) *Bulletin of the American Meteorological Society*, vol 42, No. 2, Feb. 1961, p. 131.
8. F. G. Shuman, "Numerical Methods in Weather Prediction: II. Smoothing and Filtering," *Monthly Weather Review*, vol. 85, No. 11, Nov. 1957, pp. 357–361.
9. J. Pressman, "Diurnal Temperature Variations in the Middle Atmosphere," *Bulletin of the American Meteorological Society*, vol. 36, No. 5, May 1955, pp. 220–223.
10. M. F. Harris, F. G. Finger, and S. Teweles, "Diurnal Variation of Wind, Pressure, and Temperature in the Troposphere and Stratosphere Over the Azores," (abstract) *Bulletin of the American Meteorological Society*, vol. 42, No. 3, Mar. 1961, p. 205. (To be published in *Journal of the Atmospheric Sciences*, 1962.)
11. A. Kochanski, "Temperatures and Winds at 25–35 KM. Over Russia in July 1957," Air Weather Service, Climatic Center TM–59–1, Jan. 1959, 30 pp.
12. U.S. Weather Bureau, *Daily 100-Millibar and 50-Millibar and Three Times Monthly 30-Millibar Synoptic Weather Maps of the IGY Period*, July, August, and September 1957, Washington, D.C., 1960.