

# A METHOD FOR OBJECTIVE ANALYSIS OF STRATOSPHERIC CONSTANT-PRESSURE CHARTS

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## ABSTRACT

A method of numerical objective analysis has been developed for application to stratospheric constant-pressure data at the 100-, 50-, 30-, and 10-mb. levels (approximately 16, 20, 24, and 31 km., respectively). This system evolved from successive modifications of the programs employed for operational objective analysis of lower-level charts at the National Meteorological Center. For use with stratospheric data, the Automatic Data Processing portion of these programs was expanded to correct for the errors in high-level rawinsonde temperatures and heights caused by short- and long-wave radiational effects on the temperature sensor. In addition, procedures for vertical extrapolation of rawinsonde reports and merging of off-time data were incorporated to compensate for the scarcity of reports at a given observation time.

General degradation of stratospheric data with increasing height necessitated more stringent data rejection criteria within the entire system. It was also essential that increased emphasis be placed on wind observations as an analysis parameter. The resulting charts have shown that the objective system employed produces analyses of acceptable quality. Improvements are continually being developed and incorporated to increase the efficacy and objectivity of the procedures and the quality and usefulness of the product.

The main purposes of the computerized system are to provide good quality stratospheric analyses for anticipated operational requirements and to satisfy the needs of research. Daily analysis of Northern Hemisphere charts is being performed during the IQSY and is expected to continue after the end of the period. These maps are recorded for distribution on microfilm and also on punched-card decks containing grid-point data.

## 1. INTRODUCTION

The requirements for daily analysis of stratospheric data have increased with the advent of the International Years of the Quiet Sun (IQSY). Programs such as the WMO-IQSY STRATWARM Alerting System [16, 17] demand expeditious preparation of high-level constant-pressure analyses for effective execution. In addition, analyses of sufficiently high quality may be utilized in important research on the dynamics and climatology of the stratosphere. Objective computer analysis with output consisting of constant-pressure charts, drawn mechanically, and grid-point data contained on punched cards or magnetic tape, is one means of satisfying these requirements.

Prior to the commencement of the IQSY, plans were formulated within the U.S. Weather Bureau to develop a computer system for objective analysis of the 100-, 50-, 30-, and 10-mb. surfaces. A cooperative effort was undertaken by the Atmospheric Analysis Laboratory of the Office of Meteorological Research and the Computation Division of the National Meteorological Center with the goal of producing the chart series on a daily operational basis. The development of the system

complements the experience gained by other groups [12, 15] in the processing of stratospheric data by computer methods.

A pilot study [20] carried out for the 100- and 50-mb. surfaces has illustrated the difficulties encountered in subjecting stratospheric data to the computerized analysis techniques used for lower-level charts. In general, the sparseness and inconsistencies of high-level observations necessitate extensive modifications to the Automatic Data Processing (ADP) system originally developed by Bedient and Cressman [2]. In addition, Cressman's [4] adaptation of the Bergthórsson-Döös [3] analysis scheme must be altered. For the levels involved, it was found that the most essential changes are (1) increased weighting of wind observations with respect to those of isobaric height, (2) correction of reported heights and temperatures to compensate for effects of solar radiation on radiosonde temperature sensors, and (3) use of regression equations to build up the analysis from one level to the next.

Above the 50-mb. level, the degradation of reported information with increasing height and the sparseness of observations can frequently preclude a justifiable analysis for any individual observation time. While transmission errors and premature termination of many rawinsonde ascents account for much of the reduction in high-level information, some is also lost because of a predetermined cutoff time for acceptance of reports from communication

<sup>1</sup> A number of additional Weather Bureau personnel participated in the development of the analysis system. Included were G. P. Cressman, S. Teweles, M. P. Snidero, S. Herman, A. R. Kneer, J. E. McDonell, G. V. Costello, G. S. Doore, R. G. Schnurr, R. E. Thompson, R. M. McInturff, and W. P. Townshend.

circuits supplying the computer. The scheduling of operations prohibits the input of data beyond 8 hours after observation time. A varying percentage of second transmissions, which include all of the rawinsonde reports for levels above 100 mb., is received after this cutoff time, and is thus not available for processing.

In previous stratospheric analysis efforts [13, 21, 22] sparsity of data has been surmounted by application of procedures for vertical extrapolation of temperature and height, use of nearby lower-level winds, and where necessary, the incorporation of data for more than one observation time. These procedures, as well as those mentioned previously, have been introduced into the present computer operations. The purpose of this paper is to describe the system. While the overall performance of the system is adequate, many of its components can be refined. Therefore, brief comments on possible improvements will also be included.

## 2. AUTOMATIC DATA PROCESSING

The ADP system, as originally developed for the lower levels, identifies upper-air data among incoming teletypewriter reports and prepares the pertinent information for analysis. By means of a "dictionary," the system provides for the recognition of upper-air stations, their geographical locations, and types of radiosonde instruments they employ. Another major function is the detection and interpretation of the various meteorological codes. (See [2] for complete details.) In addition, all decoded data are checked for accuracy and consistency. The decoding and checking procedures were altered, as necessary, for application to stratospheric observations. Furthermore, the ADP system was expanded to include provisions for vertical extrapolation, application of radiation corrections, and the merging of off-time data.

### DATA INPUT

Figure 1 illustrates the generalized flow of stratospheric data through the ADP system subsequent to identification and decoding. The blocks at the top represent information for three times: the 1200 GMT, or map time, observations and the 0000 GMT reports immediately previous and subsequent to map time. Data for each observation time are collected for a period of 8 hours and subjected to the various procedures shown in the lower blocks.

As will be brought out in later sections, the charts for 50, 30, and 10 mb. are analyzed primarily for the 1200 GMT observations, with the off-time reports utilized to increase coverage. At the 100-mb. level, data are sufficiently dense so that only 1200 GMT on-level reports are employed. Since circulation changes at the upper levels progress quite slowly, the merging of off-time data appears to be a legitimate procedure [11]. This method has the disadvantage of delaying analysis by 12 hr. However, the resulting superior accuracy of the product is highly desirable for research applications.

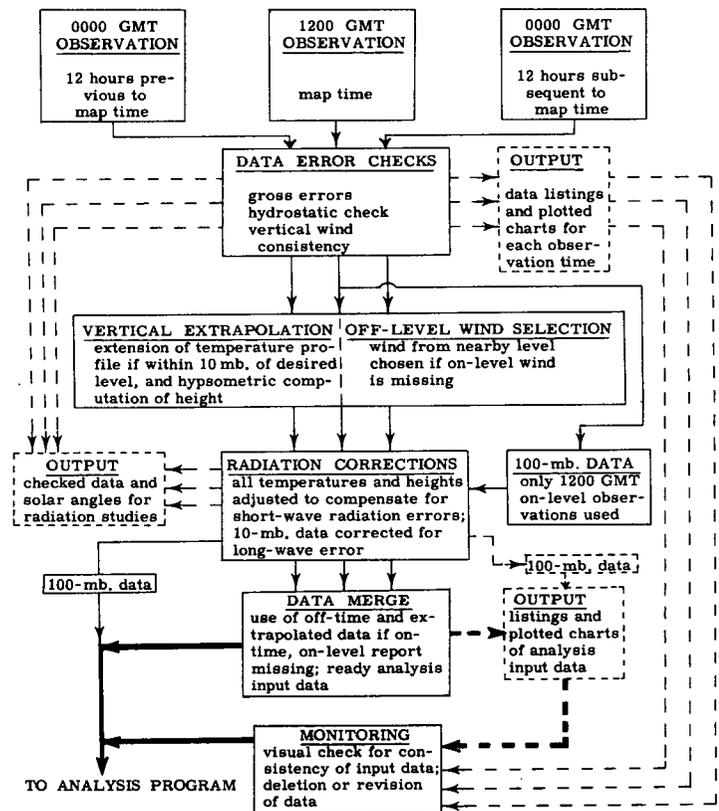


FIGURE 1.—Flow diagram of automatic data processing (ADP) system.

### DATA ERROR CHECKS

In order to obtain optimum results from the entire operation, erroneous reports must be eliminated at the earliest possible stage of data processing. Therefore, three distinct data checks are applied to rawinsonde observations within the ADP program.

(1) *Gross error check.*—This procedure is designed to discard all reported temperatures and heights which violate the predetermined limits for each level (table 1), with the assumption that such data cannot be salvaged in any manner. It can be seen that the limits vary with season and altitude. Daily operations have demonstrated the need for further refinements within this check. The limits presently employed vary only with season and altitude. However, in summer at the higher levels, the acceptable ranges for reported heights and temperatures could be narrowed by being made a function of latitude as well. During that season, the Northern Hemisphere is dominated by a warm and nearly circumpolar anticyclone, with weak horizontal gradients of height and temperature. Variation with latitude could also be included during winter if the general range of acceptance were adjusted to conform with the prevailing circulation pattern.

(2) *Hydrostatic check.*—Mandatory levels of all sound-

TABLE 1.—Temperature and height rejection limits for gross error check

Pressure level (mb.)	Season	Temperature range (° C.)	Height range (km.)
100.....	summer.....	-35 to -86.....	15.0 to 17.0
	winter.....	-35 to -95.....	14.5 to 17.5
70.....	summer.....	-30 to -81.....	17.0 to 19.3
	winter.....	-30 to -95.....	16.8 to 19.6
50.....	summer.....	-30 to -78.....	19.5 to 21.5
	winter.....	-25 to -95.....	18.4 to 21.6
30.....	summer.....	-25 to -71.....	23.0 to 25.0
	winter.....	-15 to -95.....	21.3 to 25.0
20.....	summer.....	-25 to -65.....	25.0 to 27.7
	winter.....	-10 to -95.....	23.5 to 28.0
10.....	summer.....	-25 to -60.....	30.0 to 32.5
	winter.....	+05 to -95.....	27.6 to 32.5

ings are tested for vertical consistency between heights and temperatures for adjacent levels [5]. The process is initiated by hypsometric determination of a height  $H_C$ , performed with the aid of a linear profile between the reported temperatures at the top, or test level, and the base of the layer being considered. The maximum difference ( $E_{max}$ ) that is tolerated between any given  $H_C$  and reported height was derived empirically as a function of the standard thickness between mandatory levels. For the layers 100-70, 70-50, 50-30, 30-20 and 20-10 mb., the values of  $E_{max}$  are respectively 35, 35, 50, 40, and 65 m. These constants correspond to a tolerance of approximately 3.5° C. between the actual and assumed mean temperatures. A reported height that differs from  $H_C$  by more than  $E_{max}$  is eliminated and replaced with  $H_C$ .

An obvious limitation of the present scheme is the use of only mandatory-level temperatures in the calculation of  $H_C$ . A desirable further refinement would be the inclusion of all available significant-level temperatures in the determination of this parameter.

(3) *Vertical wind check.*—Continuity of the wind profile is preserved by eliminating reported winds that differ from those at nearby levels by more than a predetermined value. Rawins, when available, are merged with mandatory-level winds to produce as complete a profile as possible. Empirically derived limits for vertical wind shears within stratospheric layers are shown in table 2. As an example of the procedure, if the speed of a wind at a given level is between 21 and 60 kt., it is eliminated if it differs from the closest winds in a 600-m. layer by more than 20° in direction or 20 kt. in speed. The tolerance increases with the distance between the tested wind and the nearest comparison wind.

It would be desirable to increase the limits of acceptable shear in the highest layers at stations south of 15° N. Considerable wind variability and large vertical shears have been noted within the layer surrounding 10 mb. over this region.

CHECKED DATA OUTPUT

Subsequent to the checking of reported data, stations are sorted in ascending order of international index number and ships are sorted by ascending latitude. Intermediate results from the ADP system, consisting of

TABLE 2.—Vertical shear limits for wind check

Layer Thickness (meters)	Tested Wind (knots)					
	0-20		21-60		Over 60	
	dd	ff	dd	ff	dd	ff
600.....	none	15	20	20	20	25
1500.....	none	20	30	30	20	40
3000.....	none	30	40	40	30	50
4500.....	none	35	40	45	30	55
6000.....	none	40	50	50	30	60

checked data, are then printed out in station listings and also in the form of plotted charts. The mechanically plotted chart shown in figure 2 indicates the areal coverage of 10-mb. data actually observed at 1200 GMT on February 16, 1965. An example of the format employed for intermediate data output is shown as a composite of three observation times in figure 3a.

VERTICAL EXTRAPOLATION OF TEMPERATURE AND HEIGHT

Present-day radiosonde ascents frequently terminate slightly below the 50-, 30-, or 10-mb. levels. In many such cases, vertical extrapolation procedures may be applied to estimate on-level temperatures and heights. Therefore, the following criteria are employed to extend the checked temperature profiles to the next higher levels:

a. If the last two reported levels (mandatory and/or significant) within a sounding differ by more than 3 mb. and the terminating level is within 10 mb. of the desired pressure surface, the on-level temperature is obtained by linear extrapolation from the last two reported temperatures.

b. If the last two reported levels differ by 3 mb. or less and the terminating level is within 10 mb. of the desired pressure surface, the extrapolated temperature is obtained by use of an empirically determined constant inversion rate (0.8° C./mb. in summer and 0.4° C./mb. in winter) between the terminating level and the analysis level. This alternative was devised because the linear method (a) may produce erratic values of extrapolated temperature when applied to a thin layer.

c. If the sounding terminates at 20 mb., the 10-mb. temperature is extrapolated by use of the constant inversion rate described in (b).

Following the establishment of an extended temperature profile by means of one of the extrapolation methods, an on-level height is computed by use of the hypsometric relation. Examination of output data has shown that extrapolated temperatures and heights obtained in this manner are, in most cases, compatible with on-level observations from surrounding stations. Erratic values are usually eliminated by the data quality controls within the analysis program.

SELECTION OF OFF-LEVEL WINDS

If mandatory-level winds are missing, reports from nearby stratospheric levels may generally be substituted

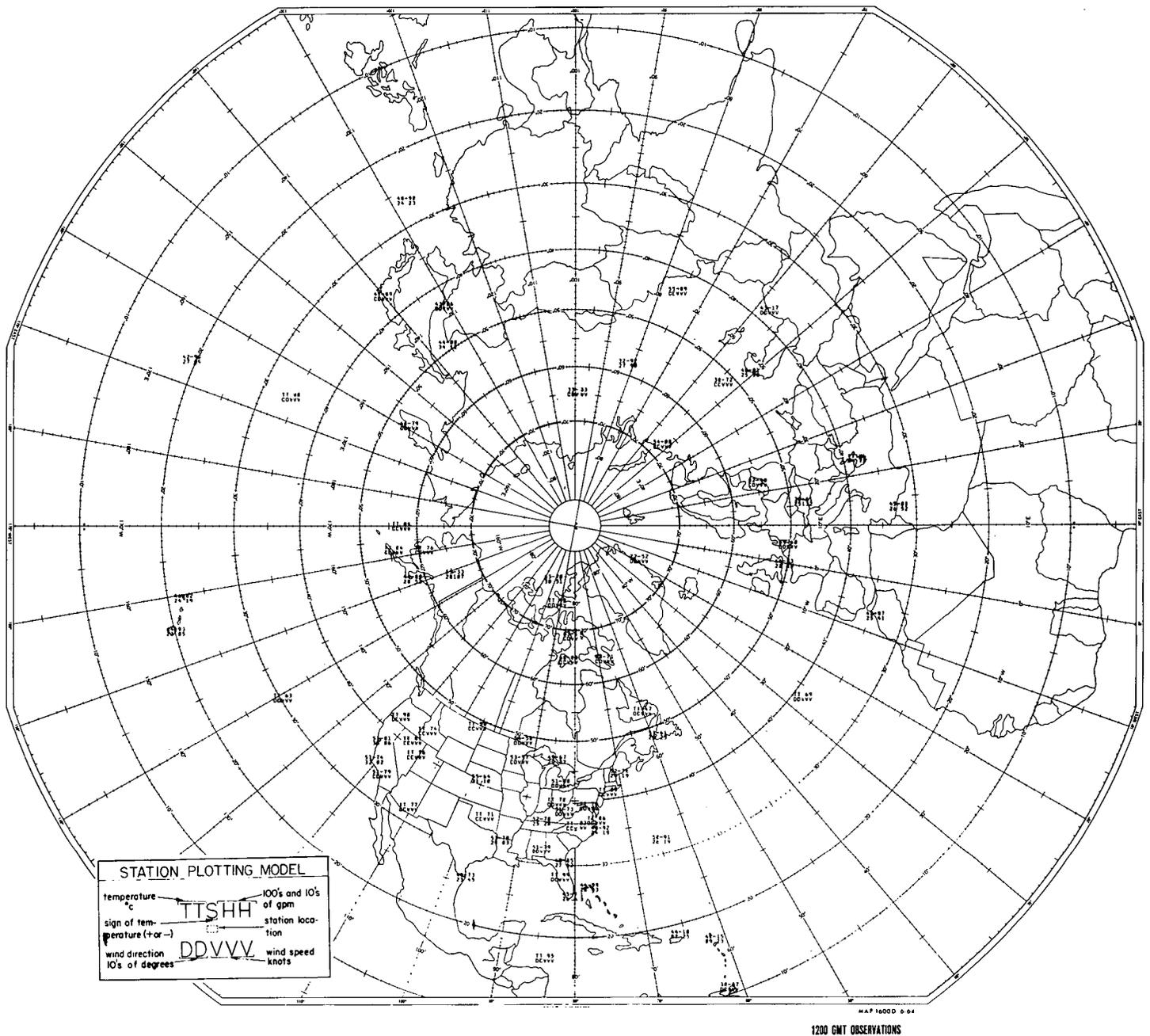


FIGURE 2.—Computer-plotted chart of checked 10-mb. data for 1200 GMT February 16, 1965. Station plotting model is shown on inset.

without significant sacrifice in reliability. Therefore, in order to obtain maximum wind information, all available rawins are utilized. The following selections are made to compensate for missing wind data at 50 mb. and above:

a. At 50 and 30 mb., the nearest wind to the desired level within a range of approximately 1500 m. above and 3000 m. below.

b. At 10 mb. the acceptable range is from 1500 m. above to 4300 m. below.

In areas where systems slope markedly with height or where strong vertical shears frequently occur, results

from this procedure are far from ideal. A more complex system, with the ranges of acceptance based on season, latitude, and circulation pattern could be developed.

#### RADIATION CORRECTIONS

(1) *Short-wave (solar) radiation correction.*—The necessity for applying solar-radiation corrections to reported stratospheric temperatures and heights at 100 mb. and above to attain compatibility has been indicated previously [19]. It was shown that these corrections, which essentially reduce all reported values to the equivalent of

DATA LISTING FOR 0+00 HRS AFTER 00 TIME.

NLINE IDENT	TIME	1000 - 300 - 070				850 - 250 - 050				700 - 200 - 030				500 - 150 - 020				400 - 100 - 010			
		HT	TEMP	DP	WIND	HT	TEMP	DP	WIND	HT	TEMP	DP	WIND	HT	TEMP	DP	WIND	HT	TEMP	DP	WIND
(a) 72926	23	55	-37	-47	30/078	1195	-30	-35	30/019	2582	-42	-37	30/023	491	-44	**	29/032	638	-52	**	28/037
16 FEB	300	822	-36	**	29/041	438	-55	**	29/031	1081	-54	**	29/038	1266	-55	**	30/042	1525	-53	**	30/060
0000GMT	070	1750	-54	**	30/061	1571	-53	**	**	2302	-54	**	**	**	**	**	**	**	**	**	**
SIGNIFICANT TEMP ** ** ** 315 -57 ** 59 -55 ** 45 -52 ** 26 -54 **																					
TROPOPAUSE DATA P 315 H 259 T -57 TD *** S 3 Z * WD **/****																					
72926	11	-6N	**	**	27/150	1125	-30	-34	30/025	2536	-32	-36	30/031	483	-45	**	30/032	638	-51	**	30/043
16 FEB	300	814	-56	**	30/029	630	-55	**	29/036	1074	-53	**	29/036	1259	-55	**	29/052	1519	-55	**	29/053
1200GMT	070	1750	-53	**	30/076	1567	-54	**	**	**	**	**	**	**	**	**	**	**	**	**	**
SIGNIFICANT TEMP 998 -40 ** 981 -38 -46 962 -37 -44 914 -38 -44 896 -33 -39 863 -30 -34																					
TROPOPAUSE DATA P 279 H 288 T -58 TD *** S 3 Z * WD **/****																					
WINDS ALOFT 600N 29/081 610N 29/083 612N 29/083																					
72926	23	70	-39	-49	30/000	1210	-28	-33	30/023	2591	-33	-38	30/027	490	-46	**	20/035	635	-54	**	28/040
17 FEB	300	819	-56	**	29/062	936	-53	**	29/055	1080	-53	**	**	1265	-53	**	**	1526	-54	**	**
0000GMT	070	1757	-51	**	**	1975	-53	**	**	2301	-58	**	**	2558	-56	**	**	**	**	**	**
SIGNIFICANT TEMP 1029 -39 -49 970 -39 -45 928 -35 -41 896 -30 -35 312 -57 ** 67 -50 **																					
TROPOPAUSE DATA P 312 H 259 T -57 TD *** S 3 Z * WD **/**** P 057 H 948 T -54 TD *** S 3 Z * WD **/****																					
WINDS ALCFT 10P 30/019 20P 30/019 30 30/021 40 30/023 50 30/025 60 29/027																					
70 29/029 80 30/027 90 30/027 100 30/031 120 29/034 140 28/035 160 28/035																					
180 28/055 200 28/043 230 28/041 250 28/048 270 29/062 300 29/054 330 29/063																					
334 29/063																					
(b) 72926	11	MSG	MSG	MSG	MSG	MSG	MSG	MSG	MSG	MSG	MSG	MSG	MSG	MSG	MSG	MSG	MSG	1519	-55	MSG	29/053
16 FEB	300	1750	-53	MSG	30/076	1967	-54	MSG	29/083	2301	-56	MSG	MSG	2558	-56	MSG	MSG	3003	-52	MSG	MSG
1200GMT	070	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**	**

FIGURE 3.—Portions of listings containing data employed for the 1200 GMT analyses on February 16, 1965. The station shown is Baker Lake, N.W.T., Canada (72926), with (a) checked data for the three observations centered on map time. Mandatory-level rawinsonde reports with level identification are displayed at the beginning of each checked-data message, followed by significant levels, tropopause, and winds-aloft data. Each mandatory-level group contains height, in geopotential meters up to 700 mb. and decameters above that level; temperature and dewpoint in °C.; and wind with direction in 10's of degrees and speed in knots. (b) Merged analysis input data for map time; this latter listing contains merged data for 100, 70, 50, 30, 20, and 10 mb.

nighttime observations, are a function of level and solar elevation angle. The procedure is initiated with the calculation of a solar elevation angle for the time at which the balloon passes through each mandatory level at 100 mb. and above. This angle  $\alpha$  is found from the formula:

$$\sin \alpha = \sin \phi \sin \delta + \cos \phi \cos \delta \cos h \quad (1)$$

where  $\phi$  is station latitude,  $\delta$  is solar declination angle, and  $h$  is solar hour angle. The angle  $\delta$  is obtained by<sup>2</sup>

$$\sin \delta = (\sin 23^\circ 26' 37.8'') \sin \sigma \quad (2)$$

where  $\sigma$  is in degrees and is given by

$$\sigma = 279.9348 + d' + 1.014827 \sin d' - 0.07925 \cos d' + 0.019938 \sin 2d' - 0.0162 \cos 2d';$$

$d'$  is the number of the day in the year minus one, multiplied by the constant 0.98565; e.g., for January 30,  $d' = 29(0.98565)$ . The solar hour angle  $h$ , the angular distance of the sun from the observation point, can be expressed in terms of time of observation and longitude relative to Greenwich. The relation takes the form

$$h(\text{deg.}) = 15(e + c + H + 36) - L \quad (3)$$

<sup>2</sup> Relations involving  $\delta$  and  $\sigma$  were derived from information provided by the U.S. Naval Observatory, Washington, D.C.

where  $e$ , the equation of time in hours, is given by  $e = -0.03 \sin t - 0.12 \cos t + 0.165 \sin 2t - 0.0008 \cos 2t$ ;  $t(\text{deg.}) = (360/365.242)(D - D_0)$ , with  $D$  representing the number of the day in the year and  $D_0$  the day of the vernal equinox ( $= 80$ );  $c$  is a function, in hours, of the difference between actual radiosonde release time and nominal observation time, and also of balloon ascension rate (table 3);  $H$  is nominal observation time, expressed as the number of hours after 0000 GMT;  $L$  is longitude of station in degrees and tenths, measured westward from  $0^\circ$  at Greenwich to  $359.9^\circ$ .

Since station latitude and longitude are known, and solar declination angle and equation of time can be

TABLE 3.—Corrections to solar hour angle as a function of balloon release time and arrival time at a specified level. These corrections are based on an ascent rate of 305 m./min.

Pressure (mb.)	Standard height (m.)	C <sub>12,00</sub> (hr.)	C <sub>11,23</sub> (hr.)
100-----	16180	0.551	0.134
70-----	18442	0.675	0.258
50-----	20576	0.791	0.374
30-----	23849	0.970	0.553
20-----	26481	1.114	0.697
10-----	31055	1.364	0.947

C<sub>12,00</sub>=corrections for stations reporting observation times of 1200 and 0000 GMT; representative release times are 1140 and 2340 GMT.  
C<sub>11,23</sub>=corrections for stations reporting observation times of 1100 and 2300 GMT; representative release times are 1115 and 2315 GMT.

determined with high precision, the only source of uncertainty in the calculation of solar elevation angle is the time of radiosonde arrival at each mandatory level. As no indication of this parameter is given in the coded rawinsonde message, an approximate release time and ascent rate must be assumed. From an inspection of individual station records, "normal" release times, to the nearest quarter hour, and typical rates of ascent have been determined for North American stations. However, since these records are not available for most of the remaining stations in the Northern Hemisphere, a release time of 20 min. prior to nominal observation time is utilized.

The solar radiation corrections programed for the computer (table 4) are based on information contained in several studies [6, 18, 19, 23]. In most cases, the effects of solar radiation on the radiosonde instrument are not satisfactorily eliminated even though various correction

schemes have been applied at the stations. In the case of the French Metox instrument, temperature and height values must be reduced by as much as 15°C. and 700 m. at the highest levels and solar elevation angles. In contrast, data reported by the British, Portuguese, and West German instruments require no additional corrections at the levels involved. Examination of input data has indicated that radiosonde instruments of the U.S.S.R. are affected by solar radiation in much the same manner as the external-thermistor U.S. Weather Bureau type; therefore a similar correction is applied.

For computer operations the temperature corrections at all levels for each instrument type are represented in tabular form. Selection of the proper correction requires identification, within the ADP dictionary, of instruments used at all Northern Hemisphere stations. However, the only height corrections stored in the computer are those for the 100-mb. level. The remaining values are

TABLE 4.—Solar radiation corrections for various radiosonde instruments as a function of pressure level and solar elevation angle. Values are added algebraically to reported temperatures and heights.

Instrument type	Level	Solar Elevation										$\Delta T$ (°C.) $\Delta H$ (m.)	
		0°	10°	20°	30°	40°	50°	60°	70°	80°	90°		
U.S.W.B. (external thermistor)	100	-0.3	-0.5	-0.7	-0.8	-0.9	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	
	50	-10	-20	-25	-30	-35	-40	-40	-40	-40	-40		
	30	-18	-34	-43	-50	-57	-63	-64	-64	-64	-64		
	10	-28	-51	-64	-73	-80	-87	-88	-88	-88	-88		
U.S. Military (external thermistor)	100	-0.1	-0.3	-0.5	-0.6	-0.8	-1.0	-1.0	-1.0	-1.0	-1.0		
	50	-2	-8	-18	-25	-38	-48	-55	-56	-56	-56		
	30	-3	-7	-11	-14	-16	-17	-18	-16	-15	-15		
	10	-6	-17	-32	-43	-58	-70	-81	-80	-78	-78		
Finnish (Väisälä)	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
	50	-12	-30	-47	-56	-62	-64	-65	-65	-65	-65		
	30	-12	-30	-47	-56	-62	-64	-65	-65	-65	-65		
	10	-12	-30	-47	-56	-62	-64	-65	-65	-65	-65		
French (Metox)	100	-0.6	-1.8	-2.1	-2.4	-2.7	-3.0	-3.4	-3.7	-3.9	-4.1		
	50	-20	-40	-50	-60	-70	-80	-90	-100	-100	-100		
	30	-43	-85	-104	-124	-143	-161	-181	-197	-211	-229		
	10	-83	-141	-172	-202	-230	-257	-286	-309	-328	-351		
Japanese (Code sending)	100	0.0	-1.5	-1.9	-2.0	-1.9	-1.8	-1.5	-1.2	-1.2	-1.0		
	50	0.0	-2.8	-3.0	-3.0	-2.7	-2.4	-2.0	-1.5	-1.4	-1.3		
	30	0.0	-3.4	-3.7	-3.5	-3.2	-2.6	-2.1	-1.6	-1.5	-1.4		
	10	0.0	-5.1	-5.7	-5.0	-3.8	-2.1	-0.5	+1.1	+1.2	+1.3		
East German (Freiberg)	100	-0.8	-2.0	-2.7	-3.1	-3.4	-3.6	-3.7	-3.8	-3.6	-3.5		
	50	-10	-35	-60	-75	-75	-75	-75	-75	-75	-75		
	30	-28	-80	-121	-146	-155	-160	-163	-166	-157	-153		
	10	-45	-122	-180	-212	-232	-242	-247	-254	-242	-232		
Pakistani (U.S.W.B. duct type)	100	-0.3	-0.7	-1.0	-1.2	-1.6	-1.9	-2.2	-2.5	-2.5	-2.4		
	50	-10	-15	-30	-40	-50	-55	-55	-50	-30	-10		
	30	-1.2	-2.7	-3.8	-4.8	-5.6	-6.1	-5.8	-4.7	-3.4	-3.1		
	10	-2.8	-5.6	-7.8	-9.5	-10.4	-11.0	-11.3	-11.4	-11.5	-11.4		

computed from level to level by means of the hypsometric relation

$$\Delta H_2 = \Delta H_1 + 14.6 (\ln[p_1/p_2]) \cdot (\Delta T_1 + \Delta T_2) \quad (4)$$

where  $\Delta H_1$  and  $\Delta T_1$  represent the height (meters) and temperature ( $^{\circ}\text{C}.$ ) corrections at the lower level, and  $\Delta H_2$  and  $\Delta T_2$  those at the upper level;  $p_1$  and  $p_2$  are the pressures at the lower and upper levels respectively.

(2) *Output for radiation correction studies.*—The application of solar radiation corrections is of such vital importance to successful stratospheric analysis that a continuing study of the subject is being undertaken. As shown previously, various types of instruments are employed throughout the Northern Hemisphere, many requiring correction. In addition, more than one known type may be used at an individual station, and newly developed instruments have been put into service without notice. Until the International Radiosonde Code can be altered to specify the type of instrument in use for each station observation, indirect methods must be employed in an attempt to deal with the problem. Output in the form of checked temperatures and heights, coupled with the appropriate solar elevation angles, is obtained from each ADP operation.

Monthly mean day-night differences are computed for all stations and compared with those derived from previous studies [6, 18, 19]. If the magnitudes of the differences for given solar angles compare favorably, it is concluded that the instrument type has not been changed. In cases where the magnitudes differ significantly, an attempt is made to determine the cause of the discrepancy. Correction tables may be modified or replaced as a result of such investigations. Unfortunately, with this procedure, the time lag between an instrument change and its discovery is considerable.

(3) *Long-wave radiation correction.*—As mentioned previously the correction of temperatures and heights to compensate for solar radiation errors of the radiosonde instrument reduces all values to the equivalent of observations in darkness. However, a recent theoretical investigation [1] has indicated that, within the range of normally expected 10-mb. temperatures and in the absence of solar radiation, the U.S. military-type radiosonde thermistor records  $1^{\circ}$ – $3^{\circ}$  C. too low because of long-wave radiational losses. Errors at higher pressures were found to be insignificant. With the assumption that most temperature sensors react in the same way as that employed in the U.S. military radiosonde, all 10-mb. data are subjected to an additional correction for this infrared radiational error. The correction takes the form

$$T'_{10} = 1.0625T_{10} + 5.09 \quad (^{\circ}\text{C.}) \quad (5)$$

$$H'_{10} = H_{10} + T_{10} + 81.4 \quad (\text{meters}) \quad (6)$$

where  $T'_{10}$  and  $H'_{10}$  are the corrected 10-mb. temperature

and height and  $T_{10}$  and  $H_{10}$  the uncorrected "nighttime" values, i.e., either actual nighttime readings or daytime data that have been corrected for solar radiation.

#### MERGING OF DATA FOR ANALYSIS INPUT

In previous sections of ADP, all data for three consecutive observation times have been checked, extrapolated, and corrected for systematic errors. A decision must be made at this point as to the particular parameters to be utilized by the analysis program. Since reported 100-mb. data for any observation are sufficiently dense to insure a representative analysis, only 1200 GMT, on-level reports are employed for that level. The selection of 50-, 30-, and 10-mb. heights and temperatures for analysis is governed by the following order of priority:

- a. On-level (50-, 30-, and 10-mb. mandatory level), on-time (1200 GMT) report.
- b. Average of the on-level 0000 GMT reports immediately preceding and following map time.
- c. Any single on-level 0000 GMT report within 12 hr. of map time.
- d. A vertically extrapolated on-time report.
- e. Average of the extrapolated 0000 GMT reports immediately preceding and following map time.
- f. Any single extrapolated 0000 GMT report within 12 hr. of map time.

The selection of winds for analysis input is independent of that of temperatures and heights, with priority as follows:

- a. On-level (50-, 30-, and 10-mb. mandatory level), on-time (1200 GMT) wind.
- b. On-time wind selected from a rawin report at a nearby level.
- c. On-level 0000 GMT wind, 12 hr. prior to map time.
- d. Off-level 0000 GMT wind, 12 hr. prior to map time.
- e. On-level 0000 GMT wind, 12 hr. following map time.
- f. Off-level 0000 GMT wind, 12 hr. following map time.

#### OUTPUT OF MERGED DATA

Upon completion of the final stage of ADP, the analysis input data are printed out in station listings and plotted charts analogous to those obtained from the initial data-checking and sorting operations. That portion of the listing including Baker Lake, Canada (72926), is shown in figure 3b. The merged information has been edited so that only analysis-level data for 100 mb. and above are presented. Data for the 70- and 20-mb. levels have been processed even though analysis for those levels is not currently performed.

The data shown in figure 3b were obtained in the following manner:

100 mb.—on-level, on-time (1200 GMT, February 16) height, temperature, and wind;

70 mb.—on-level, on-time height, temperature, and wind;

50 mb.—on-level, on-time height and temperature; on-time, off-level (61,200 ft.) wind;

<sup>3</sup> In (6),  $T_{10}$  is the number of meters algebraically equal to the temperature.

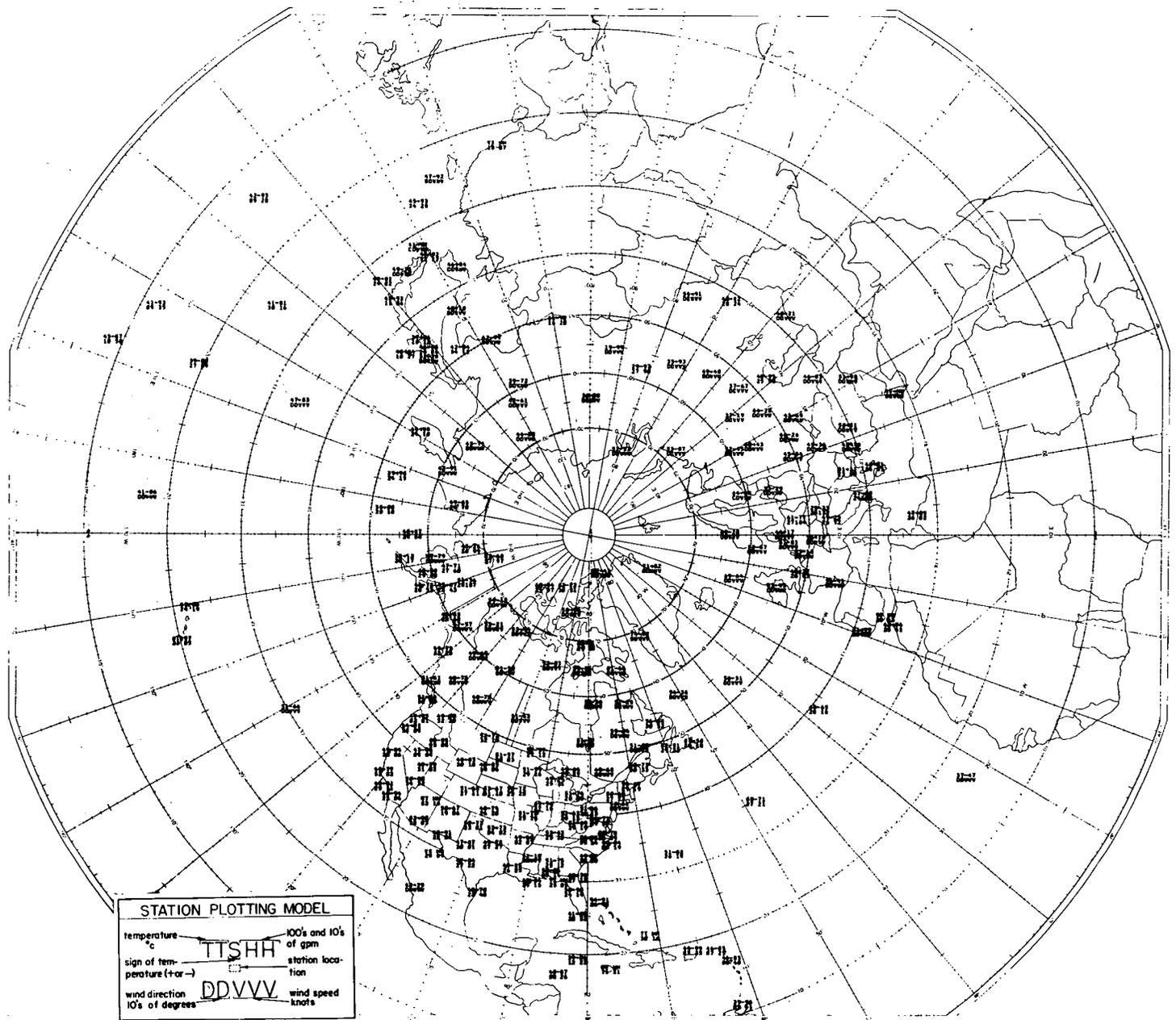


FIGURE 4.—Computer-plotted chart of merged analysis input 10-mb. data for 1200 GMT February 16, 1965.

30 mb.—average of the on-level, off-time (0000 GMT, February 16 and 17) heights and temperatures; no winds available;

20 mb.—on-level, off-time (0000 GMT, February 17) height and temperature; no winds available;

10 mb.—vertically extrapolated, off-time (0000 GMT, February 17) height and temperature; no winds available.

The Baker Lake observations for both 0000 GMT and 1200 GMT were in total darkness at all levels; hence no solar-radiation corrections were applied. The 10-mb. values, however, include long-wave height and temperature corrections of approximately 30 m. and 1.8° C., respectively.

The plotted chart of 10-mb. analysis input data is shown

in figure 4. The extrapolation and merging procedures have increased data coverage approximately threefold over that including only the 1200 GMT checked data (fig. 2). The total number of reports has risen from 76 to 220, stations with heights from 75 to 210, and stations with winds from 31 to 136.

#### COMPUTER OPERATIONS FOR ADP SYSTEM

Figure 1 illustrates the processing of three observation times for each daily map set. However, once the sequence of operations has been initiated only two observations per day are prepared, since the "previous" 0000 GMT data on the current map day coincide with the prior day's "subsequent" 0000 GMT reports.

Although the operation of the ADP system is shown in figure 1 to be a single logical sequence, daily computer functions are more complex. The approach to the operational system has been devised so that:

1. The data error-check procedures of ADP are carried out for all atmospheric levels in a single routine computer operation. This is performed after a data collection period of 8 hours following each 0000 GMT and 1200 GMT observation time. It requires between 10 and 15 min. of IBM 7094-II computer time.

2. A separate program subjects the data at 50 mb. and above to the specialized vertical extrapolation and off-level wind selection procedures. In addition, all reports at and above 100 mb. are corrected for radiation errors. This program requires 2½ to 3 min. of computer operation per observation time.

3. After the later 0000 GMT observation has been processed, the corrected data for three observation times are merged to form the input for the analysis system. Approximately one minute of computer time per day is required for the running of the last program.

### 3. MONITORING OF ANALYSIS INPUT DATA

Until computer programs can be improved to cope adequately with all of the errors and other deficiencies of observational data, non-automatic subjective monitoring will continue as an important supplement to the objective analysis operation. This monitoring takes place after completion of ADP and usually requires two man-hours for each set of four charts. At this point, listings and plotted charts containing the analysis input data are available, as well as the intermediate listings and plotted charts of the checked data for each of the three observation times. The most convenient method of monitoring consists of superimposing the input-data plotted charts on the previous day's analyzed maps, and noting the 24-hr. changes in height, temperature, and wind. Considerable difficulty has been encountered in the determination of reasonable data-rejection criteria within both the ADP and analysis systems. The limits must be set broad enough to allow for the largest probable daily changes, but they also must function as a filter for the elimination of inaccurate data. Therefore, if any reported changes appear to be unreasonable but within the analysis program limits, the monitor has the option either to suppress the report at any station or to change any parameter to conform more realistically with surrounding data. The latter result is accomplished by the insertion of artificial data into the analysis. In addition, results of the various schemes for increasing data coverage must also be examined continually in order to check their reliability with regard to characteristic circulation patterns.

### 4. THE ANALYSIS SYSTEM

Objective analysis has been defined [4] as the process of transforming data from irregularly spaced observations into values at the points of a regularly spaced grid. The

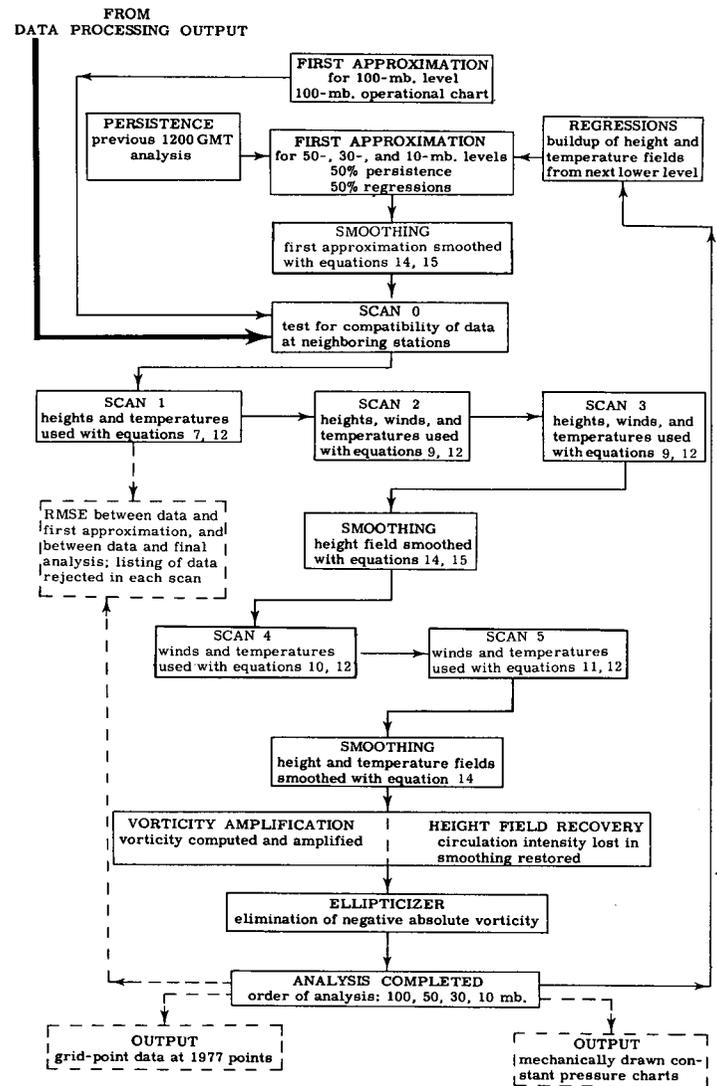


FIGURE 5.—Flow diagram of analysis system.

technique employed for the analysis of stratospheric charts utilizes the input data to effect adjustments of "first-approximation" height and temperature fields. A general flow diagram of the analysis system is shown in figure 5. This system is basically similar to that used for the lower levels [9]. However, several fundamental alterations were required to compensate for the general degradation of stratospheric data. For example, it was found that realistic analysis of the data requires relatively large wind weighting, since the magnitude of the height error increases more rapidly with altitude than that of the wind error. Smoothing procedures, which are routinely applied to all analyses, were increased in both degree and number in order to eliminate fictitious small-scale perturbations. In turn, these relatively heavy smoothings created new problems, such as attenuation of the intensities of circulation systems. To counteract this undesirable feature, the intensity of the height-gradient field is restored through amplification of the vorticity

field. As a consequence of the difficulties engendered by the data problems, changes were also made in the error-detection routines of the analysis program.

DERIVATION OF "FIRST-APPROXIMATION" FIELDS

An approximation to a given analysis may be derived by several different techniques. Day-to-day changes in the stratospheric circulation are generally small. Therefore, persistence, in the form of the previous analysis, is a useful "first approximation." An extrapolated analysis, derived by means of regression equations based on climatology [15, 21] and the completed analysis for the next lower pressure surface, may also serve and appears to excel within areas of sparse data. Both of these methods are employed for the stratospheric analyses.

Statistical regression equations have been developed jointly by the U.S. Navy Weather Research Facility and the U.S. Weather Bureau National Weather Records Center [8] for extrapolating from 200 to 100, 100 to 50, and 50 to 30 mb. The coefficients were computed on a monthly basis from a 2-year record of data stratified into seven latitude bands. The complete set employed for the month of February is shown in table 5.

For the extrapolation from 30 to 10 mb., regression coefficients for each month were determined by subjective analysis of individual scatter diagrams plotted for five latitude bands. The paucity and dispersion of data on the charts, especially those for high latitudes, led to the restriction that 10-mb. temperature be a function only of that parameter at 30 mb.

Studies of stratospheric circulation have disclosed that at least two distinct regimes sometimes occur in January and February. Therefore, separate sets of 10-mb. regression equations have been derived for each

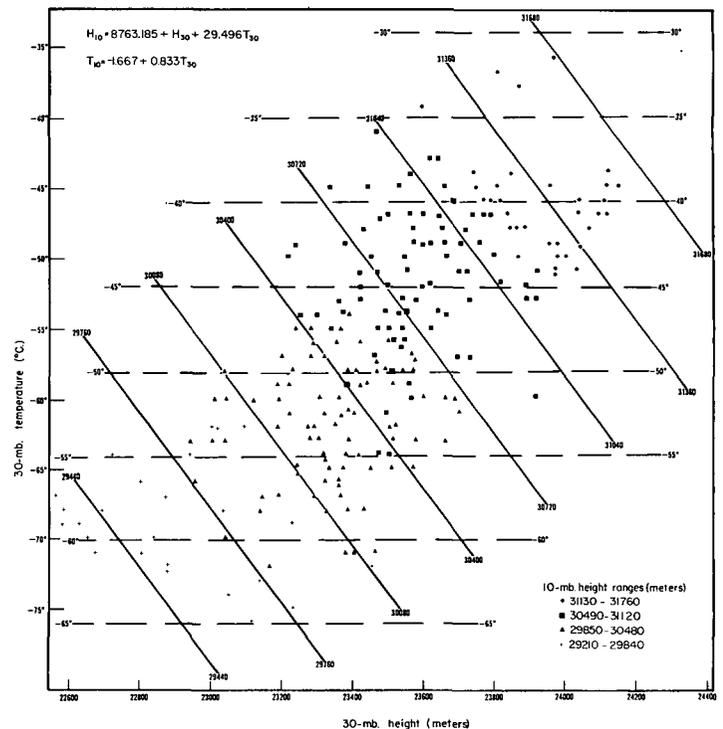


FIGURE 6.—Analyzed scatter diagram of 30- to 10-mb. regression data for February. The latitude band is 45° N. to 59° N. Plotted 10-mb. height data are separated into broad categories. Temperature data are not included on the chart. Regression lines are solid for 10-mb. height and dashed for 10-mb. temperature.

type of circulation pattern, the one appropriate to the prevailing mode being inserted into the program. Figure 6 shows the February height and temperature diagram for the 45° N. to 59° N. latitude belt. The coefficients computed from this and four other such diagrams are included in table 5. This set of regressions is for use with a stratospheric circulation pattern that has not been influenced by a mid-winter warming.

The system has been so devised that the relative contributions of persistence and of regression build-up can be varied in preparing the first approximation. After study of a number of experimental cases involving charts at 24-hr. intervals, equal weighting of these two components was determined to be the optimum combination at 50, 30, and 10 mb. The 10-mb. first-approximation chart for February 16, 1965 (fig. 7) was derived from the previous day's 10-mb. analysis and a regression build-up from the completed 30-mb. chart for February 16.

Routine operations require twice-daily 100-mb. analysis at the National Meteorological Center. However, input data for these charts are not corrected for solar radiation errors. As shown in the flow diagram (fig. 5), the 1200 GMT operational 100-mb. chart is used as the first approximation for the comparable analysis of the IQSY series.

The accuracy of the "first approximation" becomes a critical factor for stratospheric analysis, since this field, in many cases, represents the final analysis over relatively

TABLE 5.—Regression coefficients employed for January and February. General form of regression equations:

$$H_2 = A_0 + A_1 H_1 + A_2 T_1$$

$$T_2 = B_0 + B_1 H_1 + B_2 T_1$$

where  $H_1$ (meters),  $T_1$ (°C.) = height, temperature at lower level and  $H_2$ (meters),  $T_2$ (°C.) = height, temperature at upper level.

Layer (mb.)	Latitude Band (°N.)	Regression Coefficients					
		$A_0$	$A_1$	$A_2$	$B_0$	$B_1$	$B_2$
200-100	00-19	8143.348	0.722	9.747	203.267	-0.023	-0.070
	20-29	8062.531	0.716	6.589	179.589	-0.021	-0.071
	30-39	8107.357	0.713	6.149	216.363	-0.024	-0.101
	40-49	6644.336	0.859	10.118	105.748	-0.013	0.188
	50-59	5261.441	0.980	9.543	-24.195	-0.001	0.274
100-50	60-69	3752.386	1.134	14.100	-122.435	0.009	0.562
	70-90	3858.757	1.146	18.851	-126.694	0.011	0.921
	00-19	7745.859	0.819	9.042	41.201	-0.005	0.291
	20-29	10768.566	0.619	5.172	101.667	-0.010	0.002
	30-39	6699.093	0.901	12.820	-16.853	-0.001	0.421
050-030	40-49	4136.501	1.074	16.621	-161.097	0.009	0.722
	50-59	5193.348	1.027	22.087	-39.900	0.003	1.182
	60-69	5637.160	1.001	22.699	25.856	-0.001	1.230
	70-90	5413.734	1.012	21.970	5.698	0.000	1.169
	00-19	2066.017	1.082	8.713	-234.379	0.010	0.422
030-010	20-29	1253.029	1.122	8.897	-296.825	0.013	0.418
	30-39	3066.917	1.045	12.832	-111.625	0.005	0.785
	40-49	3525.057	1.028	15.081	-37.062	0.002	1.060
	50-59	4185.148	0.997	15.814	24.697	-0.001	1.104
	60-69	4264.493	0.992	15.360	67.613	-0.003	1.142
030-010	70-90	5368.256	0.943	17.587	177.576	-0.008	1.326
	00-29	8496.647	1.000	23.333	-18.233	0.000	0.450
	30-44	8480.000	1.000	24.000	-19.268	0.000	0.492
	45-59	8763.180	1.000	29.496	-1.667	0.000	0.833
	60-69	8830.222	1.000	32.178	2.500	0.000	1.000
70-90	8655.000	1.000	30.000	-8.391	0.000	0.865	

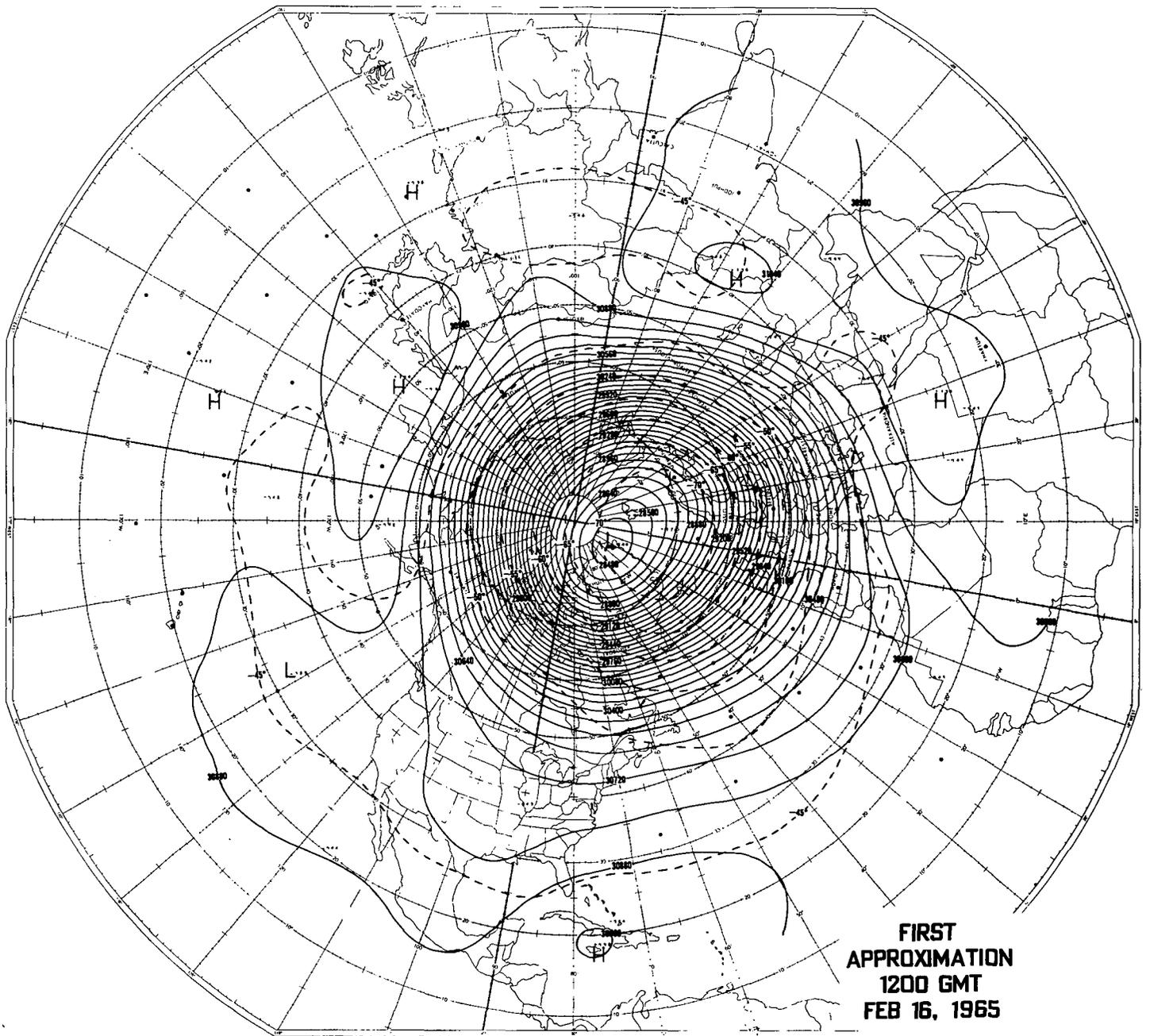


FIGURE 7.—Computer-analyzed first-approximation chart for the 10-mb. level, 1200 GMT February 16, 1965. Contour interval 80 m.; isotherm interval 5° C.

large areas. Therefore continuing investigations are being directed toward improving the system, with particular emphasis on the regression equations. The present method of stratifying the coefficients into latitude bands, without consideration of longitudinal variability, severely limits the resolution and accuracy that can be obtained. For example, a common wintertime circulation pattern at the 30- and 10-mb. levels is that of wave number one, in which a large cold cyclone and warm anticyclone, diametrically opposite, dominate the Northern Hemisphere. The temperature variation within a

high-latitude belt (e.g., 60° N.–70° N.) may exceed 50° C., with a correspondingly large range of contour height. In such cases the regression equations will fail to specify the true height and temperature patterns over large areas typical of the extremes of the range. Ideally then, the data from which the regression coefficients are derived should be classified according to the prevailing circulation and thermal patterns, rather than limited and arbitrary geographical divisions. This approach has been utilized to a small extent in the derivation of 10-mb. regression equations for two broad categories of mid-

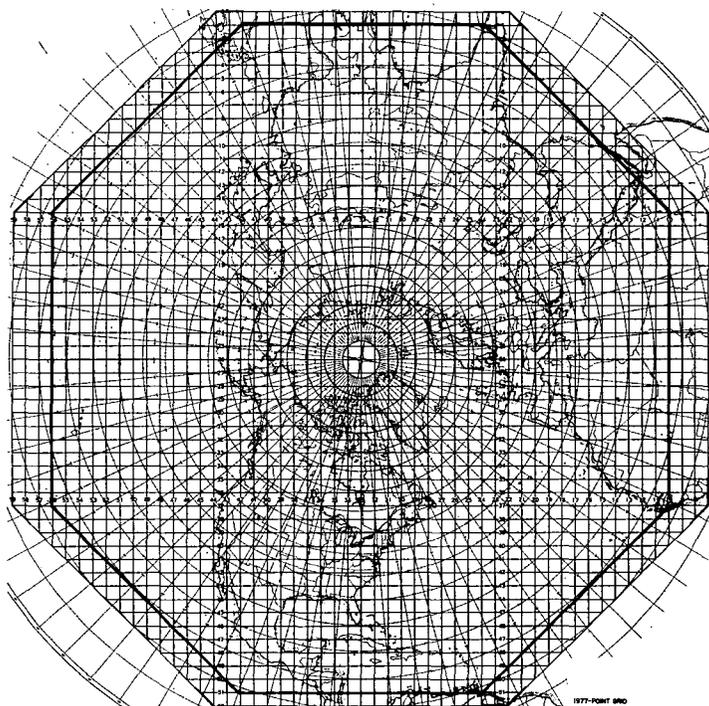


FIGURE 8.—The 1977-point hemispheric grid, delineated by inner boundary.

winter patterns, characterized by the occurrence or non-occurrence of a major stratospheric warming and circulation breakdown.

#### THE ANALYSIS PROCEDURE

Stratospheric analysis is accomplished in five consecutive scans over an octagonal grid consisting of 1977 points (fig. 8). The grid interval varies with latitude and is 381 km. at 60° N. Each scan is initiated at the lower left corner of the grid and proceeds from left to right, terminating at the upper right corner. The "first-approximation" height and temperature fields provide grid-point values for use in the initial scan. The input data contained within a circle of prescribed distance, or scan radius, from each grid point contribute to the adjustment of the grid-point values. The result of this modification becomes the approximation for the following scan. For each succeeding scan, the radius is decreased (table 6) and the grid-point values produced in the previous scan are fitted more closely to the input data.

The initial adjustment of the first-approximation height field is performed by means of the relation

$$A_H = F_{max} \frac{\sum F_H D_H}{\sum F_H} \quad (7)$$

where  $A_H$  is the height adjustment for a given grid point, and  $D_H$  is the difference between the input height and the approximation value interpolated to the station location. The general weighting factor  $F$  is given by

$$F = (N^2 - d^2) / (N^2 + d^2) \quad (8)$$

where  $d$  is the distance in grid lengths between the input report and the grid point, and  $N$  is the scan radius.  $F$  is set to zero for  $d > N$ .  $F_{max}$  is the weight of the report nearest the grid point. It can be seen from equation (8) and table 6 that a report at the grid point would have a weight of unity, while one located six or more grid lengths from the point would receive zero weight and therefore not be included in the adjustment process for that grid point.

As shown in table 6, the largest value of  $N$  is employed for the initial scan, thus allowing the greatest adjustment of the height field. However, consideration of reported winds with such a large scan radius can result in unrealistic height gradients. Therefore winds are not used in the first scan, but are weighted more heavily than the heights in scans 2 and 3. The adjustment for these scans is given by

$$A = F_{max} \frac{R \sum_{(a)} F_H D_H + \sum_{(b)} F_{H,W} D_H D_W + B \sum_{(c)} F_W D_W}{R \sum_{(a)} F_H + \sum_{(b)} F_{H,W} + B \sum_{(c)} F_W} \quad (9)$$

where  $A$  is the adjustment to the height field, and  $D_W$  is the difference between the approximation gradient, interpolated to the station location, and the input wind (which has been converted to a height gradient in components corresponding to the grid [9]). The multipliers  $R$  and  $B$ , which allow the relative influences of height-only and wind-only reports to be varied, are assigned values of 0.125 and 0.5 respectively for scan 2, and 0.125 and 0.75 for scan 3. The effect of these multipliers is to give wind reports four times the weight of heights in scan 2, and six times in scan 3.

As an example of an operation employing equation (9), assume three stations to be included within the scan circle for a given grid point. Furthermore, let one station's report consist of a height only, another of a height and wind, and the third of a wind only. These reports would be evaluated according to terms (a), (b), and (c), respectively, of the numerator and denominator.

Early in the development of the map series, the analysis procedure was limited to four scans, with the relation (9)

TABLE 6.—Analysis program scan radii and data rejection limits as prescribed for wintertime use. All values are applicable to the 100-, 50-, 30-, and 10-mb. levels.

Scan No.	Radius (grid lengths)	Parameters analyzed and rejection limits		
		Height (meters)	Temperature (°C.)	Wind (kt. vector difference)
1.....	6.0	1.25 (first approximation gradient)*+50	**16/12	not considered
2.....	4.2	160/070	11/08	60
3.....	3.0	120/060	07/05	40
4.....	2.0	100/050***	04/03	30
5.....	1.5	100/050***	04/03	30

\* Computed over a one-grid-length interval centered on the grid square containing the station.

\*\* ( ) / ( ) = north of 35° N./south of 35° N.

\*\*\* Winds only are utilized to adjust the height field; upon completion of each adjustment, reported heights are compared with the adjusted field and eliminated if they differ by more than the stated amounts.

employed in scans 2 through 4. However, study of the resulting charts revealed that contour patterns were not being sufficiently adjusted to the wind reports, especially over lower latitudes. Substantial increases in the wind-to-height weighting function did not achieve the desired results. In addition, a latitude-dependent wind weighting procedure was devised, but also proved to be unsuccessful. However, significantly superior charts were obtained by adding a fifth scan to the analysis procedure and utilizing only the wind reports for the contour adjustment during the last two scans.

The adjustment formula adopted for scan 4 is

$$A_w = \frac{\sum F_w D_w}{\sum F_w} \tag{10}$$

and for scan 5

$$A_w = \frac{\sum F_w D_w}{n} \tag{11}$$

where  $n$  is the number of wind reports within the scan area. Of these last two scans, the latter contributes less to the adjustment since the scan radius is smallest (table 6) and  $n$  is nearly always larger than  $\sum F$ .

Temperature fields are adjusted to the input data by means of

$$A_T = F_{\max} \frac{\sum F_T D_T}{\sum F_T} \tag{12}$$

where  $A_T$  is the temperature adjustment for a given grid point,  $D_T$  is the difference between the input temperature and the approximation value interpolated to the station location. This relation is used in all five scans with the same decreasing radii as are employed for the analysis of the height field.

**DATA QUALITY CONTROL WITHIN THE ANALYSIS PROCEDURE**

In spite of the extensive checking performed in ADP, errors may still be present in the analysis input data. Many of these errors can be detected only by comparing the observations with a given analysis (e.g., the first approximation) or with reports at neighboring stations. This error detection can best be accomplished within the analysis program, where all data for each specified level are readily available. During the five analysis scans, the various input-data parameters are compared with the approximation fields. Any input parameter that differs by more than a predetermined amount is eliminated from further consideration in the analysis procedure. The data rejection limits employed for the winter months are shown in table 6.

Numerous tests were conducted in order to ascertain proper values for the rejection limits. From the onset, the need for a latitudinal variation was clearly indicated. As can be seen from table 6, the preset limits for scans 2 through 5 are considerably more stringent south of 35° N. than to the north of that latitude. However, particular difficulty was encountered in prescribing the scan 1 height

TABLE 7.—Operation of data compatibility test

( $Q_M - Q_D$ )	Number of reports within scan radius of 2 grid lengths	Procedure
$\geq 80$ meters $\geq 6^\circ$ C.	3	Any parameter that exceeds scan 1 rejection limits is eliminated.
$\geq 80$ meters $\geq 6^\circ$ C.	>3	Any parameter that exceeds scan 1 rejection limits is eliminated. All others are retained for scan 2 even if they exceed the rejection limits for that scan.
<80 meters <6° C.	3	All reports are retained for scan 1 and 2 even if they exceed the rejection limits.
<80 meters <6° C.	>3	All reports are retained for scan 1, 2 and 3 even if they exceed the rejection limits.

rejection limits during the winter season. Real differences between the first approximation and the input data can be quite large within areas of intense gradients and relatively rapid changes. In order to retain valid reports within these areas it was necessary to relax the preset limits to an unreasonable degree. This difficulty was alleviated by specifying the scan 1 height rejection limit as a function of first-approximation height gradient.

Even though the synoptic situation was considered in determining scan 1 rejection limits, a small percentage of valid reports continued to fail. To reduce the likelihood of such data being discarded because of deficiencies in the first-approximation fields, the following test for compatibility of input data is performed prior to analysis [10]. If three or more reports are contained within a scan circle of two grid-length radius from a grid-point, the mean difference between these reports and the values of the first-approximation fields at the stations is computed by

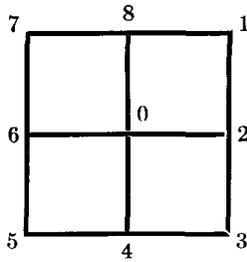
$$Q_M = \sum Q_D / n \tag{13}$$

where  $Q_D = Q_G - Q_O$ ;  $Q_G$  is the first-approximation value at the station,  $Q_O$  is the reported value at the same station, and  $n$  is the number of differences (stations) considered. The retention of compatible data as determined by this so-called "scan 0," then proceeds according to the specifications given in table 7.

The test for compatibility proved highly effective in reducing the amount of subjective monitoring. The principal remaining monitoring problems arise in sparse-data areas.

**SMOOTHING OPERATIONS**

The first-approximation map frequently contains numerous small-scale perturbations and discontinuities, especially at the boundaries of latitude belts where regression equations change. Similar undesirable features become evident after each of the analysis scans. Therefore, a smoothing of the type described by Shuman [14] is performed at various stages of the analysis. Except for boundary points, which are smoothed by a simple space-mean method, every point within the 1977-point grid becomes the center for a smoothing operation involving nine grid points. The 9-point grid array is in the form



Two different smoothing operators are available for application:

$$(\ )_0 \text{ smoothed} = \frac{1}{16} [4(\ )_0 + (\ )_1 + 2(\ )_2 + (\ )_3 + 2(\ )_4 + (\ )_5 + 2(\ )_6 + (\ )_7 + 2(\ )_8] \quad (14)$$

and

$$(\ )_0 \text{ smoothed} = \frac{1}{4} [(\ )_1 + (\ )_3 + (\ )_5 + (\ )_7] \quad (15)$$

where  $(\ )_k$  is the value of the temperature or height at point  $k$  of the array.

Numerous tests were conducted in order to determine the optimum combinations and applications of the smoothing operators. As shown in figure 5, they are utilized at three distinct stages of the analysis procedure. First-approximation height and temperature fields for 50, 30, and 10 mb. are smoothed by use of both (14) and (15). Upon completion of scan 3, the height field is subjected to the same heavy smoothing at all four levels (100, 50, 30, and 10 mb.). However, following scan 5, height and temperature are smoothed with (14) only, at all levels.

Since the scan area for each grid point is a circle, the omnidirectional distribution of height differences in the adjustment process also has a smoothing effect. This is particularly evident in areas of strong gradient, where the contours tend to be spread laterally. An elliptical scan area, with the major axis oriented parallel to the direction of flow, has been suggested [7] as one means of minimizing this undesired smoothing effect and thus of preserving the character of jet streams.

#### VORTICITY AMPLIFICATION AND HEIGHT FIELD RECOVERY

An unavoidable consequence of the smoothing method employed is the reduction in intensity of circulation features. The effect is particularly pronounced in winter when a deep cyclonic vortex dominates the higher latitudes. To restore the intensity lost in smoothing, geostrophic relative vorticity of the smoothed height field is arbitrarily increased after completion of scan 5. At every point of the 1977-point grid, except those on the boundary, the modification is given by

$$H'_{i,j} = H_{i,j} - 0.21(L_{i,j}) \quad (16)$$

where  $i$  and  $j$  are the grid coordinates (fig. 8),  $H$  is the smoothed height, and  $H'$  is the restored height.  $L_{i,j}$ , the finite-difference Laplacian of the smoothed height field, is given by

$$L_{i,j} = \frac{1}{4}(H_{i-2,j} + H_{i+2,j} + H_{i,j-2} + H_{i,j+2}) - H_{i,j} \quad (17)$$

The constant 0.21 was determined empirically, and can be altered as necessary. The effect of (16) is to lower heights in the neighborhood of a maximum in the relative vorticity field, and to raise heights in the vicinity of a vorticity minimum. Thus the height field can be recovered with strong gradients and prominent circulation features restored to more nearly their proper intensity.

#### ELIMINATION OF NEGATIVE ABSOLUTE VORTICITY

During the analysis procedure geostrophic absolute vorticity is required to be positive throughout the entire area. In application of the so-called "ellipticizer" [4], the absolute vorticity is computed from the final height field ( $H'$ ) for each grid point. If the absolute vorticity for any point is negative, the excess anticyclonic relative vorticity is distributed about the point in such a manner that the mean vorticity in the vicinity of the point is unaltered. The resultant changes in stratospheric height fields are generally very slight.

#### MONITORING OF COMPUTER ANALYSIS OPERATION

During the analysis operation an indication of the goodness of fit between the input data and approximation fields before each of the five analysis scans is provided by means of a printed listing. The portion relevant to the 10-mb. analysis for February 16, 1965 is shown in figure 9. All parameters listed under scans 1 through 5 differed from the first and successive approximation fields by more than the indicated limits. Parameters that deviated significantly from the final analysis are listed under "scan" 6. Information regarding the fit of the data to the first-approximation chart and the final analysis is also listed, along with the number of heights and temperatures utilized. In the computation of mean and root-mean-square errors for both the Northern Hemisphere and the North American region, only permanent land and ocean stations are considered.

The statistics listed in figure 9 indicate that nearly one-third of the 10-mb. heights were rejected during the five scans, while most of the temperatures were utilized fully. These ratios can normally be expected at this level during the winter season. A survey of the rejected parameters will show that only one wind was not employed during the five analysis scans. Although not shown in the listing, the data input included 136 wind reports (see fig. 4). In appraising the quantity of data rejected it should be noted that only the parameters eliminated during the first scan are not considered for any part of the analysis. All others are utilized to varying extents.

A measure of external control is also provided during the computer operation of the analysis system. At the monitor's option, the computer will halt after listing the data to be rejected for each scan. Reports that are judged valid may be retained for further analysis consideration, as in the case of those underlined in the scan 1 listing. As will be shown later, these "forced-in" reports indicated a

THE 10 MB ANALYSIS STARTED FOR 16 FEB 1965 1200Z OP-F

SCAN 1	HT DIFF	IS GRAD*(1.25)+50	T DIFF	N 16	S 12		
S/3348H78384	3106	1/2548H78897	3085	2/3346H72201	3103	3/4244H76458	3113
4/3844H72250	3070	5/3644H72232	3064	6/3842H72266	3089	7/3742H72248	3066
8/3642H72235	2810	9/4041H72270	3091	0/3641H72340	3068	1/4040H72365	3067
2/3540H72532	3096	3/3440H72429	3063	4/3140H74486	3061	5/4339H72290	3094
6/3838H72662	3085	7/3638H72655	3059	8/3737H72764	3057	9/4134H72798	3065
0/4133H74109	3061	1/5431H91285	3097	2/4227H70316	3112	3/3827H70026	2969
4/2326H10035	3017	5/5524H S113	3106	6/2124T11035	-29	7/1922H15614	3111
8/4120H32540	3083	9/1920H17130	3051	0/4819H S240	3083	1/3318T24507	-30
2/5317H91245	3103	3/3017T29231	-29	4/3017H29231	3097	5/2317H35700	3095
36 TOSS OUTS							

SCAN 1	HT DIFF	IS GRAD*(1.25)+50	T DIFF	N 16	S 12		
S/4914H91131	3081	1/4014H31960	3110	2/2513H38457	3083	3/4212H47778	3075
4/4012H47122	3084						

H	FT	**NH**	NO	ME	RMSE	**US**	NO	ME	RMSE
			195	-025	458		079	012	288
T	DEG		196	-000	005		079	002	003

SCAN 2	10	HT DIFF	N 160	S 070	T DIFF	N 11	S 09	
S/2834H	4YB	3036	1/3331H74081	2911	2/2528H06011	2964	3/2523H02963	2898
4/2323H26629	2930	5/2222H33345	3034	6/3017H29231	3097			

SCAN 3	10	HT DIFF	N 120	S 060	T DIFF	N C7	S C5
S/3743H72240	3085	1/3543H72221	3086	2/3136H72826	3034	3/3234H72907	3036
4/3432H72926	3003	5/4030H70361	3086	6/3630H72938	2994	7/3430H72924	2895
8/3928H70261	3036	9/2227T03774	-42	0/2227H03774	3037	1/2326T10035	-44
2/2126T10513	-62	3/2126H10513	2983	4/2026H16080	3050	5/2225H10393	
6/2225H10393	2977	7/2025H16044	3023	8/1922T15614	-31	9/2419H34172	3027
0/4313H47678	3081	1/4111H47827	3097				

SCAN 4	10	HT DIFF	N 100	S C50	T DIFF	N 04	S 03
S/2547T78861	-40	1/3344H7221Y	3091	2/3843H72253	3071	3/3942H72265	3087
4/3441H72327	3063	5/4338H72392	3077	6/3038H72712	3073	7/4137T72563	-43
8/3136T72826	-59	9/3134T72906	-52	0/3333H72915	2988	1/3031H04220	2892
2/3528H74072	2884	3/3926H70133	3027	4/2426H01415	2967	5/5524T S113	-41
6/4022H25954	3091	7/3121H20674	2922	8/2821H23205	2907	9/2521H27037	2945
0/2121H33837	3036	1/2519T27595	-37	2/5516T91366	-45	3/4111T47827	-41

SCAN 5	10	HT DIFF	N 100	S 050	T DIFF	N 04	S 03
S/3139W72518							
SCAN 6	10	HT DIFF	N 100	S 100	T DIFF	N 05	S 05
S/3340H72520	3065	1/3134H72906	3027	2/3733H72934	3050	3/3832H72945	3067
4/3729H72957	3012	5/4128H70326	3089	6/3328H72917	2852	7/4027H70231	3071
8/3227H74082	2841	9/2927H04320	2852	0/2127H06447	3018	1/4026H70200	3048
2/2226H10202	2981	3/2124H11035	3033	4/1824W16320		5/1821H17220	3071
6/2219H34731	3069	7/3017H29231	3097				

H	FT	**NH**	NO	ME	RMSE	**US**	NO	ME	RMSE
			122	-021	159		051	-016	138
T	DEG		184	000	001		076	000	001
			00000						

FIGURE 9.—The 10-mb. portion of the output available during computer operation of the analysis system. This listing contains the data-rejection limits for each scan (shown on same line as scan number). Also included is a listing of rejected parameters for each scan. The first rejected report is listed as S/3348H78384 3106, where 3348 is a grid identification, H indicates that the parameter is height, 78384 is the station's international index number (Roberts Field, Grand Cayman Is.), and 3106 is the value of the rejected height in decameters. The letter S preceding the solidus is for computer operational use. Also included after scan one and scan six is a statistical evaluation. This listing shows the number of heights (H) and temperatures (T) available for analysis over the Northern Hemisphere (NH) and part of North America (US). Also included are values of the mean error (ME) and root-mean-square error (RMSE).

developing warm anticyclone over Eurasia that was not portrayed on the first approximation. The necessity for manual intervention in this situation points out presently unavoidable deficiencies within the data-checking routines of the analysis program. If the high-level warming had been delineated by a denser cluster of reports, the pre-analysis data compatibility test would have specified retention of those parameters. However, control of the few available reports was transferred to scan 1, during which the data failed the prescribed limit tests.

DISCUSSION OF ANALYSIS SYSTEM OUTPUT

One of the foremost benefits of the computerized analysis system is the rapid availability of the final product. Approximately 7 minutes of computer time is required for the analysis of four maps each day. Upon completion of computer operations an electro-mechanical data-plotting and line-drawing device converts the analysis output to the conventional form of isopleths on a constant-pressure chart. The machine is programed to produce contours as solid lines and isotherms as dashed lines, to label Highs and Lows, and to print values of the various height and temperature centers. Each chart is completed in approximately 5 minutes.

The set of stratospheric charts for February 16, 1965 (figs. 10-13) is representative of the final output from the analysis system. This typical wintertime pattern is dominated by a cold-core cyclonic vortex at all levels. The westerly gradient increases markedly with altitude over northern latitudes within the "polar night" region, while to the south of the stratospheric "warm belt" the rapid decrease of gradient with altitude is equally striking.

Figures 7 and 13 illustrate the close correspondence between the 10-mb. first approximation and final analysis. Similarity between the contour fields is remarkable throughout the entire area covered by the polar cyclone. The final analysis of the temperature field, however, contains several features that were not included in the first approximation. Of particular significance is the warm center located over central Siberia. This rapidly intensifying disturbance did not appear on the previous day's chart. Furthermore, the warming apparently began above the 10-mb. level and penetrated downward with time. For these reasons it could not have been represented in the first-approximation field by either the persistence contribution or the regression build-up. As mentioned earlier, manual intervention during analysis was required to insure proper utilization of the data portraying this phenomenon.

Examination of the analyses has revealed numerous problems of varying importance. Perhaps of greatest concern is the preservation of internal, especially hydrostatic, consistency within each set of charts. This, at times, becomes difficult to achieve since the input-data field may be a composite from three observation times, the analysis procedures for temperature and height are mutually independent, and the amplification of vorticity

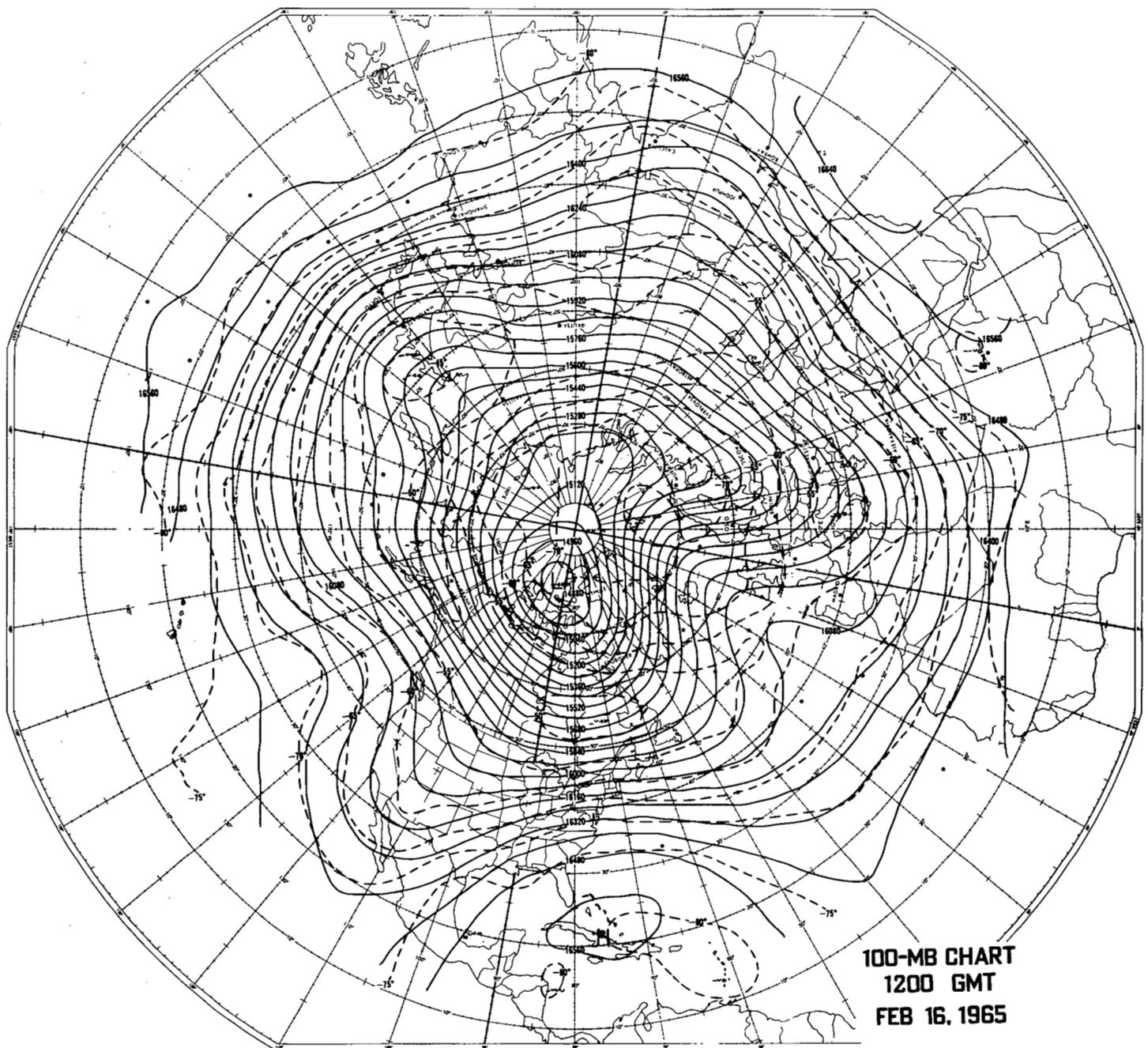


FIGURE 10.—100-mb. chart for February 16, 1965. Contour interval 80 m.; isotherm interval 5° C.

may not compensate exactly for the intensities lost in smoothing. There is no simple solution for this problem, other than subjective adjustment by the monitor. Studies are being undertaken to determine what improvements are feasible within the framework of the system.

Also of concern are isolated and not completely realistic circulation or thermal centers which often appear around isolated stations or at the edges of dense-data areas. In extreme cases, the result may be a "bull's-eye" pattern within the contours or isotherms. Careful monitoring is necessary to eliminate these undesirable features.

In low latitudes, especially near the boundaries, other deficiencies in the appearance of the charts are noticeable at times. Most evident is a lack of intermediate contours

because of the fact that only a single contour interval, determined mainly by the gradients in northern latitudes, can be employed at present. This characteristic is clearly illustrated in the low-latitude portion of the 30-mb. chart for February 16 (fig. 12). On the other hand, extraneous isopleths near the boundaries of the charts do not appear to be consistent with the overall analysis. Where such inconsistencies cannot be resolved, these short line segments are manually erased.

In order to facilitate research which utilizes analyzed stratospheric data, grid-point values of each map are obtained on punched cards as part of the output. These card decks, one each for height and temperature, contain values at the 1977 points of the octagonal grid (fig. 8).

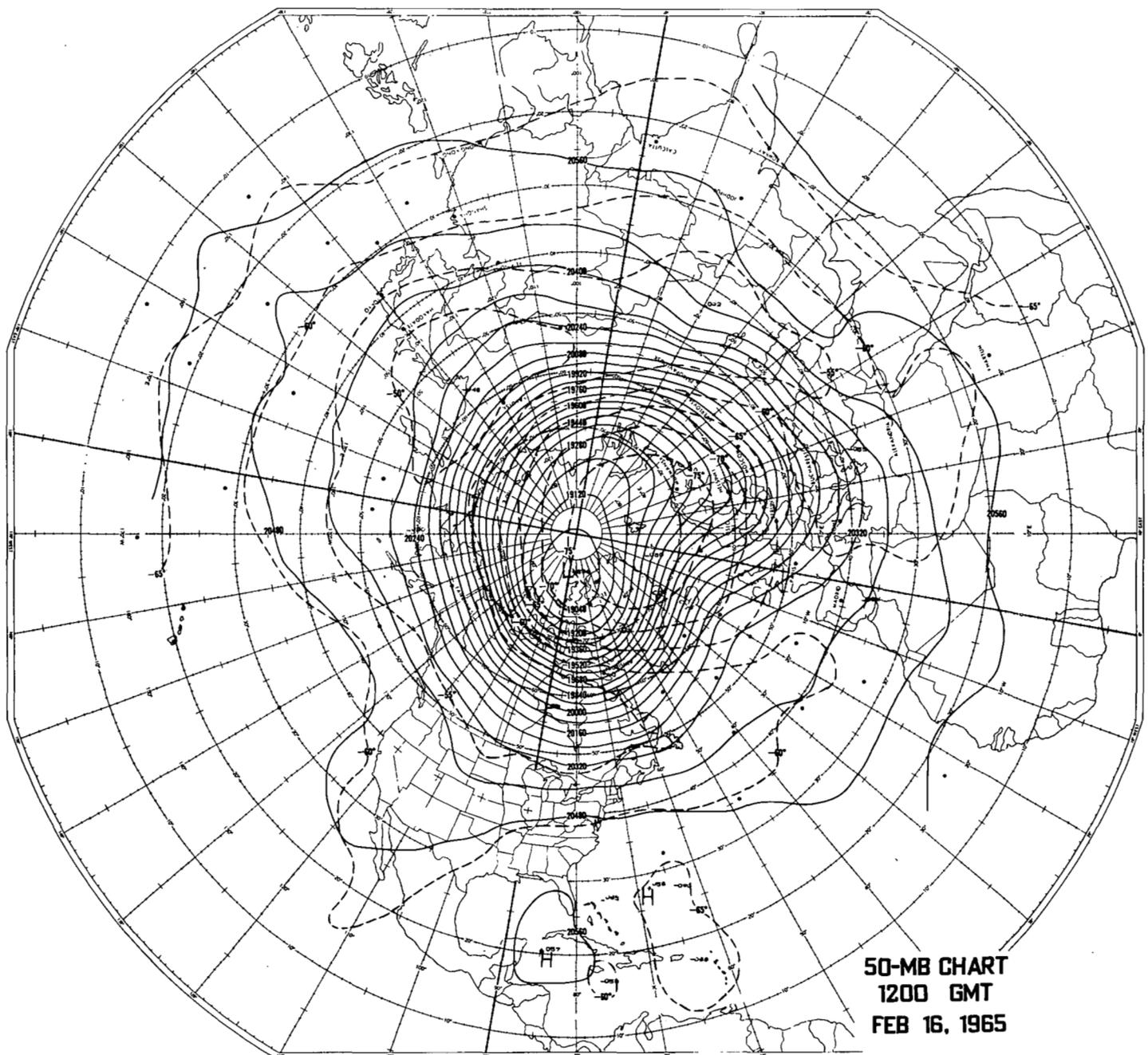


FIGURE 11.—50-mb. chart for February 16, 1965. Explanation as in figure 10.

A special packed-data format is employed to limit the number of cards to 35 for one parameter at a given level. One example of the use that can be made of the grid-point data is the auxiliary computer program regularly employed to produce monthly-mean height and temperature analyses for the four stratospheric levels.

## 5. CONCLUSIONS

Constant-pressure analysis of stratospheric data is being accomplished by essentially the same objective techniques that are employed for the lower levels. However, numerous modifications to the computer programs were necessary in order to process and analyze the high-

level data in the most efficient manner. Many of these modifications have been incorporated during the course of daily operations, which commenced at the beginning of the IQSY period. Although the present product is considered comparable in quality to results of subjective stratospheric analysis, research is continuing in several areas in order to improve the quality and usefulness still further. These efforts include continued development of several aspects of the ADP system, such as the hydrostatic check, vertical extrapolation, and radiation-correction procedures. In addition, the accuracy of first-approximation fields will be improved by new sets of regression coefficients that are being derived as more data become

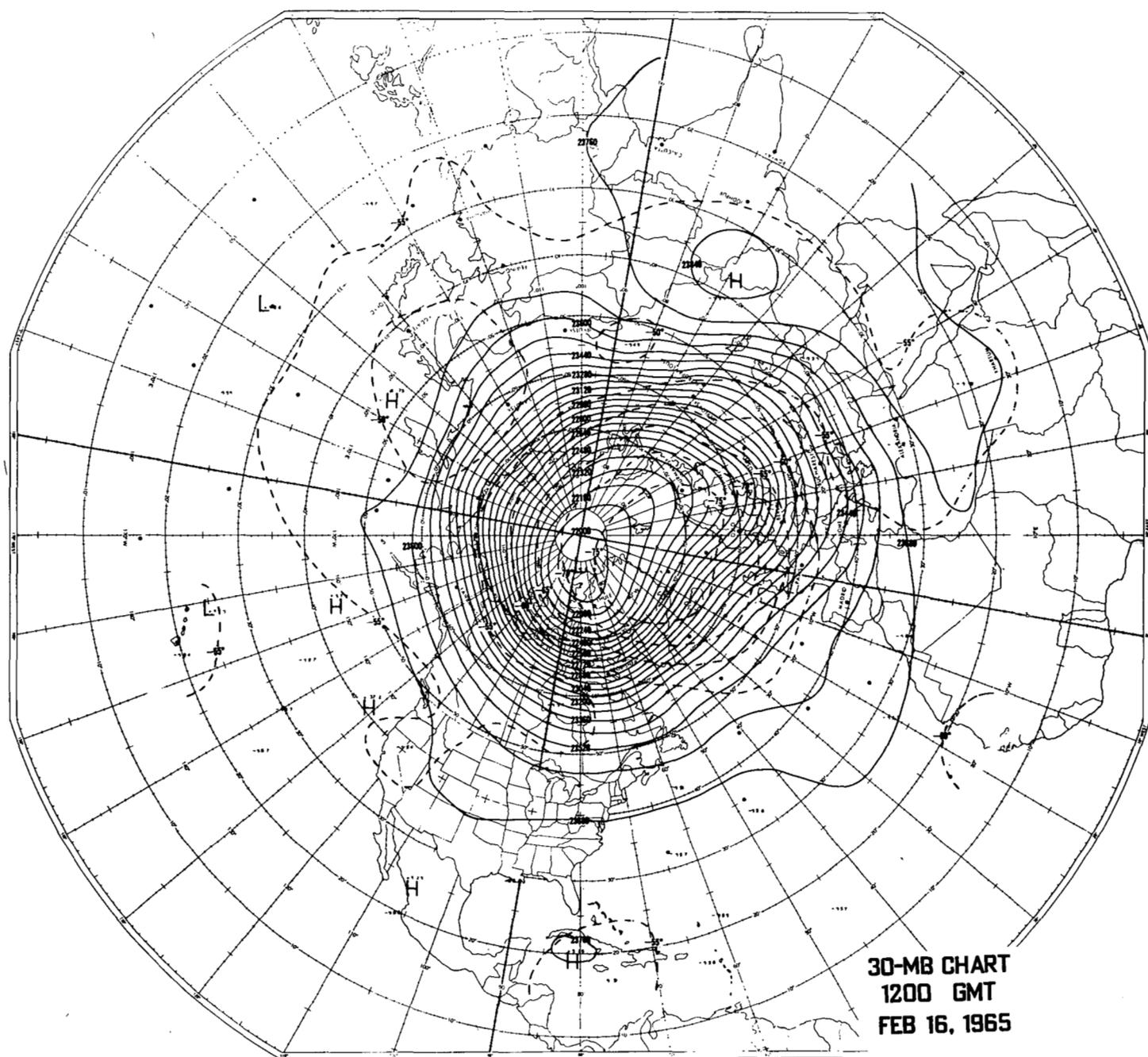


FIGURE 12.—30-mb. chart for February 16, 1965. Explanation as in figure 10.

available. A major effort is also in progress to refine the analysis portion of the system to such a degree that subjective monitoring of input data can be eliminated completely.

In recent years several novel and sophisticated approaches to objective analysis have been suggested. However, the problems of inconsistency and sparsity of present-day stratospheric data are serious obstacles to the successful implementation of such systems. Hence it is expected that the Bergthórsson-Döös-Cressman method will for some time remain the most practical and economical stratospheric objective analysis technique.

The analysis project was planned and instituted pri-

marily to aid stratospheric research efforts during the IQSY period. The series is available to all interested researchers in the form of microfilmed charts and grid-point data on punched card decks.

If a more urgent operational requirement for the charts should arise, various modifications would have to be made to the system. A major change would be the elimination of the use of three observation times to obtain input data for all levels above 100 mb. As a result the quality of analyses might suffer severely unless special attention were given to the problem of reliable transoceanic transmission of data within a reasonable time after the observation. Attainment of this goal requires adoption of rawinsonde

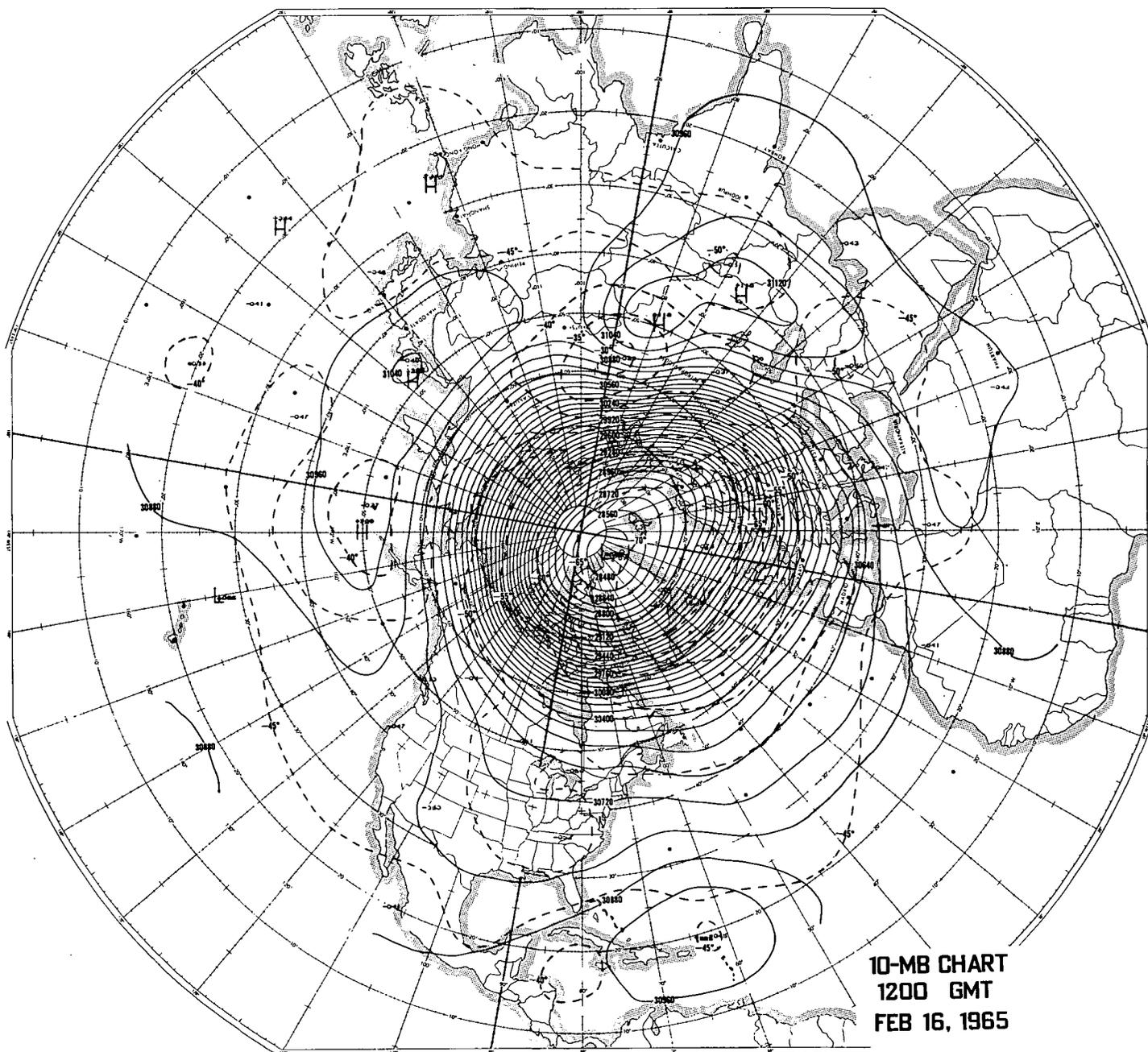


FIGURE 13.—10-mb. chart for February 16, 1965. Explanation as in figure 10.

codes designed specifically for machine processing and the use of communication channels providing higher speed and greater reliability, particularly in the relay of information between circuits. In addition, improvements in quality and quantity of stratospheric data by development of more accurate radiosonde instruments and increase in the percentage of soundings attaining high altitudes are necessary to enhance the usefulness of the analyses.

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## NEW WEATHER BUREAU PUBLICATION

*World Weather Records 1951-60*, vol. 1, North America, Washington, D.C., 1965, 535 pp. For sale by Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402. Price \$2.75.

Contains the record of monthly mean values of station pressure, sea level pressure and temperature, and monthly total precipitation for the period 1951-60 for stations listed in the previous issuances of the World Weather Records plus many new stations.

Notes concerning instrument exposure, hours of observation, etc., are included.

Data on lake levels, freeze and thaw dates, and sunspot numbers are included for stations which supplied them.

In all seven volumes are planned, each covering a geographic area. The succeeding six will be (not necessarily in this order) Africa, Asia, Europe, South America, Central America-West Indies-Caribbean-Bermuda, Australia-New Zealand-Antarctica-Oceania.