UDC 551.510.53:551.524.735"1966.2"

THE WARMING OF THE UPPER STRATOSPHERE IN FEBRUARY 1966 AND THE ASSOCIATED STRUCTURE OF THE MESOSPHERE

RODERICK S. QUIROZ

Upper Air Branch, National Meteorological Center, ESSA, Hillcrest Heights, Md.

ABSTRACT

A major warming above the 10-mb level in February 1966 is described with the aid of rocket data from high-latitude stations at Heiss Island (81° N.) and Churchill (59° N.), together with high-level radiosonde reports from Berlin, Germany. At Heiss Island a temperature increase of 85°C is deduced at an altitude of 32 km, preceded by a record wind of nearly 400 kt (at 39 km), verified through thermal wind computations. Extraordinary vertical motions reaching 60 cm sec^{-1} are calculated from the thermodynamic equation. The warming is shown to have been similar to major warmings of the lower stratosphere in several respects, including the occurrence of 1) high winds related to pressure-gradient intensification several days before the peak temperature and 2) *upward* vertical motion in high latitudes in response to strong horizontal advection. Rocket soundings extending to the mesopause indicate the occurrence of warming to a height of at least 70 km. The mesospheric data further suggest that prior to warming events the upper polar mesosphere is characteristically cold, in accord with radiative calculations for winter. However, the mesospheric analysis is hampered by poor sampling, and an improved program of observation is needed to clarify the full structure of "stratospheric" warmings.

1. INTRODUCTION

Close study of rocketsonde temperature profiles for such high-latitude stations as Churchill, Canada (59° N., 94° W.), and Heiss Island, Franz Josef Land (81° N., 58° E.), suggests that major warmings of the upper stratosphere may have occurred in winter that could not be readily detected below 10 mb (about 30 km). Documentation of such cases is now becoming possible with the aid of synoptic map analyses above 10 mb, being produced by several groups (e.g., Staff, Upper Air Branch of the U.S. Weather Bureau's National Meteorological Center, 1967*a*, 1967*b*, 1969; Kriester et al., 1967).

One event occurred in late February to March 1964, when anomalous warming led to the establishment of an anticyclone over the Pole throughout the middle and upper stratosphere, followed by the temporary return of a cyclonic circulation above 5 mb, before the onset of the normal anticyclonic circulation of summer (Quiroz, 1968). Although this warming may be described as an *asymmetric* or *single-source* case, in the terminology of Wilson and Godson (1963), it may also be termed "major" insofar as two important criteria were fulfilled: 1) a large-scale reversal of the meridional temperature gradient occurred followed by 2) a general reversal of the circulation. (In late March, easterly flow prevailed as far south as the Mexican border at levels down to 10 mb.)

Two years later in early 1966, an event occurred that is more interesting from several viewpoints and for which more extensive documentation is available. Like the major stratospheric warming of December 1967 (Johnson, 1969), this event was preceded by extraordinarily high winds, with a speed of 198 m sec^{-1} (385 kt) reached at an altitude of 39 km over Heiss Island on February 1. To our knowledge this is the maximum wind ever reported for the stratosphere,[1] exceeding the maximum wind (182 m sec^{-1}) reported over West Geirinish (57° N., 07° W.) on Dec. 13, 1967.

A preliminary description of the upper stratospheric warming of early 1966 has been given by Labitzke (1968), partly on the basis of radiosonde data for Berlin, which reached as high as 36–39 km. In addition, Williams (1968) has discussed effects of the warming on the broad circulation over the western portion of the Northern Hemisphere.

The purpose of this paper is to provide further significant details of the warming, deduced primarily from time sections extending up to the mesopause. These are based on a concentrated series of rocket soundings obtained by the Soviets at Heiss Island and on combined rocket grenade and small rocket soundings at Churchill. The mesospheric data examined not only indicate the occurrence of a warming event throughout the mesosphere, but they also suggest that the high-latitude mesosphere is relatively cold in early and late winter, in conformance with the radiative calculations of Leovy (1964). The contrasting impression of a prevailingly warm winter mesosphere in high latitudes has been based primarily on the results of rocket grenade soundings (Nordberg et al., 1965) taken predominantly in midwinter.

The warming discussed was remarkable not only for its great spatial extent but also for the intensity of the pressure gradient that prevailed in its early stages. The validity of the extraordinarily high winds observed on

[1] Winds exceeding 200 m sec^{-1} are not rare above about 70 km.

February 1 will be examined in section 4. Also noteworthy are unexpectedly great rising motions deduced for Heiss Island during the warming process (section 5). The warming at this station is explainable primarily by horizontal heat transport into the region, and it is believed that any appreciable adiabatic heating due to subsidence would have occurred at some distance from the station. The pattern of vertical motion is qualitatively similar to that recently deduced for high latitudes by Walts (1968) for the stratospheric warming of late January 1958.

2. MIDSTRATOSPHERIC INDICATIONS OF THE WARMING

At the 10-mb level, the first indication of something unusual was a temperature increase to −20°C over the Kamchatka Peninsula on Jan. 30, 1966. The daily 10-mb maps then indicate a spreading of the warm air across the pressure height contours and slightly upstream, over Arctic Eurasia. By February 7, a second area of high temperature (−20°C) is observable over western Europe as well. At the North Pole, analyzed values of the temperature and height of the 10-mb surface (fig. 1) indicate warming by about 30°C in the first week of February, followed by a dramatic rise of the pressure surface after midmonth. Synoptically, the peak height corresponds to a time around February 26 when the modified Aleutian anticyclone was centered near the Pole. By this time the polar vortex was split into two cells, one over the North Atlantic and the other over eastern Europe. At the beginning of March the anticyclone itself split and weakened, and in mid-March the principal cyclonic system returned to a normal polar position, but with a weakened circulation.

The foregoing symptoms provide only a glimpse of the warming event, with its dynamic consequences, as perceived at the 10-mb level. An analysis of the 3-mb temperature fields on January 29 (Labitzke and Schwentek, 1968) indicates the presence of a warm temperature cell (−5°C) west of France in addition to the warm air over Kamchatka. By February 10, their analysis indicates the warmest air (+5°C) to be just east of Greenland (fig. 2), but relatively warm air covers the entire hemisphere (note the −5° isotherm over central United States). (In a nonwarming winter situation, 3-mb temperatures as low as −60°C or lower are not uncommon in much of the polar area.)

3. TIME SECTIONS TO 80 KILOMETERS FOR HEISS ISLAND AND CHURCHILL

The above-mentioned analyses were drawn on the basis of both rocket and high-level radiosonde data, but without the benefit of the rocket results from Heiss Island. The measurements at this key northern station may often serve as a sensitive indicator of the changing character of the polar vortex and, moreover, provide a valuable indication of the extremely low values of temperature, pressure, and density attainable near the Pole.

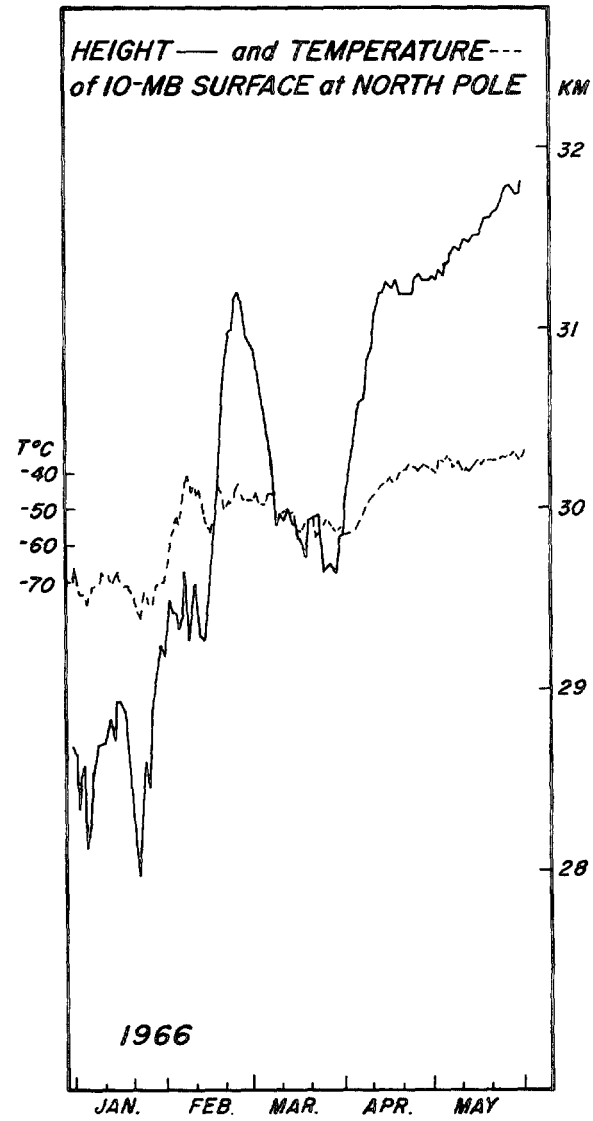

FIGURE 1.—Height and temperature of 10-mb surface at the North Pole in early 1966, based on analyzed map values.

Figure 3, analyzed from Soviet rocket soundings at Heiss Island, portrays the temperature and wind fields to the vicinity of the stratopause (to the mesopause, in 1965). This time cross-section is part of a larger figure we have prepared for the 2-yr period from mid-1964 to mid-1966. A total of 49 rocket soundings was available for the subperiod depicted in figure 3. During late January to early February, daily soundings were taken; but for practicality, data generally at 3- to 5-day intervals have been used in the cross-sectional analysis.

The data used were published (Tsentralnaya Aerologicheskaya Observatoriya, 1967, 1968) for each kilometric height, but only values at 2-km intervals to 50 km and 5-km above 50 km were used. The observational techniques have been described by Quiroz (1967) and are more amply described in the pertinent Soviet literature.

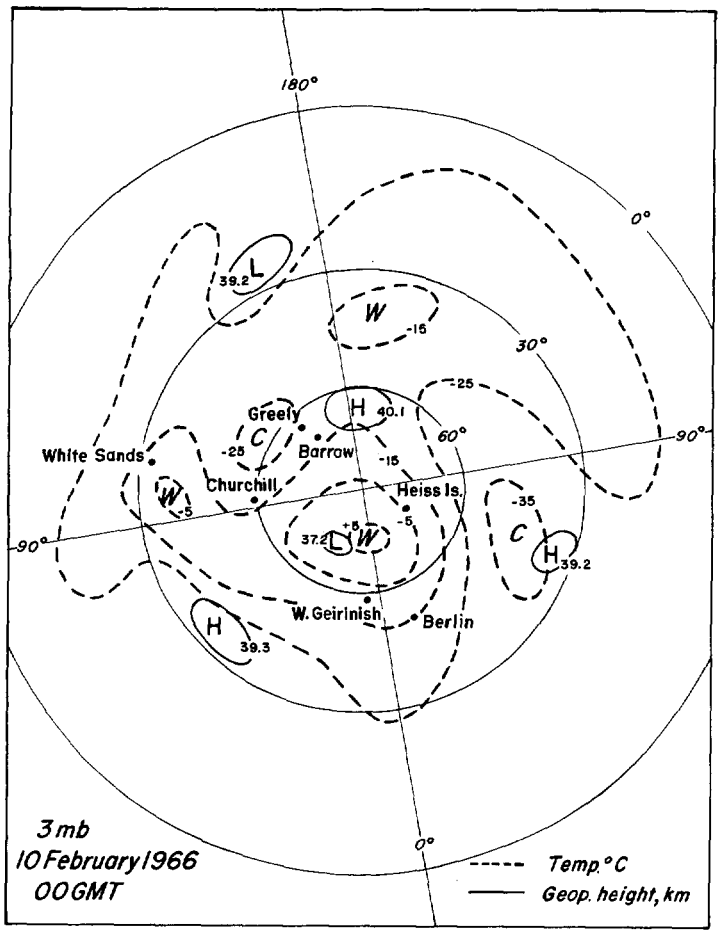

FIGURE 2.—Temperature field at 3-mb level on Feb. 10, 1966 (adapted from map prepared by Labitzke and Schwentek, 1968). Original chart contains isotherms at 5° intervals and contours at intervals of 160 gpm. Locations of stations mentioned in text are indicated. By February 10, the peak of the temperature wave had already been reached, as shown in subsequent figures.

The root-mean-square error in temperature, as given in the data reports of the Central Aerological Observatory (Moscow), is 3° at 40 km, 5° at 50 km, and 7°–10°C at 60–80 km. The winds are subject to errors of the order of 6–10 m sec^{-1}. The data reports contained radiosonde results as well. Above about 25 km, comparison of the rocket and radiosonde data in the region of overlap indicated that the rocket temperatures occasionally exceeded the radiosonde temperatures by a few degrees. In view of the possibility of infrared cooling error in radiosonde temperatures (Finger, Woolf, and Anderson, 1965), we have based the analysis on the rocket data; but in any case, the results are probably subject to an uncertainty of several degrees. The analysis for the upper mesosphere has been carried out with an awareness of not only the appreciable observational errors but also the difficulty of sampling in a part of the atmosphere that may be subject to large short-term variations (Smith et al., 1968). For Heiss Island, the rocket observations used in constructing figure 3 were taken close to 1200 GMT in 1965 and, with one exception, close to 1600 GMT in 1966.

The largest temperature increase (+85°C) at this station occurred at 32 km, where a temperature of +20°C was recorded on February 7, within a few days after the peak wind. Aside from the large amplitude of the temperature wave, the nearly simultaneous peaking throughout the 30–40-km layer is remarkable. Similar behavior was observed at Berlin, Germany, as shown in a cross section based on radiosonde data (fig. 4), at 35–38 km; i.e., the isotherms are nearly vertical in a limited layer. At Heiss Island, the warming penetrated much deeper into the middle stratosphere, and indeed was detectable as low as 20 km. A minor pulsation in the temperature field preceded the major warming at Berlin. At Heiss Island, several waves are evident, beginning with a well-defined system of warm air just below 50 km at the end of November. (The discussion of the mesospheric temperatures will be left to a later section.)

Temperatures observed over Churchill, Canada, are shown in figure 5. This time cross-section was based on routine meteorological rocket soundings, combined with a series of four rocket grenade soundings taken during the period depicted (Smith et al., 1968). The grenade temperatures, which are average temperatures of layers with characteristic thickness of 3–4 km, are subject to an average observational error of less than 4°C—error varies from one station to another, according to the local geometry of the sound measurements (Smith et al., 1968). For nonmonotonic temperature-height structures, the temperature at discrete altitudes may differ, although perhaps only by a few degrees, from the layer temperatures. Some of the difference in the two soundings for early morning and noon, February 10, is likely due to short-term variations, mentioned earlier. One important distinction in the grenade data is that the two soundings of February 10 indicate a relatively cold upper mesosphere, as compared with the temperatures of January 24 and February 2.

Figure 6 gives the amplitude of warming at the three stations, Berlin, Heiss Island, and Churchill, as a function of height. Dates of maximum temperature are also shown. This figure, which should be interpreted qualitatively in view of the possible temperature error in individual observations, clearly indicates that:

a) The warming affected a broad geographic area with a time lag consistent with the analysis of Labitzke and Schwentek (1968); compare, for example, the dates of maximum temperature at 35–40 km.

b) Warming was greatest at the most northerly station and in the Eastern Hemisphere. Moreover, the warming at Heiss Island penetrated about 5 km lower than over Berlin.

c) Maximum warming at Churchill occurred at 40–50 km, somewhat higher than at the other two stations. Comparison of the three curves suggests a general rela-

356-409 O - 69 - 3

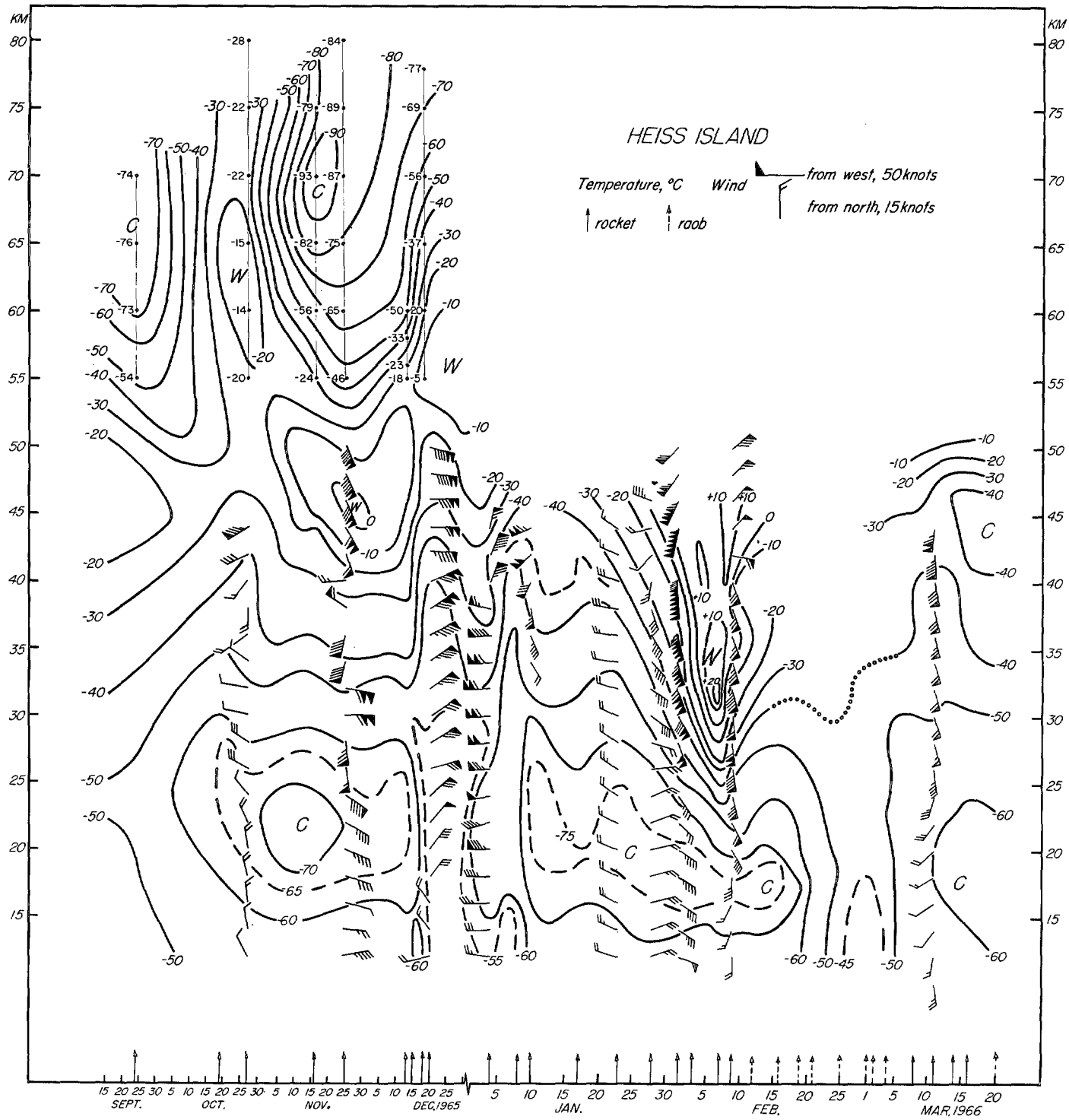

FIGURE 3.—Time section for Heiss Island, Franz Josef Land, based on Soviet rocket soundings. For readability, only temperatures above 55 km and selected wind data are entered; dates of all soundings used for the analysis are indicated at the base of the figure. Radiosonde data were used to complete the analysis in the second half of February. Except for the six mesospheric soundings entered on the figure, the rocket data used terminated generally at 45–50 km.

tionship between the intensity of warming and the altitude of maximum warming *in the stratosphere*; but more examples would be needed to arrive at a conclusion.

Such a relationship was implied by Finger and Teweles (1964), in their discussion of the major stratospheric warming of January 1963, by pointing out that adiabatic warming associated with downward motions would tend to result in greater heating of the inversion layer below the stratopause. This argument is based on the proportionality of the local temperature change to the vertical

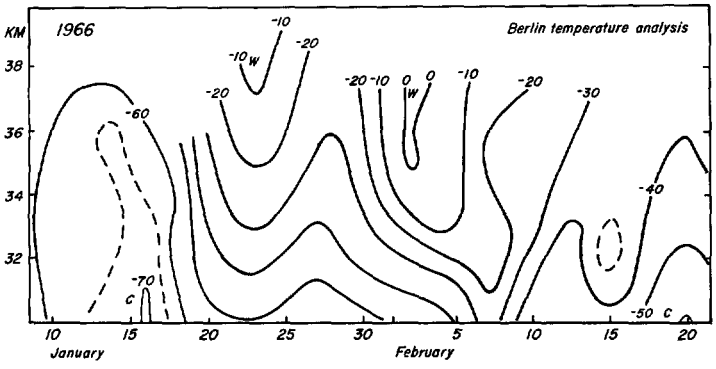

FIGURE 4.—Time section for Berlin, Germany (adapted from Labitzke, 1968), based on temperatures from high-altitude radiosonde observations. Major warming in early February was preceded by a minor pulse around January 20–25.

motion, w, and the environmental lapse rate,

$$\frac{\partial T}{\partial t} \propto -(\Gamma-\gamma)w \qquad \gamma=-\frac{\partial T}{\partial z} \qquad \Gamma=-\frac{\partial T}{\partial z_{ad}} \tag{1}$$

The local temperature change depends, in addition, on the horizontal advection and the nonadiabatic heat loss or gain. Other things being equal, however, equation (1) indicates that for the same value of downward motion the temperature change is greater in a layer of small lapse rate (or inversion).

4. THE MAXIMUM WIND

Although the cause of midwinter warmings is still obscure (Reed, 1963; Miyakoda, Strickler, and Hembree, 1969), enough cases have been observed to permit some generalizations concerning their synoptic development. It is known, for example, that at moderately high latitudes, intensification of the horizontal pressure gradient commonly occurs in connection with a warming. The increase in pressure gradient occurs after one or both of the following processes:[2]

1) lowering of the depth of the polar vortex to a midwinter minimum, in the absence of sunlight; and

2) hydrostatic buildup of an anticyclone in middle or subpolar latitudes (such as the Aleutian anticyclone), in connection with a temperature increase in its vicinity.

From the region of the anticyclone, a system of warm air is observed to "move" across the pressure contours with a net movement to higher latitudes. (In reality, the synoptic development in three dimensions may be quite complicated, with one or two anticyclones taking a part in the action and vertical motion undoubtedly playing a major role.) Following a rise of temperature in the polar region, a high-pressure system may develop, displacing the

[2] Deepening and filling of the pressure systems in early 1966 are depicted in figure 10 in the Appendix.

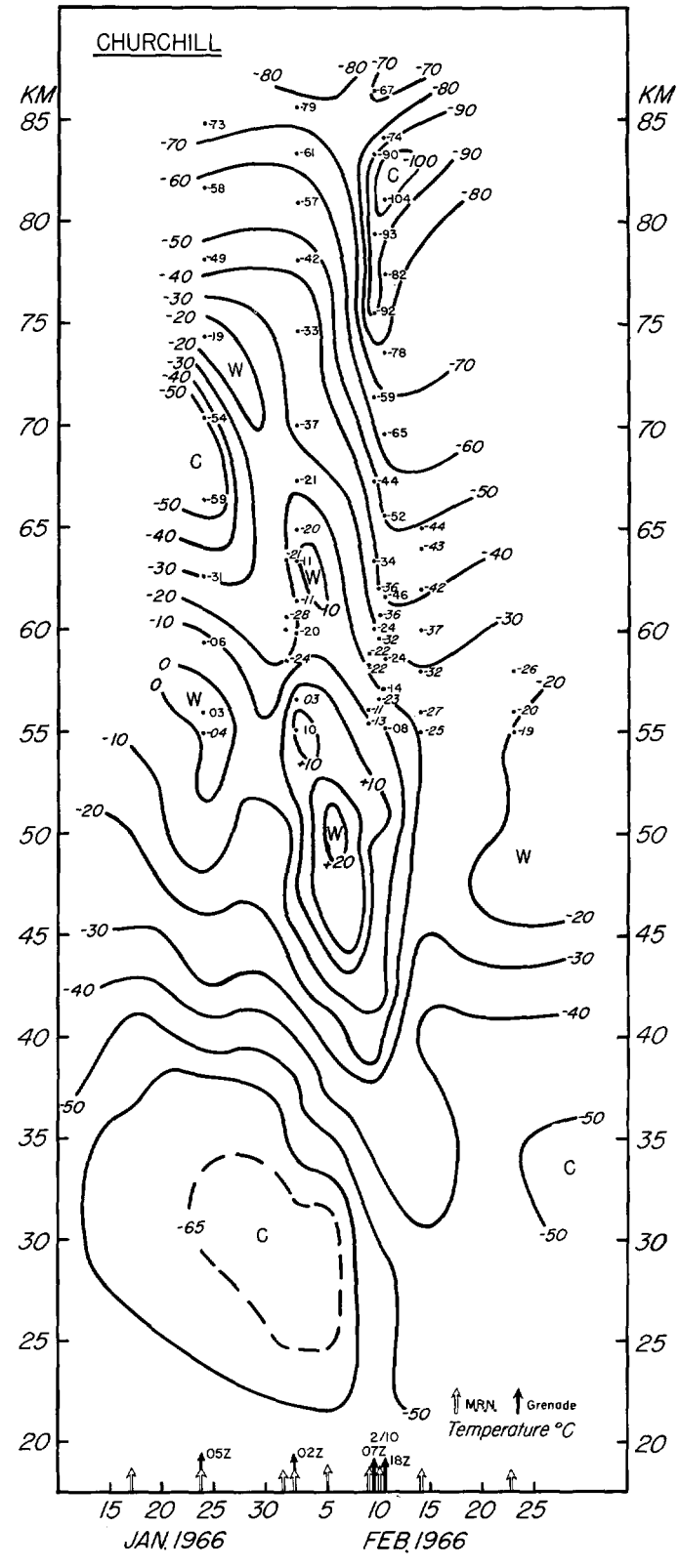

FIGURE 5.—Time section for Churchill, Canada, based on four rocket grenade observations and nine small meteorological rocket soundings. For readability, only data above 55 km are entered. Aerodynamic heating corrections were applied to the small rocket soundings above 50 km; where differences between grenade and small rocket temperatures occurred, the former were favored in the analysis. Dates of all soundings used are indicated at the base of the figure.

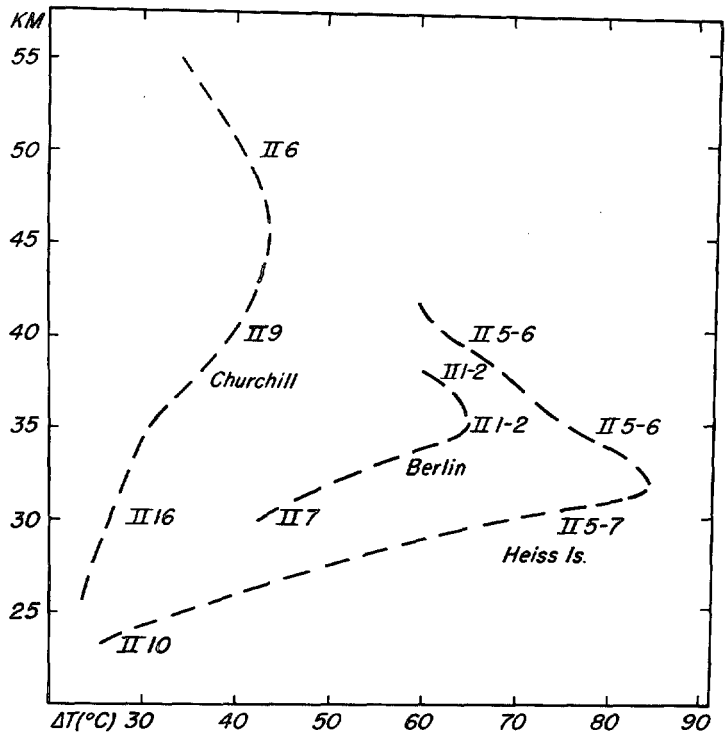

FIGURE 6.—Course of the warming at Berlin, Germany, Heiss Island, Franz Josef Land, and Churchill, Canada. Depicted is temperature increase from the lowest temperature in January to maximum temperature in early February. Dates of the peak in temperature wave are shown at specified altitudes.

polar vortex to lower latitudes, with attendant changes in the circulation. In several cases, a splitting of the polar vortex has occurred, with a change from a wave number 1 to a wave number 2 pattern in the height field.

The stage of pressure gradient intensification is particularly interesting for two reasons: 1) over a fixed location, this stage may in some cases be a precursor of local warming; and 2) high winds are to be expected. The rationale for 1) is that, as mentioned above, systems of warm air have been observed to move across the pressure contours, into the region of maximum contour gradient. At West Geirinish, the maximum winds mentioned in the Introduction occurred 8 days in advance of the maximum observed temperatures (Dec. 21, 1967). At Heiss Island, the peak wind occurring on Feb. 1, 1966, preceded the highest reported temperature by 6 days (fig. 3). Similarly, maximum winds observed in connection with the major warming of January 1963 occurred about 10 days before the height of warming (Finger and Teweles, 1964).

So extraordinary a wind (198 m sec^{-1}) should ordinarily arouse skepticism; but within the content of an advancing stratospheric warming, further examination is clearly warranted. To test the reasonableness of this wind, the thermal wind equation was applied as follows:

a) The "horizontal" temperature gradient on February 1 was calculated along the 80th parallel between 58° E. (Heiss Island) and a point at 20° E. (ΔS=737 km). At

TABLE 1.—*Winds observed at Heiss Island on Feb. 1, 1966 (columns 1–3), compared with results of thermal wind computation (column 4)**

Altitude (km)	Pressure (mb)	1 Polar direction (deg**)	2 Velocity (m sec^{-1})	3 Southerly component (m sec^{-1})	4 Reconstructed southerly component (m sec^{-1})
29.0	10			54	54
30		158	66	61	65
32		158	87	81	86
33.8	5				106
34		162	112	106	109
36		166	146	142	136
37.6	3				158
38		170	180	176	164
39		173	198	196	178
40		176	197	195	191
40.6	2				200

*Data in column 4 based on vertical shears of 12–14 m sec^{-1} km^{-1} calculated from temperature gradients in layers 10–5, 5–3, and 3–2 mb, as discussed in the text.
**Example: direction of 90° refers to wind from east.

the 10-mb level, the center of cold air was situated just to the west of this point, while warm air was advancing on Heiss Island. Gradients were determined at several pressure levels (10, 5, 3, and 2 mb) from 1) the reported temperature and pressure-height data for Heiss Island and 2) analyzed temperature data for 20° E. from the available constant-pressure maps (Kirch et al., 1966–1967; Kriester et al., 1967; Labitzke and Schwentek, 1968; and Staff of the U.S. Weather Bureau's National Meteorological Center, 1967). (These maps are based on sparse data in high latitudes and do not take into account the rocket data for Heiss Island, which were not generally available at the time of preparation. The analyzed temperatures for 20° E. could well be influenced by both of these factors.) From the gradients at the above-mentioned pressure levels, average gradients were then determined for the layers 10–5 mb, 5–3 mb, and 3–2 mb, whose thicknesses ranged from 3 to 4.8 km.

b) The vertical shear of the meridional wind component was computed by means of the appropriate form of the thermal wind equation,

$$\frac{\partial v}{\partial z}=\frac{g}{fT}\left(\frac{\partial T}{\partial x}\right)_p.$$

c) A profile of the meridional wind was constructed, beginning with the rocket-measured value at 29.0 km, the height of the 10-mb level at Heiss Island. (The rocket wind agrees closely with the geostrophic wind indicated by the 10-mb map analysis for February 1.) The profile thus constructed consisted of winds only at the pressure levels indicated above. Linearly interpolated values for every 2 km are compared with the observed data in table 1.

d) For self instruction, a second thermal wind computation was carried out on the basis of *constant-height* temperature gradients, neglecting the shear contribution

due to the slope of the isobars. The wind results differed from those in column 4, table 1, by only a few percent, in agreement with the analysis of Holmboe, Forsythe, and Gustin (1945).

Inspection of table 1 shows that the observed winds agree reasonably well with the computed values. Differences might be due to the nonlinear character of the temperature gradient and also to difficulty in obtaining representative wind data in profiles containing irregular oscillations (Miller, Woolf, and Finger, 1968). The second factor, however, is probably not significant in this case, as a plot of the Soviet rocket wind data reveals a reasonably smooth profile (not shown).

The occurrence of extremely high winds was not limited to the vicinity of Heiss Island. The orientation and intensity of the pressure height gradient at 10 mb and above at the beginning of February were such that very high northerly winds would be expected in the northwest Arctic Region of North America. A rocket grenade observation taken at Point Barrow, Alaska (71° N.), on February 1 indicated two wind maxima, 128 m sec^{-1} (from north) at 46 km and 187 m sec^{-1} (from northeast) at 56 km (for complete data, see Smith et al., 1968). For Fort Greely, Alaska (64° N.), Williams' analysis (1968) of the meridional wind, based on meteorological rocket data, shows a maximum northerly flow of 140 m sec^{-1} on February 3 at about 47 km. His data further show that a strong meridional flow, reduced by one-half, occurred as far south as White Sands, N. Mex. (32° N.). At all locations mentioned above, there were marked changes in the circulation later in the month, with strongly reduced flow. The combined evidence thus points to extraordinary changes in the zonal and eddy kinetic energies associated with the circulation of, at least, the upper stratosphere.

5. THE FIELD OF VERTICAL MOTION AT HEISS ISLAND

The vertical motion as a function of time and altitude was computed for Heiss Island for the period from mid-January to mid-February (fig. 7). The computations are at 4-km intervals, from 20 to 44 km, and were based on the observational data for the dates indicated in the figure. The thermodynamic equation was used, namely,

$$w=-\frac{1}{\Gamma-\gamma}\left(\frac{\partial T}{\partial t}+\mathbf{V}\cdot\nabla_H T-\frac{1}{c_p}\frac{\delta h}{dt}\right), \qquad (2)$$

where w is the veritcal motion (positive upward), Γ the adiabatic lapse rate, γ the environmental lapse rate; and the terms in parentheses are, respectively, the local temperature change, the horizontal advection, and the temperature change due to diabatic processes.

The local temperature change was estimated from the analyzed temperature field (fig. 3), using data over 3–5-day periods. A shorter time interval might have been used, but it was felt that data over 3–5-day intervals would

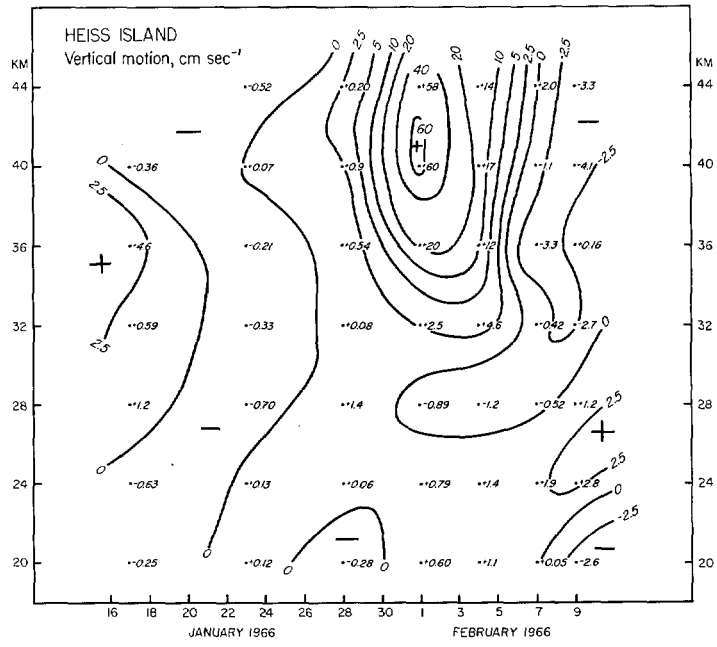

FIGURE 7.—Vertical motion (positive upward) at Heiss Island, Franz Josef Land, estimated from the thermodynamic equation (see text). Large upward motions during the warming are of special interest.

give a better indication of the general warming or cooling trends.

The advection term was computed directly from the observed wind and temperature data at the station, using data over 2-km thicknesses and making use of a transformation realizable through the thermal wind equation (Kays and Craig, 1965), namely,

$$\mathbf{V}\cdot\nabla_H T\simeq-\frac{fT}{g}V^2\frac{\partial\theta}{\partial z}, \qquad (3)$$

where $V^2=(u^2+v^2)$ and $\tan\theta=u/v$. Equation (3) involves the geostrophic approximation and is approximate, moreover, because constant-height rather than constant-pressure data were used. Only a small percentual error in the computed vertical motion should arise from the use of constant-height data, in view of the discussion in the preceding section, concerning thermal wind computations at constant height versus constant pressure.

For the diabatic heating term, cooling rates of -1°C day^{-1} at 20 km to -3°C day^{-1} at 44 km, held fixed at each altitude, have been assumed. These are based on winter solstitial values for 80° N. calculated by Murgatroyd and Goody (1958), and they are subject to considerable uncertainty. Except in the neighborhood of zero vertical motion, however, the error in this term should not greatly affect the overall results, as its contribution amounts roughly to only 1 mm sec^{-1} per degree of cooling.

More serious errors arise from other sources, and the numerical results can be judged accurate only within an order of magnitude. The greatest potential error source is

in the determination of the wind. A 10-percent error in the wind speed would lead to an error near 20 percent in w, in view of the exponent in equation (3). The largest error by far might come from measurement of the wind direction; this error would be proportional to $\epsilon/\Delta\theta$, where ϵ is the direction error, and would tend to be greater for small values of $\Delta\theta$. All the vertical motion values exceeding 10 cm sec^{-1} (fig. 7) correspond to observations with large values of the wind speed and small values of the direction change with height (all were cases of veering). In view of these limitations in the computations, only a broad qualitative interpretation of figure 7 is possible.

Previously determined maxima of the absolute value of the vertical motion in association with stratospheric warmings are in the neighborhood of 8 cm sec^{-1} (Craig and Lateef, 1962; Finger and Teweles, 1964), at levels up to 10 mb. The large values calculated for February 1, at the time of maximum wind and advection, are therefore noteworthy; near 40 km, the motion is roughly one-half meter second^{-1}. Although only an order-of-magnitude accuracy is ascribed to these data, our confidence in the results is increased by the systematic pattern indicated by the collection of soundings. In particular, it is pertinent to note that the sounding from which the largest vertical motions were deduced (February 1) involved a steady veering of the wind over a deep layer, as is shown in table 1.

More arresting, perhaps, is the occurrence of *upward* motion above 30 km from January 28 to February 5, during the period of warming. (The peak temperatures at Heiss Island, it will be recalled, were not reached until after February 5.) Craig and Lateef (1962) emphasized that, during rapid warming in late January 1957, the vertical motion pattern was characterized by a "very large area of uniformly downward motion." It is also noteworthy that the large subsiding motions were concentrated over central North America, thus in relatively low latitudes. Finger and Teweles (1964) found maxima of upward motion lying generally north of the downward maxima (10 mb, Jan. 23, 1963).

The joint occurrence of warming and rising motions in high latitudes appears initially enigmatic, but is explainable by the balance of terms required in equation (2), which we may conveniently restate as:

$$\frac{\partial T}{\partial t}=(1/c_p)(\delta h/dt)-(\Gamma-\gamma)w-\mathbf{V}\cdot\nabla_H T.$$

The local temperature increase at Heiss Island ranged up to 14°C day^{-1} during the period of warming. The advection term, however, was generally several factors greater. For a balance of terms, assuming a constant or negligibly small value of the diabatic temperature change, strong cooling with upward motion is implied. Indeed, as Walts (1968) has pointed out in his recent study of a warming event in 1958, the rate of warming under these conditions would be much higher than observed if it were not for the concurrent cooling expected with rising motion.

The preceding analysis applied to the geographical location under consideration. Strong subsidence could well have occurred at some distance from the station, creating, through adibatic compression, the source of warm air advected to the station.

Mahlman (1966) has ruled out the adiabatic descent mechanism as the cause for the 1958 warming *on the planetary scale*. The importance of subsidence for explaining large temperature rises over smaller geographical regions was not ruled out. Walts (1968) investigated the 1958 warming in limited regions between 50° N. and 80° N., at 100 and 50 mb. Interestingly, he found a general behavior that is qualitatively similar to that shown in figure 7 for Heiss Island, with rising motion as the dominant feature during warming. In each of three regions examined by Walts, there was warming by horizontal eddies (advection) and cooling by a mean rising motion. A further significant finding was that sinking motion occurred just south of the area where the warming was observed.

From the evidence accumulated to date, the vertical motion associated with stratospheric warmings emerges as a complicated function of time and space. Both subsidence and upward motion, the latter preferentially in high latitudes, appear to be of importance.

6. THE TEMPERATURE STRUCTURE IN THE MESOSPHERE

Rocket grenade observations taken at Churchill and Pt. Barrow (Nordberg et al., 1965) have indicated a *warm* upper mesosphere in winter, with the mean temperature at 70 km close to 230°K. The mesospheric analysis for Heiss Island (fig. 3), indicating temperatures down to 180°K in early winter, is therefore unexpected. A change to a warm regime is further indicated in mid-December. A real longitudinal variation, such as has been observed in the stratosphere, may partly explain the lower temperatures at the Soviet station in comparison with the data for the North American locations. The more significant feature, however, is believed to be the temperature increase in midmonth indicated in two soundings on December 13 and 18. Since the mesospheric analysis for Heiss Island is based on only six high-altitude soundings, it is pertinent to inquire if such behavior might be detected in the historical rocket grenade data for Churchill.

A review of individual soundings obtained since 1957 does indeed suggest that the winter mesosphere is relatively cold on some occasions. The two grenade soundings for Feb. 10, 1966 (fig. 5), are a case in point; these indicate temperatures of about 170°–180°K at the 80-km level, in contrast to a value of 230° given for 60° N. (January) in the *U.S. Standard Atmosphere Supplements, 1966* by the Environmental Science Services Administration, National Aeronautics and Space Administration, and U.S. Air

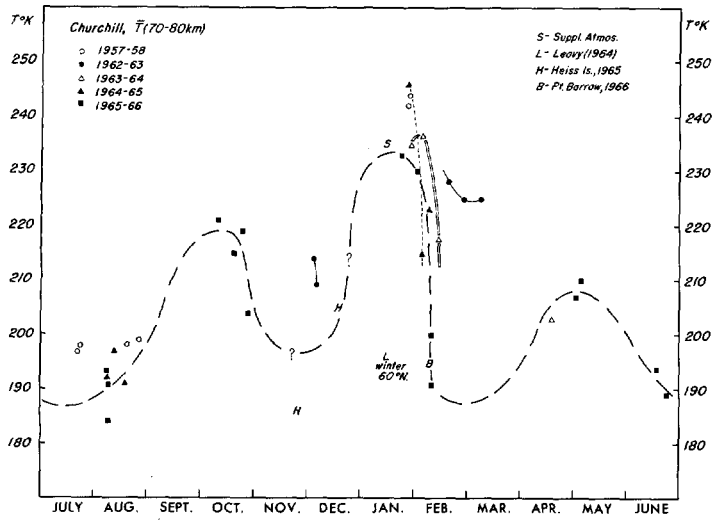

FIGURE 8.—Mean temperature of the layer 70–80 km calculated from individual rocket grenade soundings at Churchill, Canada (59° N.), 1958–1966, and entered for actual dates of soundings. Note relative lack of data in November–December. Also entered are 1) mean January temperature for 60° N. (75 km) from *U.S. Standard Atmosphere Supplements, 1966*, by the Environmental Science Services Administration, National Aeronautics and Space Administration, U.S. Air Force (1967), based largely on the rocket grenade results prior to 1966; 2) Heiss Island reported temperatures in November-December 1965; and 3) radiational cooling temperature computed by Leovy (1964) for 75 km, 60° N., winter.

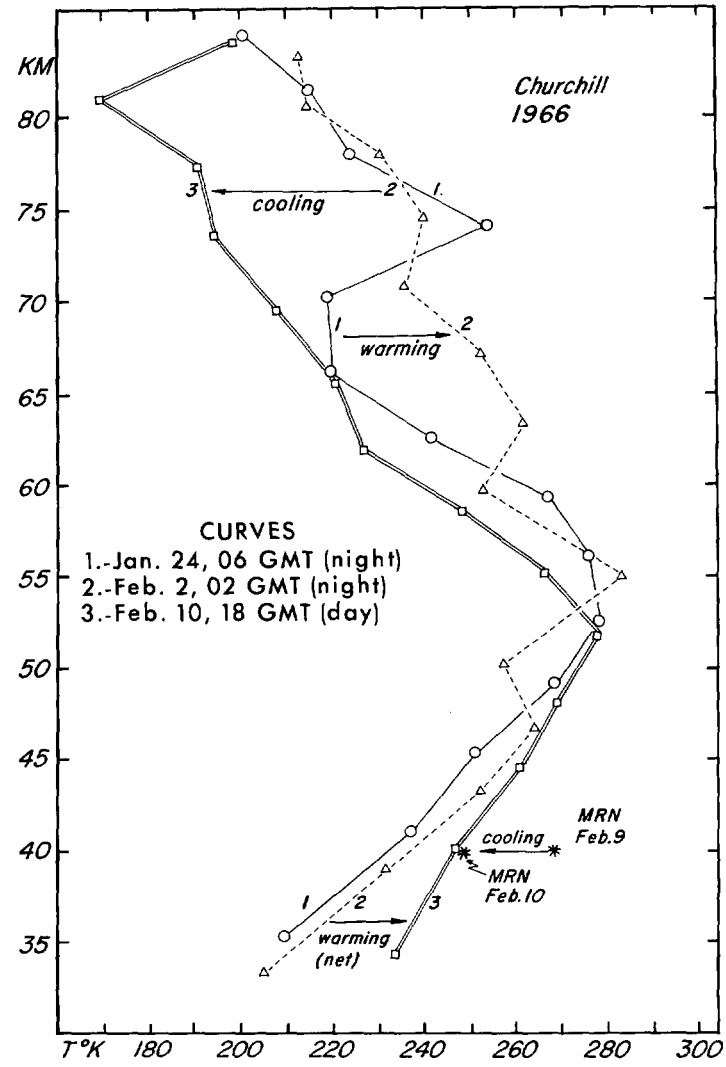

FIGURE 9.—Grenade soundings for Churchill during January–February 1966, indicating apparent progression downward of temperature wave. At 40 km, small Meteorological Rocket Network (MRN) rocket sounding indicates maximum temperature would have occurred by February 9, with rapid cooling thereafter.

Force (1967). Whereas at Heiss Island a change from a cold to a warm winter regime is suggested in December, the Churchill data indicate a change from a warm to a cold regime in February.

Careful examination of rocket grenade soundings in earlier years reveals that the change from a warm regime to a cold regime in the upper mesosphere during February is a recurring feature of the upper mesosphere. This is borne out in figure 8 depicting the mean temperature of the layer 70–80 km, as calculated from all available grenade soundings for Churchill, 1958–1966. (A low-apogee sounding in November 1956 and two soundings with questionable data in December 1957 were not used.) The following points are noteworthy:

a) A rapid temperature descent occurred in February in each of the years 1963–1966, as noted above.

b) The wintertime observational sample is heavily concentrated in late January–early February. Practically no observations are available for early winter. (A similar situation exists with regard to grenade observations at Pt. Barrow, Alaska (71° N.), and Wallops Island, Va. (38° N.).)

c) The October–December data for 1962 and 1965 suggest the occurrence of low temperature in early winter, preceding the warm temperatures observed in January–February. Heiss Island temperatures (75 km) for November–December 1965 are plotted for comparison.

d) The apparent maxima in autumn and spring suggest the presence of a semiannual variation in the temperature, but obviously its verification would require more observations. This feature is also suggested in the Heiss Island time section (fig. 3).

These points, in particular a) and c), are compatible with the concept of a warming of the entire mesosphere, penetrating down to the middle stratosphere in January–February 1966. Some details of the evolving temperature structure are not clear. Evidence has been mentioned of minor pulsations of warming of the upper stratosphere, preceding the major warming of early February; and it would be difficult to establish, for example, that the warm cell in the Churchill time section centered at 50 km was uniquely related to the warm cell at 70–75 km at the end of January. Inspection of the grenade temperature profiles for Churchill (fig. 9) during this period increases our

confidence that there was a systematic temperature change propagated from the upper mesosphere to the stratosphere. Since the dates of observation do not necessarily coincide with the dates of peaks and troughs in the temperature wave, the full amplitude of cooling and warming is not shown. For example, peak temperature at 40 km was reached before February 10, as indicated by the data from routine meteorological rocket soundings. By February 10, the 40-km temperature had lowered to a value close to 248°K measured in both the grenade and routine rocket soundings.

The winter temperature structure described in this section is therefore bimodal, with low temperatures in early winter and near the end of winter on the one hand and high temperatures around midwinter on the other. Such a structure has been well known in the stratosphere for many years. A better definition of the mesospheric temperature structure will require more observations in early winter.

It is interesting to note that a mesopause temperature in the neighborhood of 196°K seems plausible for early winter (60° N.), on the basis of the data presented here. Such a value has been predicted by Leovy (1964), from computations based on radiative heating and cooling alone. Since the midwinter events which heretofore have been referred to as *stratospheric* warmings appear to be, in general, warmings of both the mesosphere and stratosphere, it is believed that final identification of the source of heat for the upper mesosphere in winter may well depend on the explanation of stratospheric warmings. In view of past interest in explaining the winter warmth of the upper mesosphere (Kellogg, 1961; Newell, 1963; and others), more examples of stratospheric warmings need to be studied at mesospheric levels as well.

7. SUMMARY

The upper stratosphere warming of February 1966 was in many respects similar to midwinter warmings that have clearly penetrated the lower stratosphere. The warming affected a large part of the Northern Hemisphere, as shown by data for three disparate locations, Heiss Island, Berlin, and Churchill. The largest temperature increase was observed at Heiss Island (about 85°C), where indeed warming was detected as low as 20 km ($\sim$ 45 mb).

At this station a wind of nearly 200 m sec^{-1} was reported near 40 km. Thermal wind computations were carried out that support the validity of this wind, believed to be the highest yet observed in the stratosphere. The maximum wind occurred several days in advance of the peak temperatures, as has been observed in other stratospheric warmings, such as the major events of January 1963 and December 1967. The occurrence of high winds in advance of local warming may be explained by pressure-gradient intensification prior to the advance of warm air.

Upward vertical motions to 60 cm sec^{-1} were calculated during the warming at Heiss Island, although only an order-of-magnitude accuracy is ascribed to the results. Evidence is cited indicating that both subsidence and rising motions occur with stratospheric warmings, with the latter occurring preferentially in high latitudes and being attributable to strong warm-air advection.

Examination of special rocket soundings to the mesopause obtained at Heiss Island and Churchill suggests that the warming was part of an event that affected the mesosphere as well.

Some of the mesospheric data indicate low temperatures in early winter, consistent with the radiative-equilibrium results of Leovy (1964) and in contrast to the concept of a prevailingly warm upper mesosphere in the winter of high latitudes. More observations of the mesosphere, particularly in early winter, are needed to clarify the mesospheric structure and to understand better the full vertical structure of "stratospheric" warmings.

APPENDIX

In this study, no attempt was made to find a relationship between the warming of the upper stratosphere and events in the troposphere. A graph of selected stratospheric and tropospheric parameters (fig. 10), however, suggests that the warming event may have taken place in response to tropospheric behavior.

Curve (c) was obtained by subtracting the central height value of the 10-mb polar vortex (curve b) from the highest height value found north of 45° N. (curve a) and is, therefore, a rough measure of the pressure gradient between middle and high latitudes (see discussion in section 4). The two peaks of curve (c), occurring around January 20 and 30, are of special interest, since they precede the two pronounced temperature maxima (curve d) for Berlin, 35 km, by about 3 days. The first peak in curve (c) is due to both a buildup of the Aleutian anticyclone and a deepening of the polar vortex, but is mainly due to the latter. The main peak, around January 30, is clearly due to a strong buildup of the Aleutian anticyclone.

It is also noteworthy that the peaks in curve (c) are preceded by an upward vertical flux of energy through the 100-mb level (curve e), which took place nearly concurrently with minima in the 700-mb zonal index (curve f). The vertical flux of geopotential depicted is in planetary wave number 1. Large negative values in wave number 2 (not shown) occurred around January 7 and February 19.

Whether the behavior shown in figure 10 might be typical of stratospheric warmings in other years appears to merit investigation. The selection of parameters to be compared is obviously of some importance, particularly in regard to the altitude and location(s) chosen for depicting the temperature changes.

It is emphasized that from a physical point of view the parameters represented in figure 10 may not be strictly comparable. The zonal index values shown, for example, refer to middle-high latitudes (55°–70° N.) of the Western Hemisphere, whereas the parameter for the vertical flux of geopotential $[\omega^* z^*]$ represents a zonal average (denoted by the brackets) integrated from 17.5° N. to 82.5°

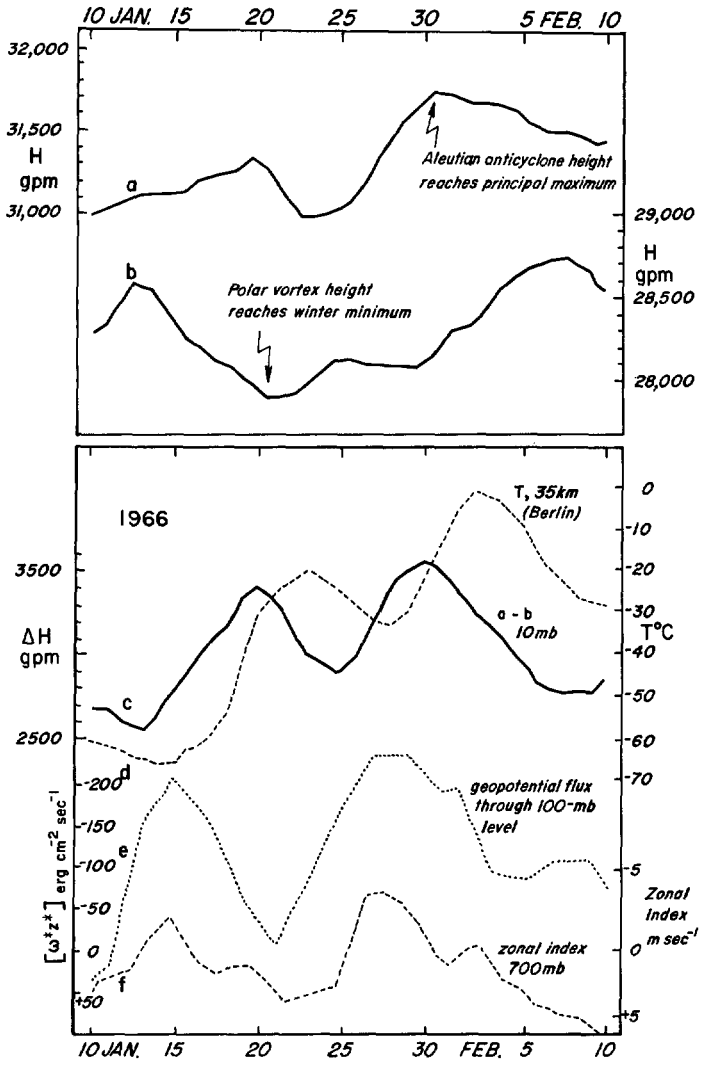

FIGURE 10.—Tropospheric and stratospheric parameters during early 1966. (a) maximum height of 10-mb surface north of 45° N.; during period depicted, this was the height of the Aleutian-Siberian anticyclone. (b) central height of 10-mb polar vortex, from maps analyzed at the Berlin Free University (Kirch et al., 1966, 1967; Kreister et al., 1967). (c) difference, (a) minus (b). (d) Berlin, Germany, temperature, 35 km from Labitzke cross-section (1968). (e) vertical flux of geopotential, integrated over latitudes 17.5°–82.5° N., through the 100-mb level, wave number 1. Negative values refer to upward flux. (f) polar zonal index (55°–70° N.), 700 mb, Western Hemisphere. Note parallelism of (e) and (f), both leading (c) by 3–5 days. Berlin temperature, 35 km, lags (c) by about 3 days. Low zonal index values in mid- and late January were associated with blocking of westerlies.

N. This parameter has been considered previously in energy studies of stratospheric warmings, e.g., by Perry (1967) and Miller and Johnson (1969). Miller and Johnson have kindly provided the data for curve (e) of figure 10, calculated by an approximate method described in their paper.

Further interest in the event of January–February 1966 is evinced by other analyses (Koshelkov and Tarasenko, 1968; Hirota, 1968), which became available after completion of our study. Although these studies vary widely in scope from the present study, there is essential agreement on points in common. In harmony with our main thesis, Hirota suggests that "the stratospheric circulation including planetary waves should be treated as a whole system from the lower to the upper stratosphere."

ACKNOWLEDGMENTS

This work was supported by the Langley Research Center' National Aeronautics and Space Administration (NASA). The continuing interest of H. B. Tolefson and R. M. Henry, of that Center, is especially appreciated. I am also grateful to F. G. Finger and A. J. Miller, of the Upper Air Branch, National Meteorological Center, for informative comments on the nature of stratospheric warmings.

REFERENCES

Craig, R. A., and Lateef, M. A., "Vertical Motion During the 1975 Stratospheric Warming," *Journal of Geophysical Research*, Vol. 67, No. 5, May **1962**, pp. 1839–1854.

Environmental Science Services Administration, National Aeronautics and Space Administration, and U.S. Air Force, *U.S. Standard Atmosphere Supplements, 1966*, Washington, D.C., **1967**, 289 pp.

Finger, F. G., and Teweles, S., "The Mid-Winter 1963 Stratospheric Warming and Circulation Change," *Journal of Applied Meteorology*, Vol. 3, No. 1, Feb. **1964**, pp. 1–15.

Finger, F. G., Woolf, H. M., and Anderson, C. E., "A Method for Objective Analysis of Stratospheric Constant-Pressure Charts," *Monthly Weather Review*, Vol. 93, No. 10, Oct. **1965**, pp. 619–638.

Hirota, I., "Planetary Waves in the Upper Stratosphere in Early 1966," *Journal of the Meteorological Society of Japan*, Vol. 46, No. 5, Oct. **1968**, pp. 418–429.

Holmboe, J., Forsythe, G. E., and Gustin, W., *Dynamic Meteorology*, John Wiley and Sons, Inc., New York, **1945**, 378 pp., (see p. 216).

Johnson, K. W., "A Preliminary Study of the Stratospheric Warming of December 1967–January 1968," *Monthly Weather Review*, Vol. 97, No. 8, Aug. **1969**, pp. 553–564.

Kays, M., and Craig, R. A., "On the Order of Magnitude of Large-Scale Vertical Motions in the Upper Stratosphere," *Journal of Geophysical Research*, Vol. 70, No. 18, Sept. **1965**, pp. 4453–4461.

Kellogg, W. W., "Warming of the Polar Mesosphere and Lower Ionosphere in Winter," *Journal of Meteorology*, Vol. 18, No. 3, June **1961**, pp. 373–381.

Kirch, R., Kriester, B., Labitzke, K., Scherhag, R., and Stuhrmann, R., "Daily and Monthly Northern Hemisphere 10-Millibar Synoptic Weather Maps of the Year 1966," *Meteorologische Abhandlungen*, Vol. 68, No. 1, Institut für Meteorologie und Geophysik, Freie Universität Berlin, **1966–1967**.

Koshel'kov, Iu. P., and Tarasenko, D. A., "Stratosfernoe Poteplenie v Fevrale 1966 g.," (Stratospheric Warming in February 1966), *Trudy*, No. 85, Tsentral'naia Aerologicheskaia Observatoriia, Moscow, **1968**, pp. 69–81.

Kriester, B., Labitzke, K., Scherhag, R., and Sieland, K., "Daily and Monthly Northern Hemisphere 5-Millibar Synoptic Weather Maps of the Year 1966," *Meteorologische Abhandlungen*, Vol. 78, No. 1, Institut für Meteorologie und Geophysik, Freie Universität Berlin, **1967**.

Labitzke, K., "Midwinter Warmings in the Upper Stratosphere in 1966," *Quarterly Journal of the Royal Meteorological Society*, Vol. 94, No. 401, July **1968**, pp. 279–291.

Labitzke, K., and Schwentek, H., "Midwinter Warmings in the Stratosphere and Lower Mesosphere and the Behaviour of Ionospheric Absorption," *Zeitschrift für Geophysik*, Vol. 34, Physica-Verlag, Würzburg, West Germany, **1968**, pp. 555–566.

Leovy, C., "Radiative Equilibrium of the Mesosphere," *Journal of the Atmospheric Sciences*, Vol. 21, No. 3, May **1964**, pp. 238–248.

Mahlman, J. D., "Atmospheric General Circulation and Transport of Radioactive Debris," *Atmospheric Science Paper* No. 103, Colorado State University, Fort Collins, Sept. **1966**, 184 pp.

Miller, A. J., and Johnson, K. W., "On the Interaction Between the Stratosphere and Troposphere During the Warming of December 1967–January 1968," National Meteorological Center, ESSA, Suitland, Md., **1969**, 17 pp., (unpublished manuscript).

Miller, A. J., Woolf, H. M., and Finger, F. G., "Small-Scale Wind and Temperature Structure as Evidenced by Meteorological Rocket Systems," *Journal of Applied Meteorology*, Vol. 7, No. 3, June **1968**, pp. 390–399.

Miyakoda, K., Strickler, R. F., and Hembree, G. D., "Numerical Simulation of the Breakdown of the Polar-Night Vortex in the Stratosphere," Geophysical Fluid Dynamics Laboratory, ESSA, Princeton, N.J., **1969**, 45 pp., (unpublished manuscript).

Murgatroyd, R. J., and Goody, R. M., "Sources and Sinks of Radiative Energy from 30 to 90 Km," *Quarterly Journal of the Royal Meteorological Society*, Vol. 84, No. 361, July **1958**, pp. 225–234.

Newell, R. E., "Preliminary Study of Quasi-Horizontal Eddy Fluxes from Meteorological Rocket Network Data," *Journal of the Atmospheric Sciences*, Vol. 20, No. 3, May **1963**, pp. 213–225.

Nordberg, W., Katchen, L., Theon, J., and Smith, W. S., "Rocket Observations of the Structure of the Mesosphere," *Journal of the Atmospheric Sciences*, Vol. 22, No. 6, Nov. **1965**, pp. 611–622.

Perry, J. S., "Long-Wave Energy Processes in the 1963 Sudden Stratospheric Warming," *Journal of the Atmospheric Sciences*, Vol. 24, No. 5, Sept. **1967**, pp. 539–550.

Quiroz, R. S., "Meteorological Rocket Observations and Research in the Soviet Union," *Bulletin of the American Meteorological Society*, Vol. 48, No. 9, Sept. **1967**, pp. 697–703.

Quiroz, R. S., "Synoptic Analyses for the Middle Atmosphere and Related Research," *Proceedings of the Seventh Stanstead Seminar on the Middle Atmosphere, Publication in Meteorology* No. 90, McGill University, Montreal, Quebec, Mar. **1968**, pp. 187–219.

Reed, R. J., "On the Cause of the Stratospheric Sudden Warming Phenomenon," *Meteorologische Abhandlungen*, Vol. 36, Institut für Meteorologie und Geophysik, Freie Universität Berlin, **1963**, pp. 315–334.

Smith, W. S., Katchen, L. B., and Theon, J. S., "Grenade Experiments in a Program of Synoptic Meteorological Measurements," *Meteorological Monographs*, Vol. 9, No. 31, Apr. **1968**, pp. 170–175.

Smith, W. S., Theon, J. S., Swartz, P. C., Katchen, L. B., and Horvath, J. J., "Temperature, Pressure, Density, and Wind Measurements in the Stratosphere and Mesosphere, 1966," *NASA Technical Report* TR R-288, Aug. **1968**, National Aeronautics and Space Administration, Washington, D.C., 91 pp.

Staff, Upper Air Branch, National Meteorological Center, Weather Bureau, "Weekly Snyoptic Analyses, 5-, 2-, and 0.4-Millibar Surfaces for 1964," *ESSA Technical Report* WB-2, Environmental Science Services Administration, Silver Spring, Md., Apr. **1967***a*, 176 pp.

Staff, Upper Air Branch, National Meteorological Center, Weather Bureau, "Weekly Synoptic Analyses, 5-, 2-, and 0.4-Millibar Surfaces for 1965," *ESSA Technical Report* WB-3, Environmental Science Services Administration, Silver Spring, Md., Aug. **1967***b*, 173 pp.

Staff, Upper Air Branch, National Meteorological Center, Weather Bureau, "Weekly Synoptic Analyses, 5-, 2-, and 0.4-Millibar Surfaces for 1966," *ESSA Technical Report* WB-9, Environmental Science Services Administration, Silver Spring, Md., Jan. **1969**, 169 pp.

Tsentralnaya Aerologicheskaya Observatoriya, *Byulleten Raketnogo Zonderovaniya Atmosfery. O. Kheisa 1966 g. (Pervaya Polovina)*, Moscow, **1967**, 121 pp.

Tsentralnaya Aerologicheskaya Observatoriya, *Byulleten Raketnogo Zondirovaniya Atmosfery. O. Kheisa 1964 g. (Vtoraya Polovina), 1965 g.*, Moscow, **1968**, 50 pp.

Walts, D. S., "Transport Processes during Stratospheric Warming and Cooling Processes," *Technical Report*, Contract AT(11-1)-1340, Colorado State University, Fort Collins, Dec. **1968**, 62 pp.

Williams, B. H., "Synoptic Analyses of the Upper Stratospheric Circulation During the Late Winter Storm Period of 1966," *Monthly Weather Review*, Vol. 96, No. 8, Aug. **1968**, pp. 549–558.

Wilson, C. V., and Godson, W. L., "The Structure of the Arctic Winter Stratosphere over a 10-Year Period," *Quarterly Journal of the Royal Meteorological Society*, Vol. 89, No. 380, Apr. **1963**, pp. 205–224.

[*Received February 17, 1969; revised April 30, 1969*]