Rocket Observations of the Structure of the Mesosphere

W. Nordberg, L. Katchen, J. Theon and W. S. Smith
Goddard Space Flight Center, NASA, Greenbelt, Md.

(Manuscript received 23 April 1965, in revised form 7 September 1965)

ABSTRACT

Pressure, density, temperature and wind measurements in the upper stratosphere and in the mesosphere resulted from a total of 53 rocket-grenade soundings conducted during the period 1960–1965. Most of the soundings were performed over North America (Wallops Island, 38N and Churchill, 59N) but some results were also obtained over the tropical Atlantic (Ascension Island, 8S) and over Northern Europe (Kronogard, 66N). Soundings were carried out simultaneously at these sites and were coordinated with soundings measing similar parameters over other areas of the globe.

Seasonal and latitudinal variations in the structure and circulation of this region of the atmosphere were derived from the results. Stratosphere temperatures vary with season and latitude in accordance with solar heating rates and with established circulation models. Temperatures above 65 km are substantially warmer in winter than in summer. Average seasonal temperature differences are about 40K at 80 km. They are very pronounced at midlatitudes (Wallops Island) and become even more extreme at high latitudes where in summer mesopause temperatures as low as 140K were observed. Maximum stratopause temperatures were observed during late winter-early summer. At Wallops Island these maxima of about 280K coincided with the period of transition from winter to summer circulation. Temperature profiles for all seasons at all sites intersect between 60 and 65 km at a temperature range of 230 to 240K.

The strong westerly flow in winter shows two pronounced cores, one persistent throughout the winter just above the stratopause, the other somewhat weaker and less persistent near 75 km. Deviations from the zonal flow indicate the existence of meteorological circulation cells on a synoptic scale with the average meridional flow at Churchill strongly from the north during both summer and winter and at Wallops Island somewhat weaker from the south during the winter.

1. Introduction

After the successful exploration of the structure of the upper stratosphere with rocket-grenade soundings at White Sands, N. Mex., Churchill, Canada, and Guam, Mariana Islands, during the International Geophysical Year (Nordberg and Stroud, 1961), we conducted a series of soundings at various latitudes in the Atlantic and North American region during the period of minimum solar activity. Simultaneous, seasonal measurements of temperature, pressure, density and winds were planned at four sites: Point Barrow, Alaska (71N); Churchill, Manitoba, Canada (59N); Wallops Island, Virginia (38N); and Ascension Island (8S). While successful soundings were conducted at each of these locations during 1960–1965, operational difficulties have limited the number of soundings at the various sites, and to date simultaneous observations have been made only at three of the four sites. These took place recently when three successful soundings were conducted each at Pt. Barrow, Wallops Island and Churchill during January and February 1965. Results from this recent series are not yet completely reduced, and only preliminary data from the Pt. Barrow soundings were considered in this analysis. The Point Barrow observations are the first known direct measurements of the structure of the mesosphere north of 70N. Only four successful acoustic grenade soundings were possible at Ascension Island, one each in January and February and two in August 1964. The August observations were made nearly simultaneously with soundings at Churchill, Wallops Island and at Kronogard, Sweden (66N). Data from Kronogard, however, are, as yet, available only for summer 1963, and only preliminary data from the other three sites were considered in this analysis. In addition to the grenade soundings in which temperature, pressure, density, and wind are derived from observations of the soundwaves generated by the exploding rocket-borne grenades, there were three soundings in February and April 1964 at Ascension Island in which pressure, density, and temperature up to 105 km were measured by the pitot-static tube technique. Results of these measurements were reported by Horvarth and Simmons (1964) and are included in this analysis.

Acoustic grenade rocket soundings at Churchill were resumed in December 1962 after a fire had destroyed the launch facility there in 1960. A total of 15 soundings were carried out during December 1962, February and March 1963, January, February, April and August 1964 and January and February 1965. All but one of these soundings were conducted nearly simultaneously

TABLE 1. Dates, times and locations of GSFC meteorological sounding rocket experiments, 1960–65.

Date	Time (GMT)	Location
1960		
9 July	0359	Wallops Island
1961		
14 February	2350	Wallops Island
17 February	0226	Wallops Island
5 April	1257	Wallops Island
5 May	2300	Wallops Island
6 May	0454	Wallops Island
13 July	2207	Wallops Island
14 July	1602	Wallops Island
20 July	1030	Wallops Island
16 September	2355	Wallops Island
1962		
2 March	0001	Wallops Island
2 March	1115	Wallops Island
23 March	2354	Wallops Island
28 March	0004	Wallops Island
18 April	0928	Wallops Island
7 June	0105	Wallops Island
8 June	0153	Wallops Island
1 December	2125	Wallops Island
4 December	0705	Churchill
6 December	0532	Wallops Island
6 December	0543	Churchill
1963		
20 February	2334	Churchill
20 February	2347	Wallops Island
28 February	2147	Churchill
28 February	2211	Wallops Island
9 March	0001	Wallops Island
9 March	0001	Churchill
7 December	1312	Wallops Island
1964		
24 January	0016	Wallops Island
29 January	0411	Wallops Island
29 January	0417	Churchill
29 January	0418	Ascension Island
4 February	0135*	Ascension Island
4 February	0146	Wallops Island
5 February	0040	Churchill
5 February	0320	Wallops Island
13 February	0430	Wallops Island
13 February	0430	Churchill
13 February	0455	Ascension Island
7 March	0245	Wallops Island
15 April	0122*	Ascension Island
15 April	1556*	Ascension Island
18 April	0039	Churchill
18 April	0100	Wallops Island
7 August	0600	Wallops Island
8 August	1000	Churchill
12 August	0149	Wallops Island
12 August	0215	Churchill
16 August	0315	Wallops Island
16 August	0553	Ascension Island
17 August	1255	Ascension Island
18 August	0115	Churchill
18 August	0125	Wallops Island
1965		
27 January	2132	Point Barrow
4 February	0445	Point Barrow
8 February	2215	Point Barrow

All soundings were rocket grenade experiments except the pitot-static experiments which are noted with an asterisk (*).

with soundings at Wallops Island. Data from all soundings up to August 1964 were included in this analysis, although the August 1964 data are still of a preliminary nature.

By far the largest number of soundings was obtained at Wallops Island, Virginia since that launch site has been available for the longest period. Forty-two successful soundings were conducted at Wallops Island between July 1960 and February 1965. Soundings were taken during every month of the year except October. Results have been analyzed through August 1964.

The times and location of all soundings included in this discussion are summarized in Table 1. Space does not permit the presentation here of the complete data from each sounding. However, complete tabulations and graphic presentations of the data for 1960–1963 have been compiled in a report by W. Smith *et al.* (1964). A similar report for the complete 1964 data is now in preparation.

Only the basic and salient features of the observations will be summarized here with particular emphasis on their latitudinal and seasonal variations and their relationship to the basic physical processes governing the stratosphere and mesosphere. These results are of interest also because they permit a comparison between the structure of the mesosphere observed during the present period of minimum solar activity and during the IGY when solar activity was at its maximum.

Results from the large number of wind observations obtained from Meteorological Rocket Network soundings analyzed by Webb (1964) were also considered as they overlapped our observations at the lower altitudes.

2. Discussion of the observational results

a. The temperature structure. In the stratosphere, temperatures are qualitatively in accord with the solar heating rates expected at the various latitudes and seasons. The highest temperatures are generally observed at high latitudes during summer where maximum heating rates are expected, while the lowest temperatures prevail at high latitudes in winter during minimum solar illumination. Quantitatively, however, the observed stratopause temperatures of 255K near 60N in winter (Churchill Winter 1962–64 in Fig. 1) are about 25C higher than temperatures for the same latitude and season calculated by Leovy (1964a) solely on the basis of heating and cooling rates given by the radiative properties of oxygen, ozone and carbon dioxide. At 60N in summer (Churchill Summer 1964 in Fig. 1) the observed temperatures of 275K are about 20C lower than calculated. Thus, the observed seasonal variation in the stratopause temperatures amounts to 20C (Fig. 2), instead of 65C calculated from radiative heating and cooling alone. At lower latitudes (Wallops Island) observed average seasonal temperature variations are only about 10C. Fig. 1 shows that latitudinal temperature gradients at the stratopause level

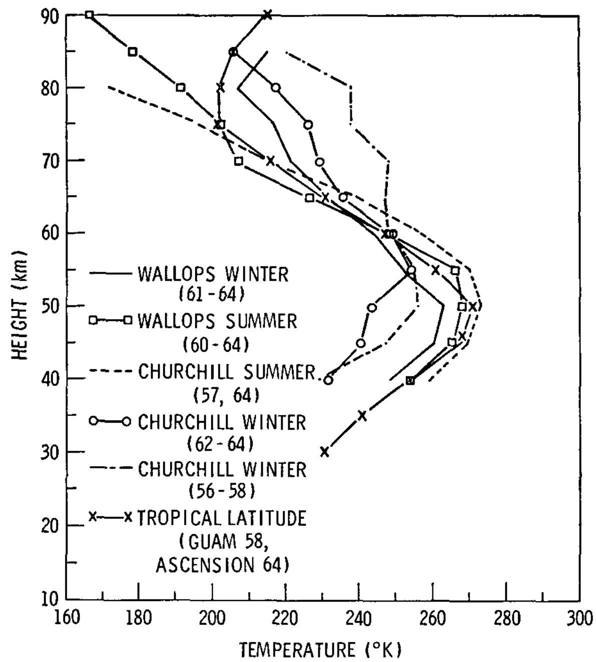

FIG. 1. Average 1960–64 summer and winter temperatures for Wallops Island (38N), 1962–64 winter temperatures for Churchill (59N), 1964 summer temperatures for Churchill and winter 1964 temperatures for Point Barrow (71N) are compared to average summer and winter temperatures obtained at Churchill during the IGY (1957–58). The IGY Churchill summer temperatures were quite similar to averages from three summer 1964 soundings in Churchill, thus only one profile is shown. An average temperature profile for tropical latitudes obtained in November 1958 at Guam (13N) and in February 1964 at Ascension Island (8S) is shown for comparison. The average profiles are derived from the following number of individual grenade experiment soundings listed in Table 1: Wallops winter—17, Wallops summer—10, Churchill winter (IGY)—5, Churchill winter (1962–64)—8, High Latitude summer—8, Low Latitude—6 (Guam) plus 7 (Ascension Island). 1962–64 soundings were conducted nearly simultaneously at Churchill and Wallops.

are much larger in winter than in summer. This is again in good qualitative agreement with radiatively predicted gradients.

Quantitatively, the discrepancy by about a factor of two between the radiatively predicted and the observed seasonal temperature variations in the stratosphere, especially at high latitudes, requires equatorward and poleward energy transport in the summer and winter hemispheres, respectively. Dynamic processes which carry out this energy transport have been postulated by Murgatroyd and Singleton (1961) on the basis of the IGY temperature observations and more recently by Newell (1963) on the basis of Meteorological Rocket Network wind observations.

The change from cold winter temperatures to warm summer temperatures in the stratosphere takes place very rapidly during the end of each winter season (March–May, Fig. 3). Maximum temperatures occur near 45 km, about 5 km lower than during the period of maximum solar heating in midsummer. Furthermore, many temperature profiles during spring exhibit maximum temperatures equal to or exceeding those reached at 50 km later in the year suggesting the stratopause to be warmest and lowest during spring. This phenomenon is obvious at Wallops because of the large number of observations at that site, but results from Churchill are insufficient to confirm its existence there (Fig. 4). Indications are that the warm upper stratosphere in late winter exists also at relatively low latitudes in the southern hemisphere (Groves, 1964). It may be expected that these temperature maxima are dynamically induced and are caused by the final breakdown of the predominantly cyclonic winter circulation which occurs during the same time period. This phenomenon will be considered further in the discussion of the wind observations

In the lower mesosphere there are practically no seasonal and latitudinal temperature variations in the altitude range of about 60 to 65 km. Indeed, considering the results reported by Groves (1964) for Woomera, Australia (31S), our earlier IGY data (Nordberg and Stroud, 1961) and those shown in Fig. 1, one may conclude that temperatures at this altitude range generally between 230 and 240K over the entire globe during all seasons.

The largest variations in the observed temperature take place in the upper mesosphere and at the mesopause and are especially evident at Churchill and Wallops Island (Fig. 2). Average seasonal temperature variations at 80 km during the 1962–64 period are about 45C at Churchill and about 15C at Wallops Island. It must be concluded that this variation di-

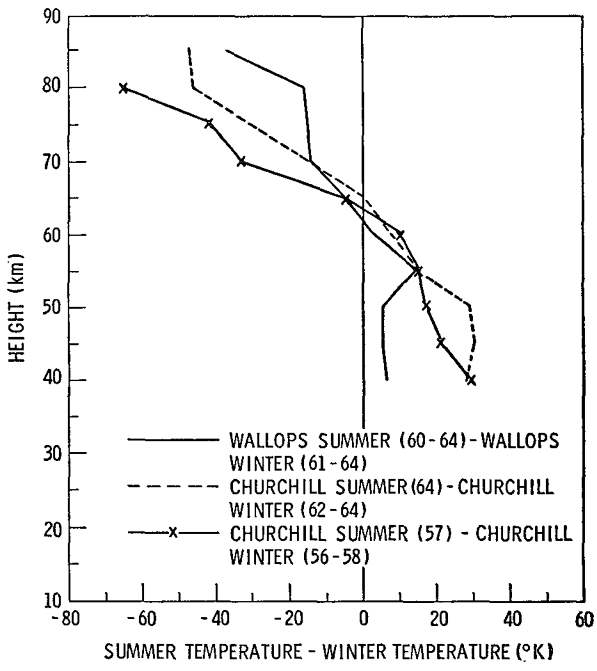

FIG. 2 Average summer temperatures minus average winter temperatures for Wallops Island (1960–64) and Churchill (1956–58 and 1962–64) as a function of height.

minishes at low latitudes since no appreciable seasonal variation can be detected in Groves' (1964) results at Woomera and in our (1961) results at White Sands (33N). At equatorial latitudes, for which an average profile is shown in Fig. 1, there have not been sufficient soundings yet to positively deduce any absence of seasonal variations. However, the trend demonstrated in the Churchill, Wallops Island, White Sands and Woomera observations and the fact that at all altitudes the average equatorial temperature profile lies between the summer and winter profiles observed at higher latitudes leaves little doubt that at equatorial latitudes the seasonal variations are at a minimum. It should be noted that the variation at Churchill during 1962–64 was only one half the variation observed during the IGY (Fig. 2). More soundings will have to be made during the next solar maximum to determine the possible significance of this result.

The large average lapse rates found during maximum solar heating (high latitude summer), suggest that a very cold upper mesosphere always occurs in conjunction with a warm and high stratopause. The Swedish grenade soundings made during the summer of 1963 (Witt, *et al.*, 1965) confirm the existence of a warm stratopause (280K) occurring with a cold mesopause (140K) at 66N latitude. On the other hand, dur-

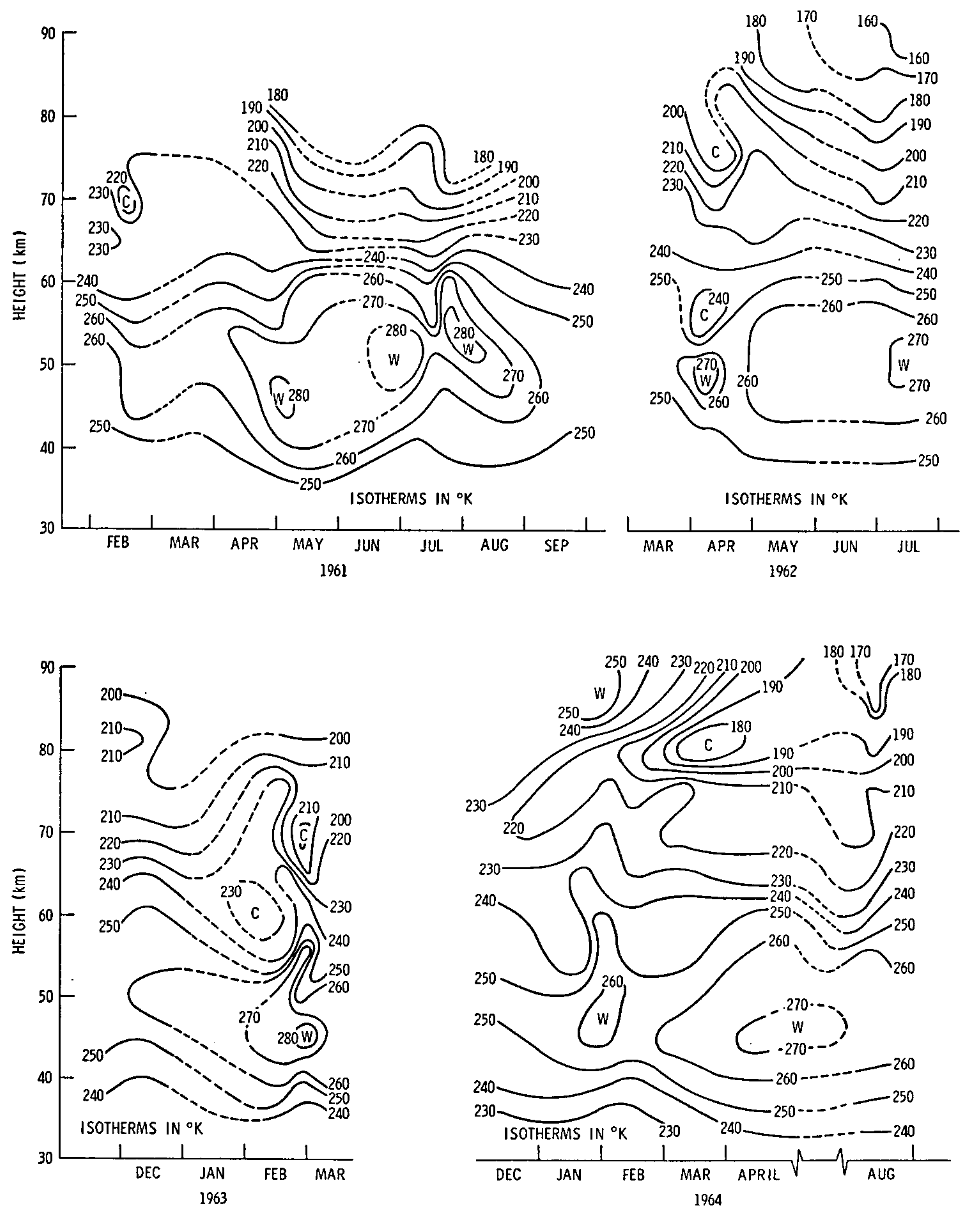

FIG. 3. Variation of temperatures in the stratosphere and mesosphere with altitude and season over Wallops Island (38N) during 1961–64. Isotherms are based on 34 grenade soundings listed in Table 1.

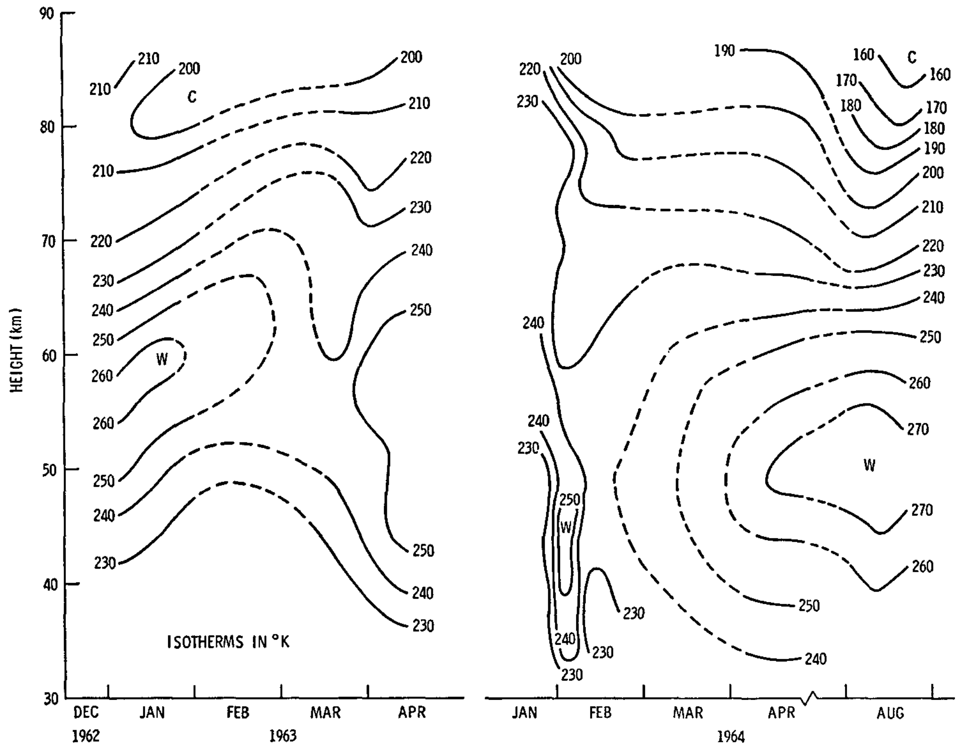

Fig. 4. Variation of temperatures in the stratosphere and mesosphere with altitude and season over Churchill (59N) during 1962–64. Isotherms are based on 12 grenade soundings listed in Table 1.

ing minimum solar heating (high latitude winter), the average lapse rate between 50 and 80 km becomes very small, suggesting that a warm upper mesosphere is always found in conjunction with a cold stratopause. Preliminary data from Point Barrow, Alaska (71N) during January 1965 (Fig. 5) indicate a more nearly isothermal atmosphere from about 40 to 70 km. The seasonal temperature variations which are of opposite sign in the stratosphere and upper mesosphere (Fig. 2) seem to pivot around the level of nearly constant temperature between 60 and 65 km. These observations disagree both qualitatively and quantitatively with temperature distributions computed solely on the basis of radiative properties (Leovy, 1964a). The computations require a much colder mesosphere in winter.

Table 2. U. S. Standard Atmosphere 1962, pressure vs. height.

Altitude (km)	Pressure (newton m^{-2})
30	1197.0
35	574.6
40	287.1
45	149.1
50	79.8
55	42.8
60	22.5
65	11.4
70	5.5
75	2.5
80	1.0
85	0.4
90	0.2

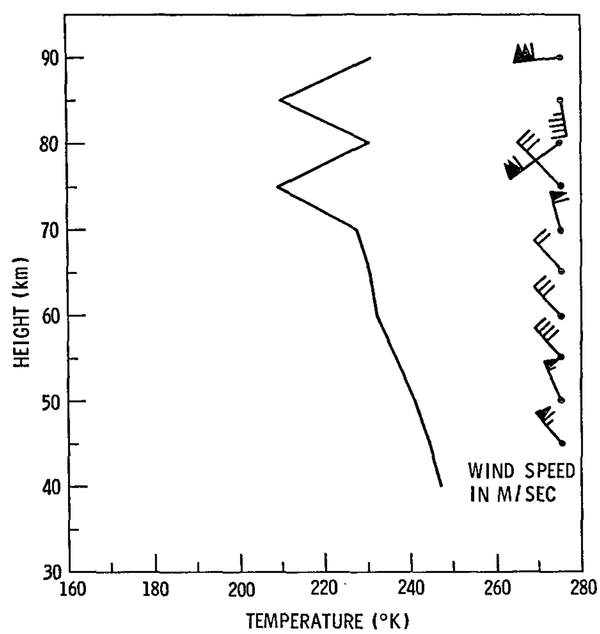

Fig. 5. 1965 winter stratosphere and mesosphere average temperature and average wind profiles at Point Barrow (preliminary data).

Radiative heating and cooling alone require winter mesopause temperatures of 190K and summertime temperatures of 230K at 60°N. Observations (Fig. 1) show 170K in summer and 220K in winter at the same latitude. This discrepancy again necessitates a large scale dynamic mechanism to transport energy meridionally and vertically. The mechanism of mean meridional and vertical motions postulated by Murgatroyd and Singleton (1961) produces upward motion in the summer mesosphere, downward motion in the winter mesosphere, and meridional motions from summer to winter pole thus, qualitatively at least, explaining the departures of the observed temperatures from radiative equilibrium. Leovy (1964b) has developed a quantitative model of such a mean circulation. Our observations agree in general with the temperatures of Leovy's model in the upper mesosphere but disagree quantitatively in the lower mesosphere and at the stratopause. Obviously more sophisticated dynamic models will be needed to conform with the observations.

Heat sources other than solar radiation have been suggested by Kellogg (1961) who pointed out the possibility of heating the polar upper mesosphere by recombination of atomic oxygen transported downward from the ionosphere and by Maeda (1962) who investigated the possibility of heating by auroral particles. The recent simultaneous observations at Churchill and Wallops Island, however, indicate that the warm upper mesosphere is found at both locations and require an explanation which holds at latitudes outside the polar cap as well as inside. Fig. 1 indicates that the observations made during the IGY (Churchill winter 1956–58) show considerably higher temperatures than the most recent observations (Churchill winter 1962–64) obtained during low solar activity. Advocates of the auroral heating concept might be tempted to use this finding as evidence for the existence of a heat source depending on solar activity. But, aside from the scarcity of the data sample which invalidates any such evidence, one would still have to explain the observed low summer temperatures which are nearly 100K colder than those calculated from radiative transfer for 80 km at 60° latitude (Leovy, 1964a). Significantly, summer temperatures throughout the mesosphere at Churchill shown in Fig. 1 for 1964 are practically the same as those observed during the IGY.

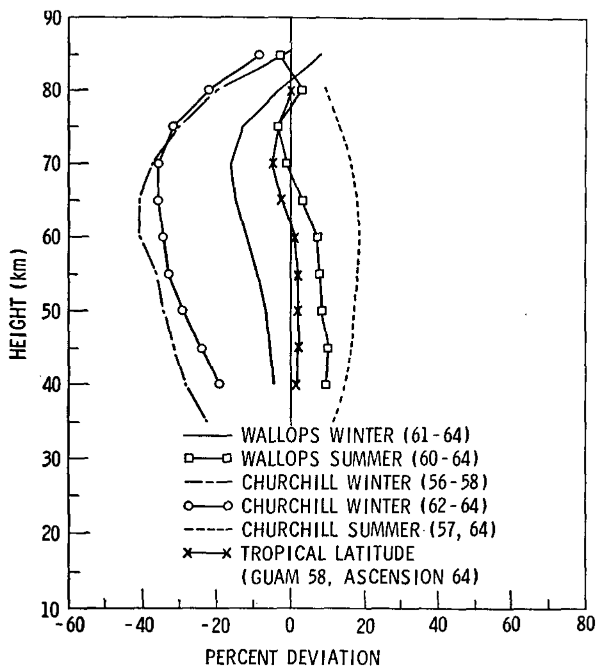

FIG. 6. Seasonal pressure averages as a function of height for Wallops Island (38N), Churchill (59N), and equatorial latitudes. Averages are based on the same soundings for which average temperature profiles are shown in Fig. 1. Because of their rapid variations with height, observed pressures are shown as deviations from the U. S. Standard Atmosphere, 1962. Absolute values of standard pressures which apply to the zero per cent deviation coordinates are shown in Table 2.

b. Pressure distributions. The average pressure graphs shown in Fig. 6 were obtained by integrating the hydrostatic equation for each of the temperature soundings mentioned in Fig. 1, and averaging the resulting pressures at each altitude for the appropriate season and location. A measured pressure (usually by balloon sondes) at the lower boundary of each temperature profile was used as the initial value in the integration. The pressure profiles are very useful to demonstrate the relationship between the seasonal and latitudinal temperature variations and the wind patterns described below.

The stratosphere and mesosphere are dominated by very systematic latitudinal and seasonal pressure variations (Fig. 6). These variations are of considerable magnitude throughout the entire region and they converge toward minima at the lower and upper boundaries. Extrapolation of the pressure profiles in Fig. 6 to lower altitudes shows that there is a minimum pressure variation in the lower stratosphere, a fact which can also be derived from balloon and Meteorological Rocket Network soundings. It is evident from the data shown in Fig. 6 that another minimum exists near the mesopause. Average pressure profiles for all seasons at the three sites seem to converge toward a common value slightly larger than the 1962 U. S. Standard Atmosphere at 90 km.

In winter, throughout most of the stratosphere and mesosphere, pressures at Churchill are more than 20 per cent lower than at Wallops Island, and close to 30 per cent lower than at equatorial latitudes where the pressure is closest to the standard. The greatest latitudinal pressure gradient in winter occurs near 55 km. The maximum deviation from the standard at all latitudes takes place in winter at Churchill near 65 km.

The variation of the latitudinal pressure gradient with height in winter is plausible on the basis of the temperature profiles. The much colder winter stratosphere and stratopause at high latitudes cause the pressure to decrease with height more rapidly at high latitudes than at low latitudes, resulting in a gradual increase of the latitudinal pressure differences above the level of minimum pressure differences at the lower stratosphere. In the mesosphere the warmer temperatures at the higher latitudes bring about a smaller pressure decrease with height than at lower latitudes causing the latitudinal pressure differences to decrease above 60 km and to reach a second minimum near 90 km.

In summer, pressures are higher at Churchill than at Wallops Island at all altitudes, but differences between the two sites are considerably less than in winter. This is because the high latitude summer stratosphere and stratopause are only moderately warmer than their low latitude counterparts. Pressure differences between Wallops Island and Churchill in summer are about one half of the differences observed in winter. Differences between Wallops Island and tropical latitudes are of about equal magnitude during both seasons.

The large seasonal pressure variations of a factor of two between summer and winter at Churchill which were reported during the IGY (Nordberg and Stroud, 1961) are still prevalent although with a somewhat diminished amplitude (factor of 1.8). At the latitude of Wallops Island, the seasonal variation is considerably less and ranges between a factor of 1.15 and 1.2. At equatorial latitudes, soundings have not been made with sufficient continuity to reach a very definite conclusion, but all observations to date indicate that variations in the average pressure are quite small, generally less than the accuracy of the observations which is better than 5 per cent.

c. Wind patterns. Wind observations in the stratosphere and mesosphere have been more numerous than any other type of observation. The basic features of the general circulation in these regions are, therefore, fairly well understood. A number of publications (Newell, 1963; Leovy, 1964b) have recently explored these features in greater detail based on our earlier IGY observations and on the large number of meteorological rocket soundings throughout the stratosphere and into the lower mesosphere which have been regularly conducted since 1961. Our observations are summarized in Figs. 7 through 12. They confirm that the features observed in the stratosphere by the meteorological network soundings exist throughout the mesosphere, but undergo a major change in the 70 to 80 km region. All observations generally confirm the existence of the expected strong cyclonic circulation around the North Pole in winter and a somewhat weaker anticyclonic motion in summer. Average zonal wind speeds are considerably greater at almost all altitudes at Wallops Island than at Churchill, both in winter and summer (Fig. 7), although occasionally the maximum wind measured at one given altitude in one given sounding at Churchill may exceed the wind speed measured simultaneously at Wallops Island.

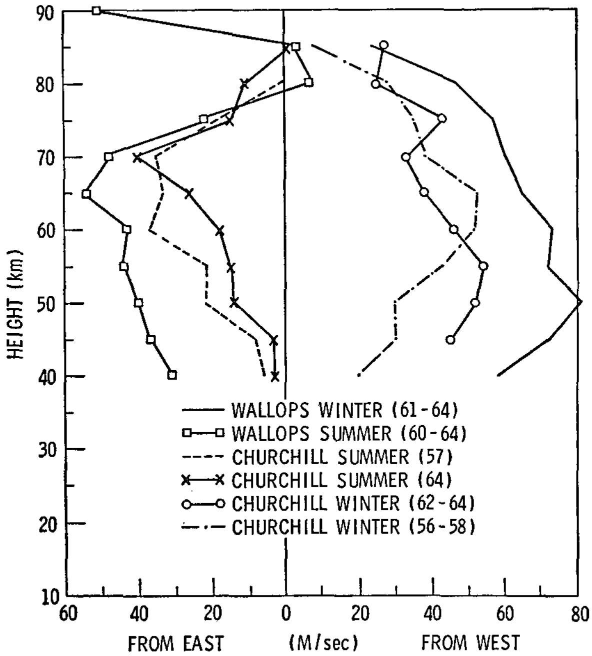

Fig. 7. Average zonal wind components vs. altitude for Churchill and Wallops Island. Graphs are based on the same soundings as those shown in Fig. 1.

A time cross section of the zonal wind components at Wallops Island (Fig. 8) clearly displays two wind maxima during each winter since 1961. One maximum is located very consistently near 55 km in midwinter, but moves gradually to lower altitudes (45 km) toward the end of the winter. This maximum is also obvious in the average zonal wind profile in Fig. 7. The second maximum occurs consistently each winter between 70 and 80 km, but it is generally of lesser intensity and shorter duration than the lower altitude maximum. Except for 1962, where no midwinter data exist, the maximum occurs only during January-February. It is for this reason that the upper maximum does not appear in the average profile in Fig. 7. The higher wind speeds throughout the *entire* winter season in the lower maximum completely overshadow the upper maximum in the average profile. There is a possibility that the weaker easterlies occurring in summer also form two cores during midsummer, but they are certainly not as pronounced as the two westerly jets. Observations in the mesosphere at this time have not been made with sufficient continuity to determine the persistence in the reversals of the zonal flow from westerly in winter to easterly in summer and vice versa. However, such studies have been made at lower altitudes by Webb (1964) on the basis of Meteorological Rocket Network soundings which showed a very consistent pattern in the seasonal reversals: at low and mid latitudes the reversals always occur during mid May and September. Fig. 8 shows a slope in the springtime zero isotachs from the upper left to the lower right. From this and from the gradual migration of the lower core to lower altitudes, it seems to follow that the winter to summer reversal in the lower cores follows the reversals in the upper cores. Sufficient data do not exist for the fall reversals to draw similar conclusions.

In general, the altitude level of maximum average zonal windspeed is higher in summer than in winter. This is consistent with the height of the maximum latitudinal pressure gradient described above. The comparison of the windspeeds between Wallops Island and Churchill places a steeper latitudinal pressure gradient in the vicinity of Wallops Island than at Churchill. There is complete consistency for the entire region between the average pressures shown in Fig. 6 and the average zonal windspeeds in Fig. 7. Maximum zonal winds occur at the heights and seasons where maximum latitudinal pressure differences are shown, and the average zonal windspeeds are smallest at those altitudes where the pressure variations are at a minimum.

The time cross section of zonal winds at Wallops Island (Fig. 8) also shows that the periods of maximum temperature in the upper stratosphere during late winter and early summer (Fig. 3) seem to coincide with the seasonal reversal in the zonal winds. Indeed, during 1961 the maximum temperature occurred exactly when the winter westerlies had dropped to zero. In 1962,

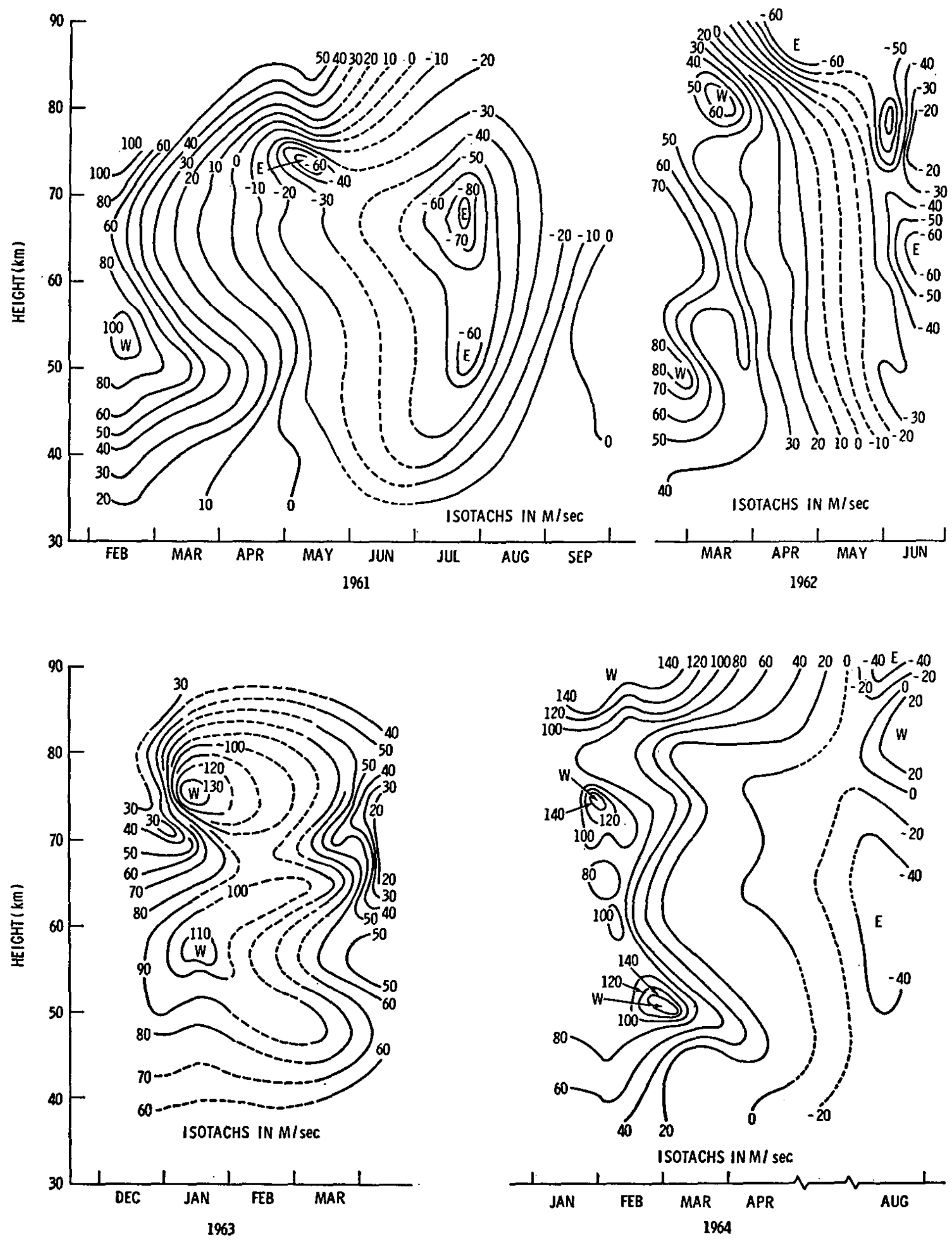

FIG. 8. Variation of zonal wind components with altitude and season over Wallops Island, 1961–64.

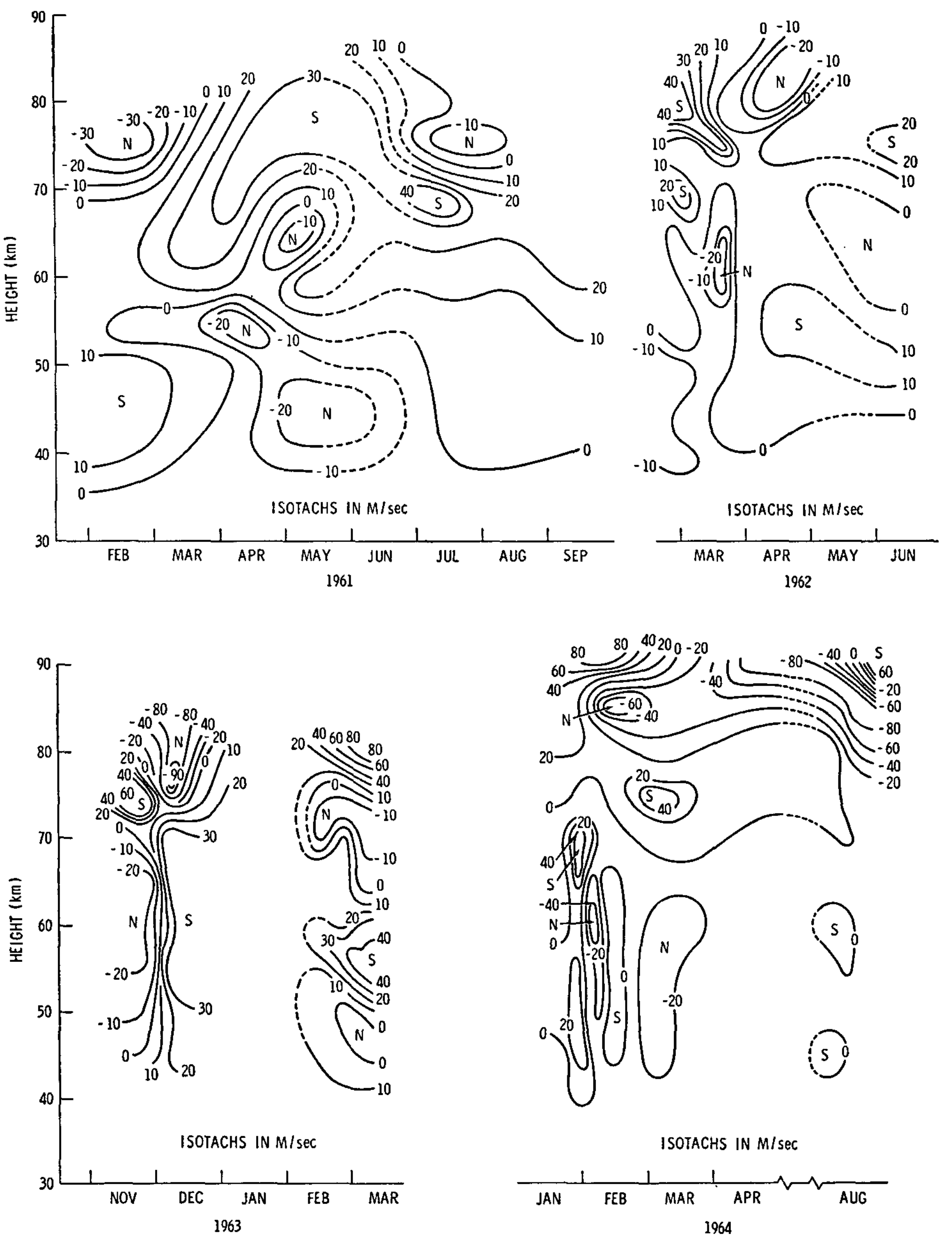

FIG. 9. Variation of meridional wind components with altitude and season over Wallops Island, 1961–64.

measurements were made in April and June showing temperatures of 270K during both months. Fig. 8 shows that in April the westerlies were still pronounced, while in June easterly circulation had already set in and the temperature maximum probably occurred during May, again when the zonal winds reversed directions. In 1963, temperatures were already very high in March when winds had diminished from their maximum of about 100 m sec^{-1} to about 50 m sec^{-1}. No temperature measurements exist during April or May for that year, but one may speculate again that the temperature continued to rise until the zonal winds reversed direction in May.

There is no evidence of any increase in the meridional wind components (Fig. 9) or of any predominance in either the southerly or northerly component during the time of the high late winter temperatures. Zonal circulation simply undergoes maximum changes during these times. Webb (1964) has analyzed the very large number of wind data near the 50-km level resulting from the Meteorological Rocket Network soundings and has found that except for December, January, and February, the average meridional wind components are very small and show no particular increase in spring.

Webb's analysis also shows that average meridional winds are from the south during the entire year at all

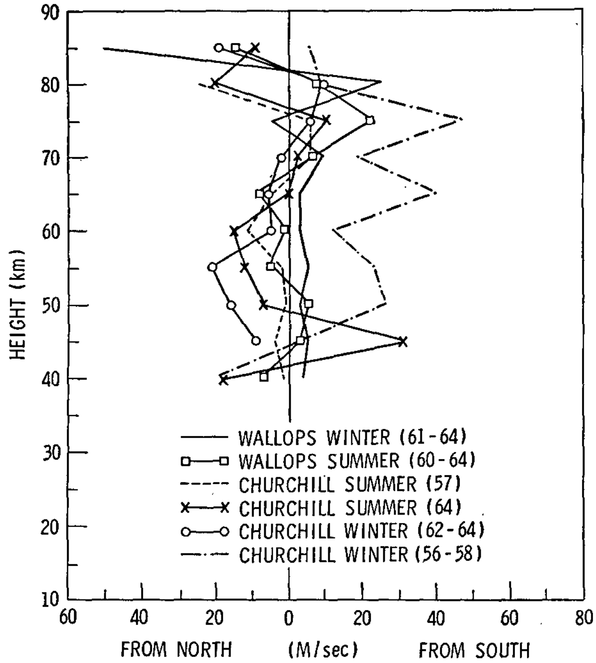

FIG. 10. Average meridional wind components vs. altitude for Churchill and Wallops Island. Graphs are based on the same soundings as those shown in Fig. 1.

low and mid latitude North American stations. Although the meridional flow is not nearly as well organized as the zonal flow, our soundings do show a consistent average component from the south during the winter at all heights up to 70 km at Wallops Island and, with the exception of winter 1957–58, an equally consistent component from the north at Churchill during both summer and winter (Fig. 10). These average meridional wind components are much larger than the "mean" meridional winds postulated in models such as Murgatroyd and Singleton (1961). One may therefore conclude that the observed winds reflect large scale pressure disturbances at these longitudes and that the data are too sparse to derive true mean meridional motions. The Churchill meridional winds indicate a more or less permanent position of these pressure disturbances.

These pressure disturbances are apparently very deep, reaching well into the mesosphere. They are especially pronounced in winter at the very high latitudes. For example, wind data at Wallops indicate a very strong and steady zonal flow from the west during midwinter (Figs. 8 and 9), while at the same time at Churchill the westerly wind component is much weaker and a steady northerly component exists in general (Figs. 11 and 12). This is also confirmed by the most recent soundings at Point Barrow (Fig. 5), suggesting a high pressure cell over the North Pacific and Gulf of Alaska and low pressure over the North Atlantic. This implies that the well-known Aleutian anticyclone may exist up to altitudes of 70 km. A more detailed analysis of one series of simultaneous soundings at Churchill and Wallops Island by Warnecke and Nord-

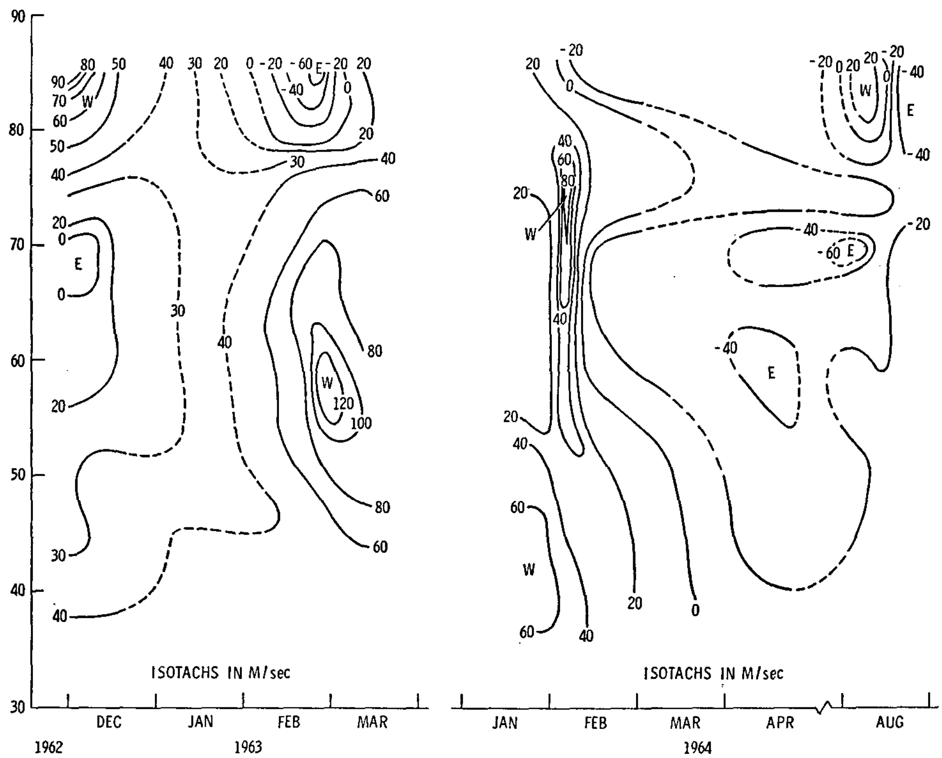

FIG. 11. Variation of zonal wind components with altitude and season over Churchill, 1962–64.

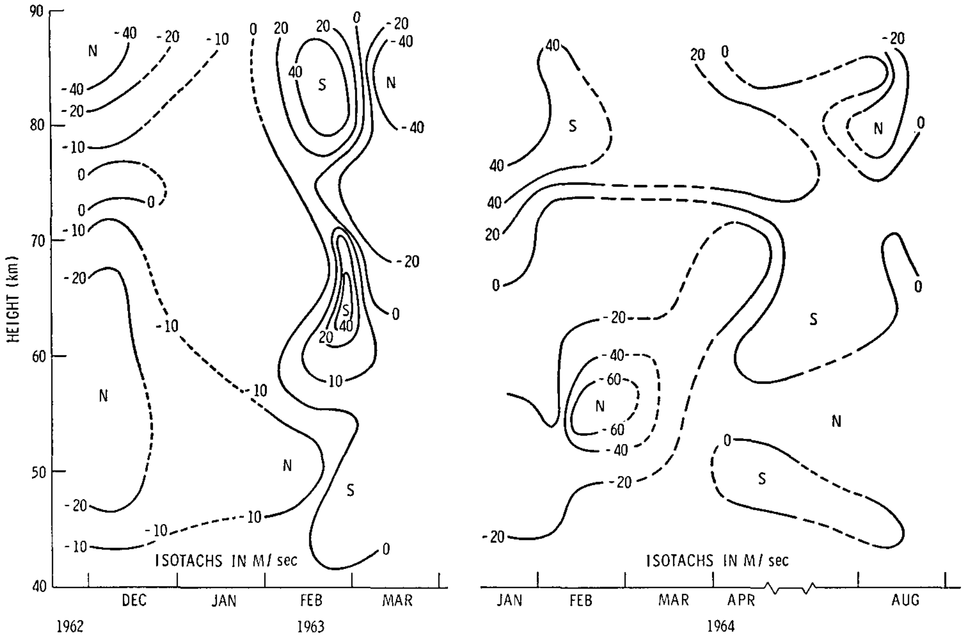

Fig. 12. Variation of meridional wind components with altitude and season over Churchill, 1962–64.

berg (1965) supports this speculation. In contrast to the more recent observations, the averages for the meridional winds for Churchill for 1956–58 show southerly instead of northerly components (Fig. 10) because these data are dominated by measurements made during January 1958 when a breakdown in the circulation occurred. During that period the high pressure cell lay to the east and low pressure to the west of Churchill (Teweles, 1961). All observations at Churchill since then have displayed northerly winds, leading to the conclusion that, in general, high pressure is rather stationary to the west of Churchill and low pressure to the east, and that the 1958 measurements specifically reflected the displacement of the pressure cells during "break down" conditions. It seems somewhat surprising, however, that the average meridional wind components at Churchill are from the same direction during both summer and winter, indicating great persistence in the longitudinal position of the pressure cells. Naturally, a much larger number of soundings distributed over a wider range of longitudes would shed some further light on this subject.

The analysis by Warnecke and Nordberg (1965) of a number of the acoustic grenade soundings supplemented by sodium release wind instruments above 70 km showed that the generally accepted circulation patterns cease to exist above about 75 km. Above that altitude the circulation seems to be governed by variations of much smaller time scales than in the stratosphere and mesosphere. Tidal phenomena seem to be of much greater importance at those altitudes than the synoptic scale pressure variations described here for the lower regions.

3. Conclusions

The warm upper mesosphere originally observed at Churchill during the IGY was still present at both Churchill and Wallops Island during the recent years of low solar activity. However, at 80 km, winter temperatures during 1962–64 were only about 45C warmer than summer temperatures at Churchill and 15C warmer at Wallops Island, while during the IGY at Churchill, the corresponding temperature difference was 70C. The possibility that the less intense winter warming of the upper mesosphere over Churchill during the IQSY is associated with the solar cycle cannot be sufficiently substantiated by the small data sample. Summer temperatures at the mesopause at high latitudes were consistently colder than 160K which does not support the postulation of an additional extraterrestrial heat source to explain the difference between observed and predicted mesosphere temperatures. Dynamic processes can account better for these differences.

In the stratosphere maximum temperatures occurred at Churchill, Wallops Island and tropical latitudes during the end of the winter season. At that time the stratopause temperatures at 40–45 km were equal to or higher than stratopause temperatures at 50–55 km during midsummer. Wallops Island data suggest that the stratopause is warmest and lowest during early spring. This phenomenon is probably related to the breakdown of the polar vortex which occurs at the same time of year.

A region of minimum seasonal and latitudinal temperature variation exists at 60 km, while minimum pressure variations occur below 25 km and near 85–90 km. There are not sufficient data available to draw any definite conclusions about the seasonal variation of temperature and pressure at the tropics, but indications are that these variations are at a minimum, being probably only a few per cent over the entire year.

In midwinter at Wallops Island, the mesosphere exhibits two pronounced maxima in the westerly winds at 55 km and 75 km. The upper maximum disappears usually in February, while the lower maximum migrates toward lower altitudes at the end of the winter. The persistence of meridional flow from the north at Churchill during the entire year indicates fairly permanent large scale pressure systems in the northern latitudes. Preliminary results from Point Barrow show an average temperature profile with the smallest absolute lapse rate yet observed, 0.67C per km from 40 to 70 km. As at Churchill, a steady northerly component exists, indicating the existence of a high pressure cell over the North Pacific and Gulf of Alaska, and low pressure over the North Atlantic.

Acknowledgments. The authors gratefully acknowledge the contribution of Philip C. Swartz of GSFC for processing the data to final form; Superior Engineering Company for fabrication and pre-launch preparations of the payload; New Mexico State University's Physical Science Laboratory for rocket trajectory data; and Texas Western College's Schellenger Research Laboratory for sound ranging support.

REFERENCES

Groves, G. V., 1964: Meteorological and atmospheric structure studies with grenades. *Space Research IV*, Amsterdam, North Holland Publishing Company.

Horvath, J., and R. Simmons, 1964: Measurements of upper atmosphere parameters by the pitot static technique. *Trans. Amer. Geophys. Union*, **45**, Abstract, p. 617.

Kellogg, W. W., 1961: Chemical heating above the polar mesopause in winter. *J. Meteor.*, **18**, 373–381.

Leovy, C., 1964a: Radiative equilibrium of the mesosphere. *J. Atmos. Sci.*, **21**, 238–248.

——, 1964b: Simple models of thermally driven mesospheric circulation. *J. Atmos. Sci.*, **21**, 327–341.

Maeda, K., 1963: On the heating of the polar upper atmosphere. *Proceedings of the International Symposium on Stratospheric and Mesospheric Circulation.* Berlin, Germany, Verlag Von Dietrich Reimer.

Murgatroyd, R. J., and F. Singleton, 1961: Possible meridional circulations in the stratosphere and mesosphere. *Quart. J. R. Meteor. Soc.*, **87**, 125–135.

Newell, R., 1963: Preliminary study of quasi horizontal eddy fluxes from Meteor. Rocket Network data. *J. Atmos. Sci.*, **20**, 213–225.

Nordberg, W., and W. Smith, 1963: Rocket measurements of the structure of the upper stratosphere and mesosphere. *Proceedings of the International Symposium on Stratospheric and Mesospheric Circulation*, Berlin, Germany, Verlag Von Dietrich Reimer.

——, and W. G. Stroud, 1961: Seasonal, latitudinal and diurnal variations in the upper atmosphere. NASA Technical Note D-703.

——, W. R. Bandeen, G. Warnecke and V. Kunde, 1965: Stratospheric temperature patterns based on radiometric measurements from the TIROS VII Satellite. *Space Research V*, Amsterdam, North Holland Publishing Company.

Smith, W., L. Katchen, P. Sacher, P. Swartz and J. Theon, 1964: Temperature, pressure, density, and wind measurements with the rocket grenade experiment 1960–1963. NASA TR R-211.

Teweles, S., 1961: Time section and hodograph analysis of Chuchill rocket and radiosonde winds and temperatures. *Mon. Wea. Rev.*, **89**, 125–136.

Warnecke, G., and W. Nordberg, 1965: Inferences of stratospheric and mesospheric circulation systems from rocket experiments. *Space Research V*, Amsterdam, North Holland Publishing Company.

Webb, W., 1964: Stratospheric solar response. *J. Atmos. Sci.*, **21**, 582–591.

Witt, G., Martin-Löf, N. Wilhelm and W. S. Smith, 1965: High altitude summer mesospheric temperatures and winds with particular regard to noctilucent clouds. *Space Research V*, Amsterdam, North Holland Publishing Company.