Temperature Changes in the Mesosphere and Stratosphere Connected with Circulation Changes in Winter[1]

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ABSTRACT

The midwinter temperature changes of the mesosphere and stratosphere are described by means of Satellite Infrared Spectrometer and Selective Chopper Radiometer data, rocketsondes, and rocket grenade data, which show that the so-called stratospheric midwinter warmings extend at least into the upper mesosphere. Temperature changes of opposite sign take place at the same time at different levels, probably as a result of vertical motion. The event begins around a very high stratopause, ~60 km, which descends 20 km within several days while the warming intensifies. At the same time the upper mesosphere and lower stratosphere cool. When the polar vortex breaks down, the warming reaches the lower stratosphere, the warm stratopause region is destroyed through cooling of the layer between 30 and 60 km, and the upper mesosphere warms.

The mean vertical temperature profiles suggest that the upper mesosphere is cold at high latitudes in early winter and again in late winter, and that the warm upper mesosphere observed in late January–early February is associated with the breakdown of the stratospheric polar vortex.

1. Introduction

The most interesting synoptic-scale event of the circulation in the stratosphere and mesosphere is the midwinter warming. Ever since its discovery by Scherhag (1952) many have studied and attempted to explain this phenomenon. The first investigations were limited to the stratosphere due to the lack of data at higher levels, but when rocket data became available (Teweles, 1961; Finger and Teweles, 1964), it became obvious that the warmings and circulation changes affect a deep layer of the atmosphere up to at least 60 km.

It has also been noted (Warnecke and Nordberg, 1965) that climatological features of the stratosphere, such as the Aleutian anticyclone, extend to 70 km, producing standing waves and therefore longitudinal differences.

Today, documentation of the synoptic-scale motions above 10 mb (30 km) is produced by several groups [e.g., Staff Upper Air Branch, NMC, NOAA (1967a, b, 1969, 1970); and Staff Stratospheric Research Group, Free University Berlin (1967, 1971)]. However, above radiosonde-level the analyses are generally limited to North America and adjacent areas, although they are sometimes extended to western Europe and the Pacific. Above 55 km, very few data are available, especially at higher latitudes. This is the reason why the Committee on Extension to the Standard Atmosphere (COESA) (1966) hesitated to present a reference atmosphere for winter conditions above 30 km north of 60N. For this region the concept of a prevailingly warm upper mesosphere at high latitudes in winter has been accepted.

It is the purpose of this study to stress Quiroz' ideas of a cold upper mesosphere in early winter and to explain the observed "warm region" in January/February as a result of a special *synoptic* situation.

2. Standard atmospheres

In Fig. 1 the standard atmospheres for January at 60N (*U. S. Standard Atmosphere Supplements, 1966*; Groves, 1970) are shown. The stratopause is assumed to lie between 50 and 55 km, and although the *Supplements* presents profiles for cold and warm *stratospheric* conditions, the stratopause is kept at the same level in both instances.

3. Comparison with observations

In the following, these model profiles will be compared with observations, especially in situations before, during, and after the so-called stratospheric warmings.

a. Early winter

At the beginning of the winter, November or early December, the undisturbed stratospheric-mesospheric

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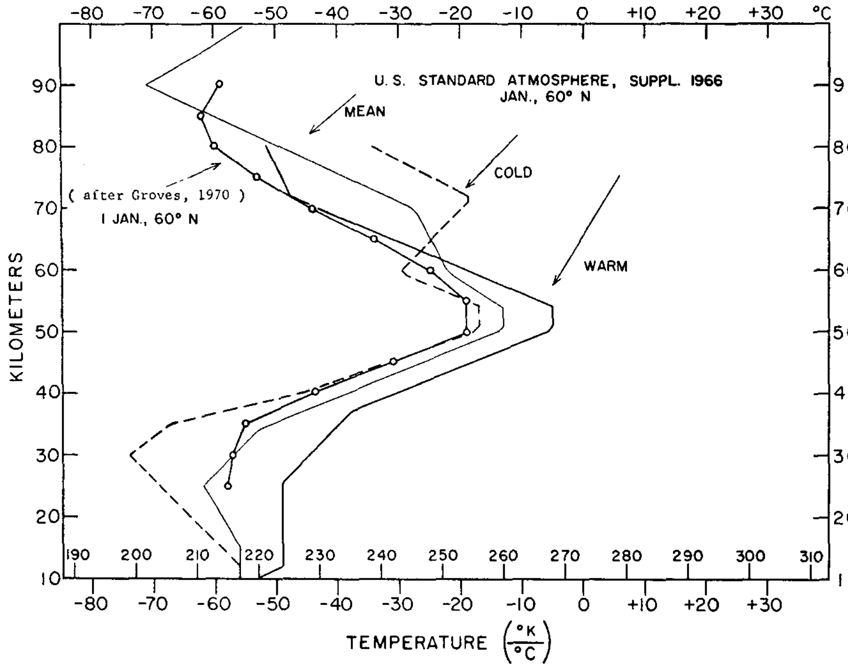

FIG. 1. Standard atmospheres at 60N for January.

circulation predominates in middle and high latitudes, i.e., a cold stratospheric polar vortex with minimum temperatures below −80C. In Fig. 2, the temperature field of the 30-mb level, as representative of the middle stratosphere (Staff, Stratospheric Research Group, Free University Berlin, 1970) is compared with the radiances[4] of channel 8 of the Satellite Infrared Spectrometer (SIRS), flown on Nimbus 4.

The maximum of the weighting function of channel 8 (669 cm^{-1}) is close to 23 km (30 mb) (Wark and Hilleary, 1969), and it is thus appropriate to compare these two sets of data. One should not, however, expect complete coincidence, as the radiances received in channel 8 of SIRS represent a layer 30–35 km thick.

The midwinter warmings seem to progress in a similar way in most winters. Therefore, using the rocket data of the last five winters of West Geirinish (57N) in Scotland, and of Ft. Churchill (59N) in Canada, typical mean temperature profiles have been derived for the following stages:

0 early winter, undisturbed
1 early winter, beginning of the warming at the highest levels reached by small meteorological rockets, i.e., about 60 km
2 peak of midwinter warming (as far as observed)
3 advanced stage of warming
4 termination of warming in the stratosphere (breakdown of the stratospheric circulation; cooling of the lower mesosphere; warming of the upper mesosphere)
5 late winter (not shown)

In Fig. 3 the profiles for stages 0 and 1 of the early winter (at West Geirinish) are compared with the profile for a *cold* stratosphere (U. S. Standard) and with Groves' data for 1 December. Profile 0 compares very well with

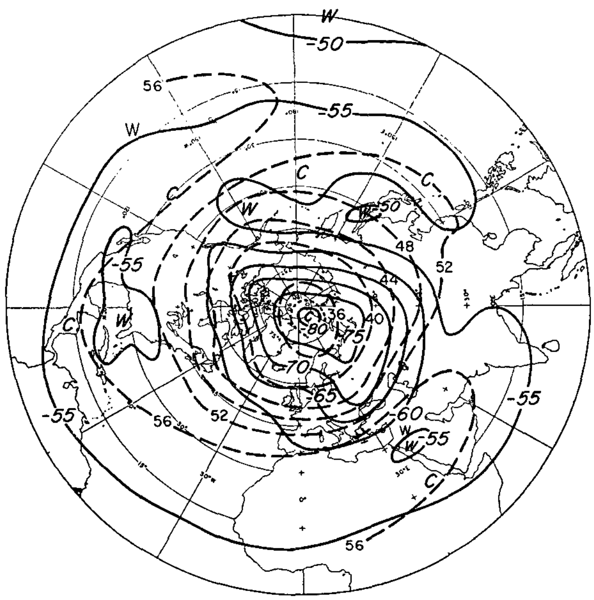

FIG. 2. Temperatures at 30 mb (°C) for 7 December 1970 (solid lines) and radiances (erg/) of SIRS channel 8 (dashed lines) for 6 December 1970.

[4] The radiance units are ergs cm^{-2} sec^{-1} sr^{-1} $(cm^{-1})^{-1}$, abbreviated to erg/.

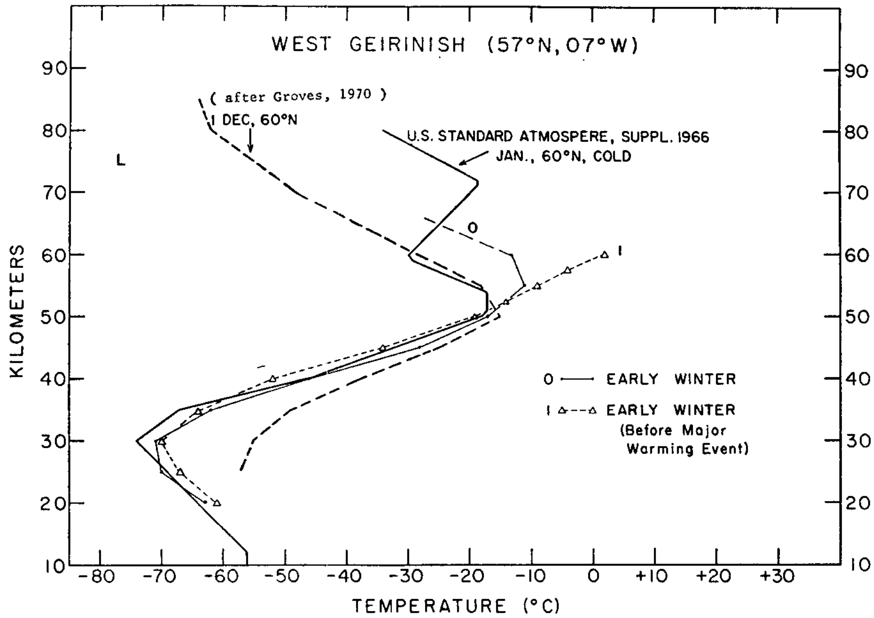

FIG. 3. Profiles 0 and 1 for West Geirinish, the Standard Atmosphere for January at 60N (cold), and Groves' model for 1 December.

the models, except that Groves' temperatures are much higher below 40 km because of his choice of stations. At the highest level reached by small meteorological rockets, a positive error of a few degrees is very likely.

As pointed out by Quiroz (1969) there is evidence of low temperatures in the upper mesosphere, between 70 and 80 km, in early winter. A mesopause temperature of −77C (for 75 km, 60N, winter) was predicted by Leovy (1964) from computations based on radiative heating and cooling. This value has been entered as L in Fig. 3. Remembering that the temperatures of the uppermost part of profile 0 may be too high, an extension to the low values at 75 km seems feasible.

Profile 1 demonstrates the early stage of the mid-winter warming and is composed of data from three different winters. Unfortunately, no rockets reached the stratopause in this stage. The beginning of a warming at the 60-km level is, however, clearly indicated. As the stratopause must be higher than in profile 0, it is also probable that the mesopause is higher during this stage of the development.

In Fig. 4 the synoptic situation at the beginning of the warming is demonstrated. Fig. 4a (12 December 1970) shows the temperature at 30 mb and the SIRS radiance data of channel 8 for the same day. The warm region connected with the Aleutian high agrees well with the maximum radiances. The radiance minimum is farther west than the temperature minimum. This indicates a westward tilt with height of the axis of the polar vortex, as the radiation received in channel 8 also reflects conditions in the upper stratosphere.

In Fig. 4b preliminary radiance[5] data of channel A of the Selective Chopper Radiometer (SCR) are compared with the temperature field at 45 km[6] for 13 December

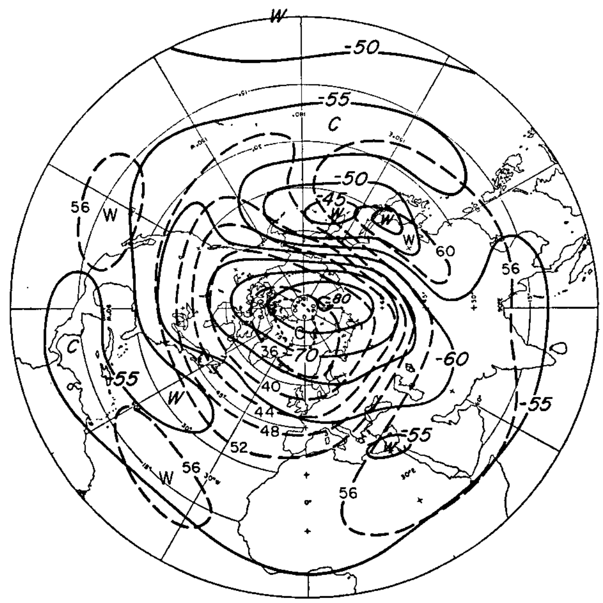

FIG. 4a. Temperatures at 30 mb (solid lines) and radiances of SIRS channel 8 (dashed lines), for 12 December 1970.

[5] The radiance units are mW m^{-2} sr^{-1} (cm^{-1})$^{-1}$, abbreviated to mW/.

[6] The temperature fields at 45 and 60 km have been analyzed independently from the SCR data, using all rocket observation (rocob) reports available within 3 days before and after the map date. Temperatures are entered without any corrections; wind measurements ending 2 km below the map level have been entered with broken shafts. The data for Thumba (India) became available later (Fedinsky and Pisharoty, 1971)[7].

[7] Fedinsky, A., and P. R. Pisharoty, 1971: A brief report on the upper winds and temperatures over Thumba (India) (1970–71). Paper presented at the XIVth COSPAR meeting, Seattle, Washington, June 1971.

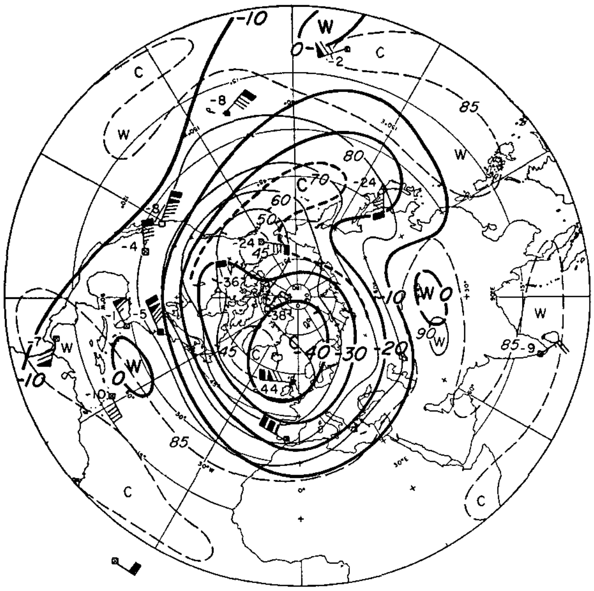

Fig. 4b. Temperatures at 45 km (heavy lines) and radiances (thin lines) of channel A of SCR (mW/) for 13 December 1970 based on all rocket observations available within 3 days before and after the map date. The following notation has been used for the different days:

△ 3 days before	● map day
△ 2 days before	■ 1 day after
▲ 1 day before	□ 2 days after
	⊠ 3 days after

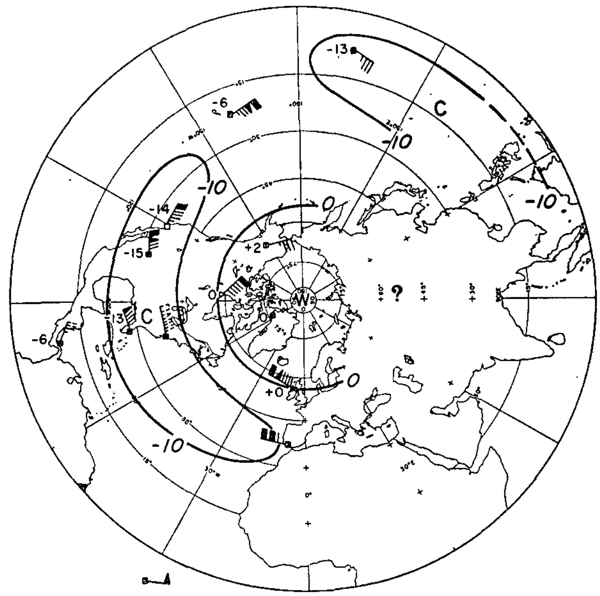

Fig. 4c. Temperatures at 60 km for 13 December 1970 (with the notation of Fig. 4b).

1970. The greater part of the radiation measured by channel A originates in a layer about 20 km thick centered at about 42 km (Ellis *et al.*, 1970). Thus, the radiance field reflects the large-scale features of the temperature field and may be used as a substitute over regions with no data. The westward sloping cold pole is clearly indicated, as well as the existence of a warm region (> 90 mW/) over Central Asia.

At 60 km (Fig. 4c) the circulation pattern, with generally strong westerly winds, is not much different from that of the lower levels. The *temperature field* is

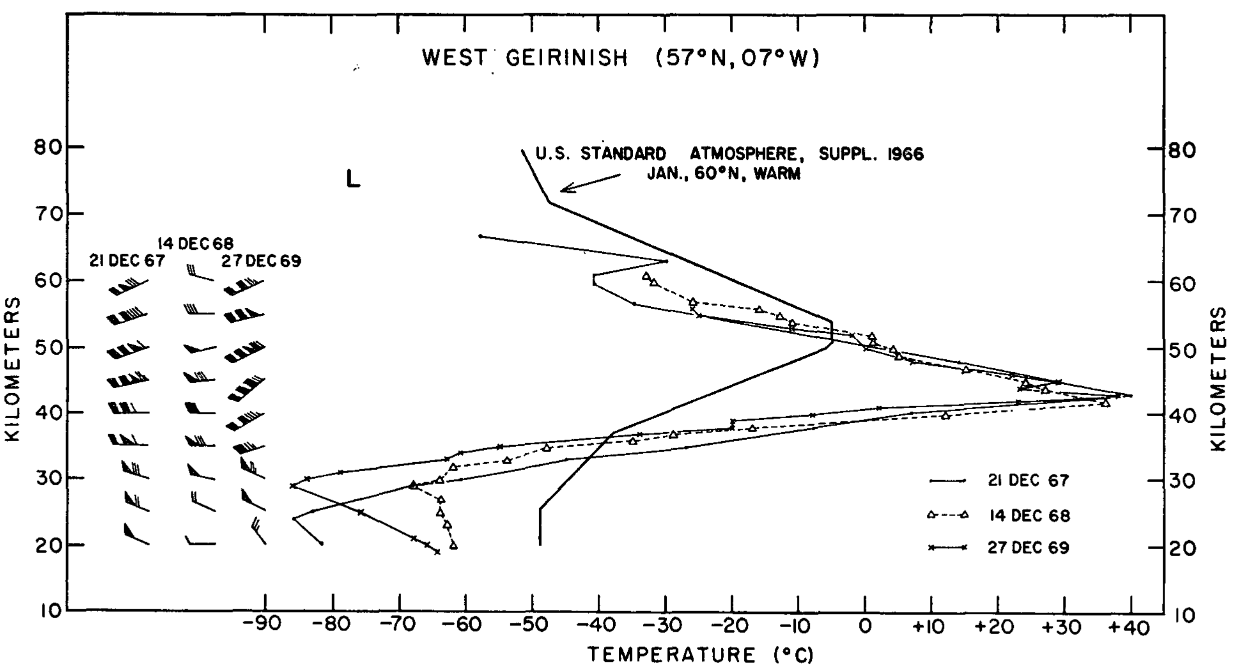

Fig. 5. Three profiles of rocketsonde data at West Geirinish and the U. S. Standard for January at 60N (warm).

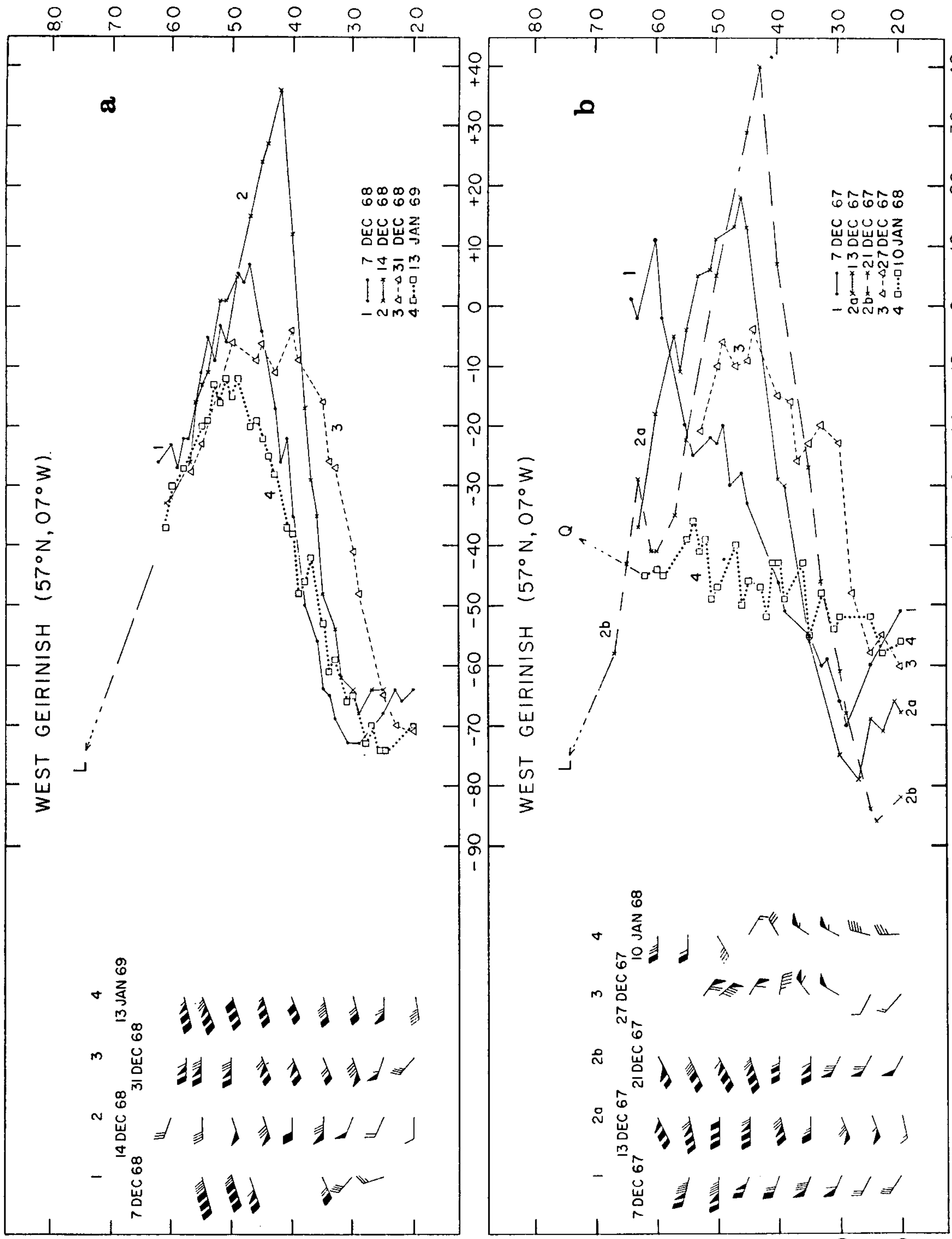

FIG. 6. Sequence of profiles of rocketsonde data at West Geirinish during the winter 1968–69, a., and for the winter 1967–68, b.

completely reversed, however, with warm air over the north pole. During this stage the stratopause is very high over polar latitudes, close to 60 km (cf. profile 1 in Fig. 3), and slopes to below 50 km at middle latitudes with temperatures around 0C.

b. Midwinter

In Fig. 5, the data of three rockets launched at West Geirinish are shown. These soundings were obtained during three different winters and all show the highest temperature measured by rockets during those winters (stage 2). During the winter of 1967–68, temperatures of 40C were measured for the first time over West Geirinish at a height of 43 km, on 21 December 1967, and the reality of this value was confirmed the two following winters with temperatures >35C at 42 and 43 km. Profile 2 in Fig. 11a for West Geirinish is composed of these three soundings.

Such extremely high temperatures had never been measured before (in addition to the three successive measurements at West Geirinish a similar value was observed over Ft. Churchill in January 1970) and were not expected, as all our knowledge of the atmosphere above radiosonde level was mainly from rocket data over North America. The northernmost stations here are Ft. Greely and Ft. Churchill, Canada. The influence of the Aleutian anticyclone extends to 70 km, and the two North American stations are generally within the circulation of the anticyclone. Ft. Churchill is only occasionally influenced by the polar vortex, Ft. Greely rarely. The midwinter warmings develop, however, south of the stratospheric polar jet stream (Matsuno, 1971). Due to the eccentric stratospheric circulation with the polar vortex over the Greenland Sea, the maximum of the stratospheric polar jet stream is situated between 50 and 60N over western and central Europe. This can be deduced, for example, from the 10-mb mean maps (Labitzke *et al.*, 1972). Gaigerov *et al.* (1970)[8] have pointed out, for instance, that at the 2-mb level the mean speed of the west wind is twice as large over Berlin (75 m sec^{-1}) as over the United States and that farther east it decreases to 65 m sec^{-1} over Volgograd. As West Geirinish is situated close to the maximum of the stratospheric polar jet stream, extreme temperatures are more likely above this station than over the North American stations.

The similarity of the profiles in Fig. 5 in the upper stratosphere/lower mesosphere is striking, especially the almost identical peak values of the stratopause, within a range of 1 km.

The very warm conditions of stage 2 are compared in Fig. 11a with the profiles of the atmosphere just before the warming started. In addition to the lowering of the stratopause to heights just above 40 km and the strong warming of the upper stratosphere and lower mesosphere, there is an intense *cooling* of the levels above 55 km. Profile 2 can easily join the value given by Leovy (−77C at 75 km). The lower stratosphere, below 30 km, cools too, which is a well-known feature during a warming at higher levels. Thus, the lower stratosphere is coldest, with a minimum around 25 km, at the same time as the upper stratosphere and lower mesosphere are warmest.

Because of the similarity of the three profiles when the temperatures were highest (Fig. 5), one might have expected that the further developments of the stratospheric warmings were also similar. This was, however, not the case: there were *major* midwinter warmings with a complete breakdown of the circulation in all of the stratosphere in the winters of 1967–68 and 1969–70, whereas the warming did not penetrate into the lower stratosphere in 1968–69. The only apparent difference between the two soundings associated with a complete breakdown and that which did not develop into a major warming, is noticeable in the wind. The two former show considerably higher wind speeds above 30 km, between 50 and 55 km about six times higher, than the latter.

Fig. 6a contains a sequence of rocket soundings for the minor warming in the winter of 1968–69. Profiles 1 and 2 demonstrate the development of the warming, with winds >300 kt on 7 December (profile 1) and with considerably lower winds together with the extreme temperature of 36C at 42 km in profile 2. Profile 3 shows the advanced stage when the warming had reached levels between 25 and 30 km. During the next days gradual cooling took place, such that finally profile 4

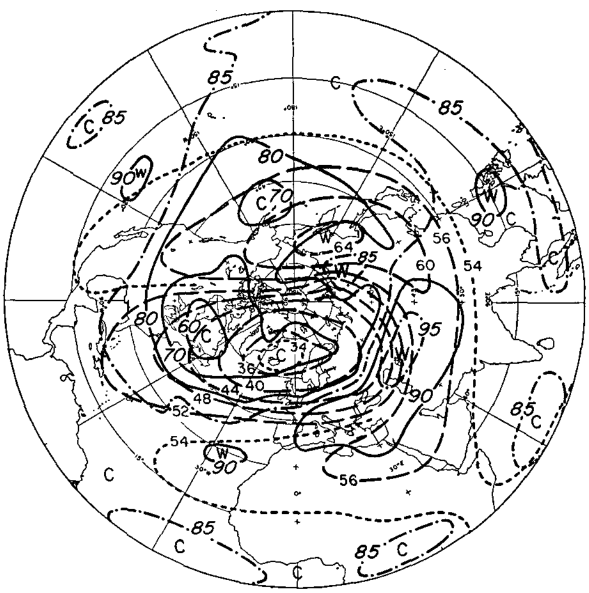

Fig. 7. Radiances of SIRS channel 8 (dashed lines) and of SCR channel A (solid lines) for 30 December 1970.

[8] S. S. Gaigerov, B. P. Zaichikov, M. Ja. Kalikhman, V. E. Sedov, D. A. Tarasenko and E. G. Shvidkovsky, 1970: Vertical distribution of the main meteorological parameters and large-scale processes in the stratosphere and mesosphere. Paper presented at the XIIIth COSPAR meeting, Leningrad.

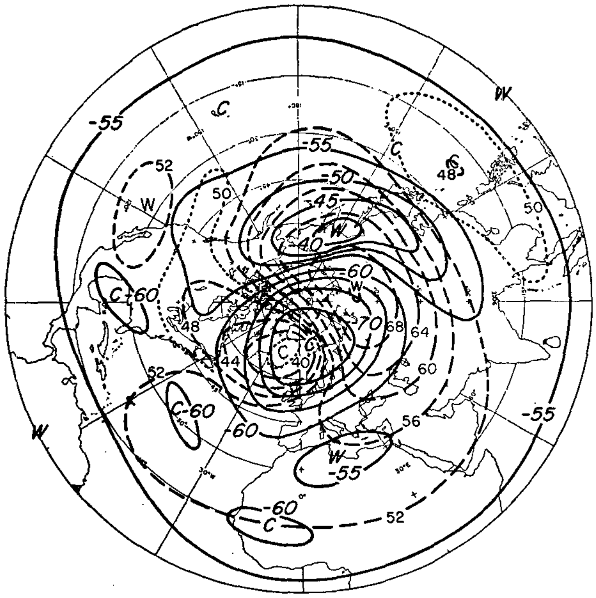

FIG. 8a. Same as Fig. 4a, except for 7 January 1971.

becomes similar to profile 1 (Fig. 6a). During this warming only the region below 55 km (usually in the upper stratosphere) was affected. Above 55 km the profiles show little change, all indicating a lapse rate which could reach the value given by Leovy (L in Fig. 6a).

A series of selected rocket soundings over West Geirinish is shown for the major midwinter warming of 1967–68 in Fig. 6b. It was the first time that such high temperatures were observed, and the warming has been extensively examined (Labitzke and Schwentek, 1968; Johnson, 1969; Miller and Johnson, 1970; Scherhag *et al.*, 1970). During the peak of the warming in December 1967 profiles 2a, 2b, 3 are similar to those in Fig. 6a. However, comparing Figs. 6a and 6b it is interesting to note the differences between profiles 1 and particularly between profiles 4. After the minor warming (1968–69) the temperature of the stratosphere and lower mesosphere returned to "normal" values, with the suggestion of a cold upper mesosphere. After the major midwinter warming in 1967–68, however, the strato-spheric-mesospheric circulation broke down. Profile 4 in Fig. 6b changes little between 20 and 60 km, i.e., *a complete destruction of the warm stratopause layer took place.* The value plotted as Q in Fig. 6b is the peak value in Quiroz' (1969) observed temperature curve at 70–80 km in winter, and also the value of the U. S. Standard Atmosphere at 60N for mean conditions at this level in January (see Fig. 1). I suggest that profile 4 in Fig. 6b is the one which should be connected with Quiroz' value in the upper mesosphere; in other words, *only when a complete breakdown has occurred in the stratosphere does the temperature in the mesosphere reach this comparatively high value.* As pointed out by Quiroz, the rocket grenade observations taken in winter at Ft. Churchill and Pt. Barrow (Nordberg *et al.*, 1965) show a warm upper mesosphere with the mean temperatures at 70 km close to −43C; but as he notes these observations were all made in late January–early February. This is the termination period of the midwinter warmings, i.e., the time and stage of profile 4 (cf. Figs. 6b, 11 and 12). The data are concentrated in late January–early February because the warmings are observed late at those relatively low stratospheric levels which are routinely reached by radiosondes; and as rocket grenade firings were scheduled to take place during warmings as observed by radiosondes, they were too late to give a complete picture of the events in the mesosphere.

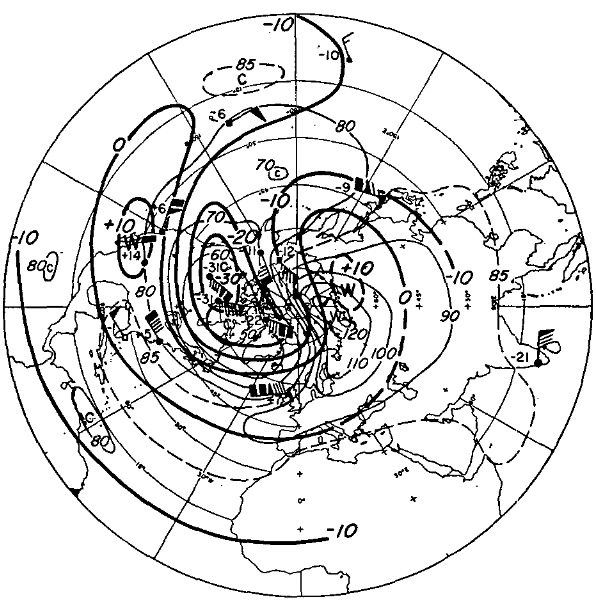

FIG. 8b. Same as Fig. 4b, except for 6 January 1971.

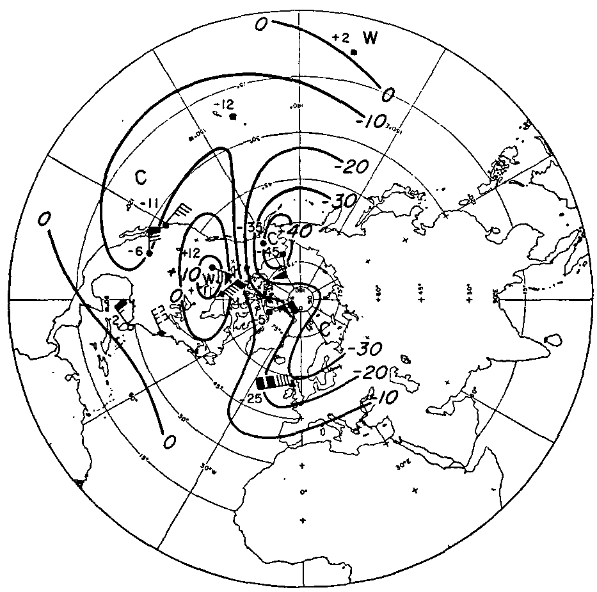

FIG. 8c. Same as Fig. 4c, except for 6 January 1971.

4. Discussion of synoptic maps

So far we have been primarily concerned with observations at single stations, but in the following, synoptic maps (Figs. 7–10) are used to show the development of the warming in the winter of 1970–71, one of the major midwinter warmings.

Radiance data of channel 8 of SIRS and of channel A of the SCR are shown for 30 December 1970 in Fig. 7. Note 1) the northwestward tilt of the warm region (high radiances) associated with the intensifying Aleutian high, 2) the southwestward tilt of the cold pole (low radiances), and 3) the large region of high radiances (>95 mW/) measured with the SCR near the Caspian Sea. According to Barnett *et al.* (1971) this was the second warm pulse observed and it had developed three days earlier at 25N, 20E. It is *this* warm area which, moving poleward during the next days, develops into a major midwinter warming of both stratosphere and mesosphere. This is the first time we can follow such an event which, as the data of the SCR clearly show, is a development separate from the Aleutian high.

The next set of maps (Fig. 8) shows the intense development over Asia on 6 and 7 January 1971. In Fig. 8a the 30-mb temperatures are compared with the radiances of channel 8 of SIRS. The northwestward displacement of highest radiances from the warm region of the Aleutian high is very pronounced, indicating a strong development in the *upper* stratosphere, since conditions in the lower stratosphere (100 and 50 mb) are known to be similar to those at 30 mb. The lowest radiances are also found somewhat west of the cold pole. The pronounced wavenumber 1 should be noted.

On 6 January (Fig. 8b), the highest radiances of channel A have reached polar latitudes and are found west of the center of warmest air at the 45-km level, though this, of course, can be stated only tentatively because of the few rocket observations. Comparing the position of the lowest temperatures with the lowest radiances, we note that the distribution is not the same as in early winter and that it differs from that of the lower stratosphere in Fig. 8a. The center of lowest radiances in Fig. 8b is found east of the lowest temperatures which reflects an eastward tilt with height of the axis of the cold pole. This agrees with the temperatures at 60 km (Fig. 8c) where one part of the cold pole is found over the Barents Sea.

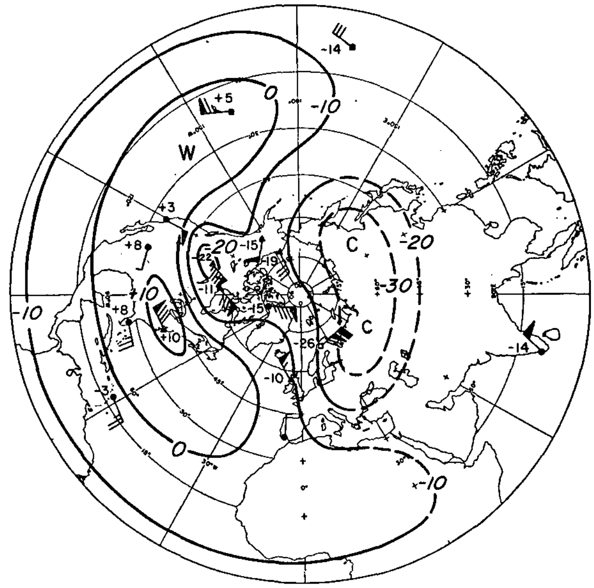

Fig. 9b. Temperature field at 45 km for 13 January 1971.

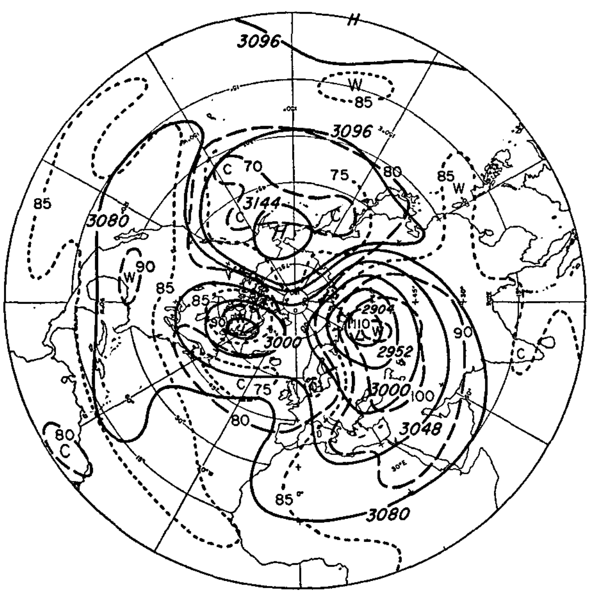

Fig. 9a. Height field at 10 mb in geopotential dekameters (solid lines) and radiances of SCR channel A (dashed lines) for 13 January 1971.

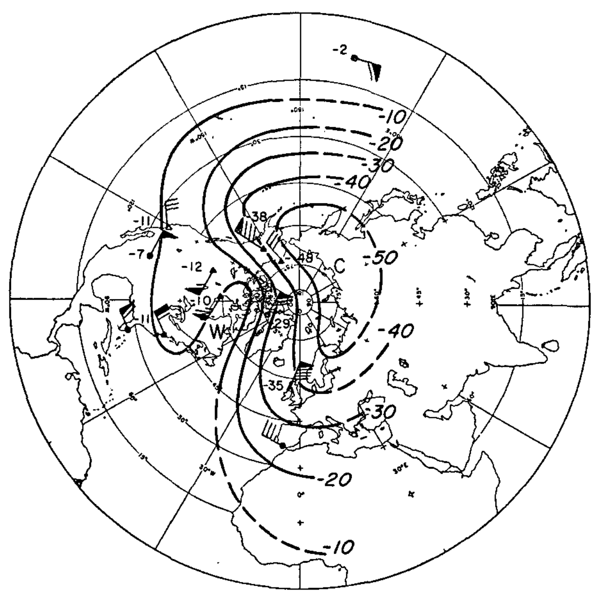

Fig. 9c. Temperature field at 60 km for 13 January 1971.

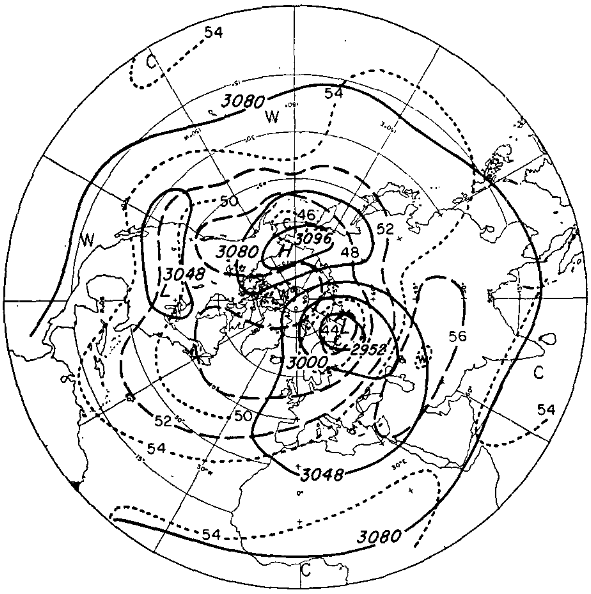

FIG. 10a. Height field at 10 mb (solid lines) and radiances of SIRS channel 8 (dashed lines) for 28 January 1971.

The axis of warmest air slopes with height across the polar region and at the 60-km level (Fig. 8c) it is found over Canada, right above the cold pole of the upper stratosphere. Cooling took place at 60 km over Asia, Europe and Alaska, i.e., above the intense warming area where the stratopause descended to about 40 km; and the northerly winds over Canada and Alaska indicate that the Aleutian high moved toward northern Siberia, dominating the circulation over the whole arctic, while the center of the polar vortex was displaced toward Iceland.

The breakdown of the stratospheric circulation continued. After the polar vortex split as the Aleutian high approached, wavenumber 2 dominated the further developments. This is demonstrated in Fig. 9a, which shows the height field of the 10-mb map of 13 January 1971 together with the radiances of channel A of the SCR. The picture is one of thermal compensation, i.e., warmth (high radiances) over the cyclones and cold (low radiances) over the anticyclones.

The circulation at the 45-km level over the pole (Fig. 9b) was controlled by the Aleutian high, whose center must be close to Pt. Barrow. Cooling took place over Eurasia (cf. Fig. 8b) while the warming penetrated into the middle stratosphere.

A similar picture emerges at 60 km (Fig. 9c). Here the winds show that the center of the Aleutian high has reached northern Canada in a complete reversal of the normal winter circulation. At the same time, the cooling noticed already on 6 January (Fig. 8c) continued over most of the hemisphere.

The termination of the warming is illustrated in the last set of maps. Fig. 10a shows the 10-mb heights for 28 January 1971, together with the radiances of channel 8 of SIRS. There still is warm air over the pole, i.e., the reversed temperature gradient persists. But now the minimum of the radiances coincides with the polar vortex over northern Russia, indicating an intensification of this vortex which later migrated to the polar region. In Fig. 10b, at 45 km on 27 January, the temperature field and the circulation pattern have returned to early winter conditions with the center of the polar vortex together with the center of coldest air over polar regions, in agreement with the radiance data. At the 60-km level, too, the lowest temperatures are now in the polar region (< −40C in Fig. 10c). This is the reverse pattern of that shown in Fig. 4c for the early winter.

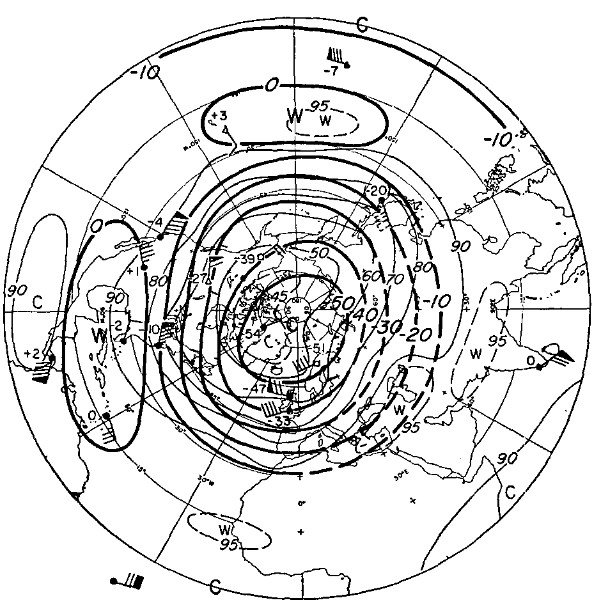

FIG. 10b. Same as Fig. 4b, except for 27 January 1971.

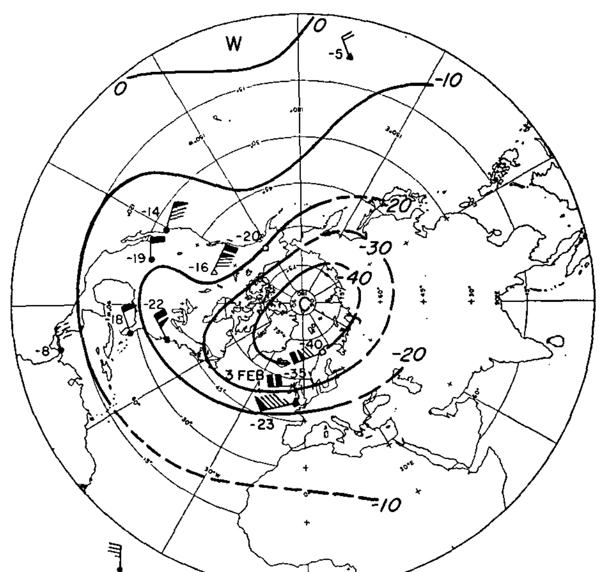

FIG. 10c. Same as Fig. 4c, except for 27 January 1971.

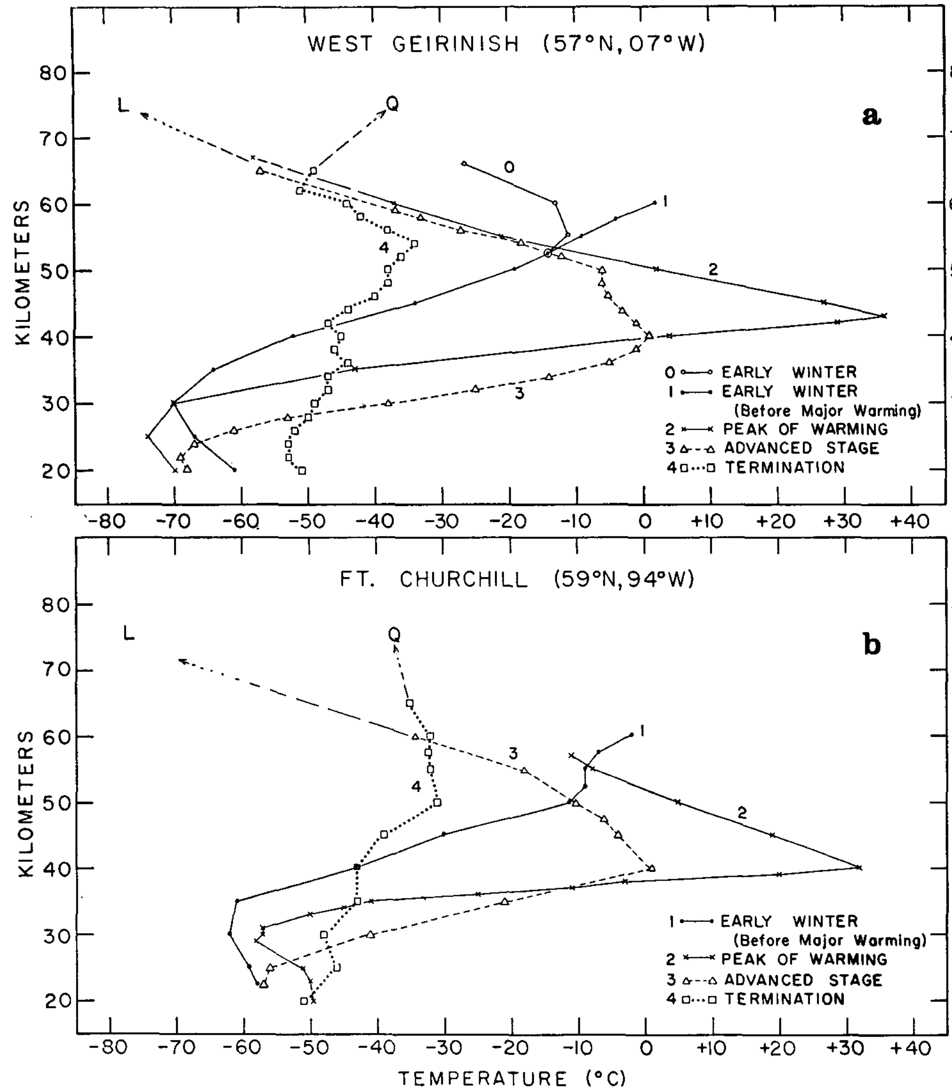

Fig. 11. Typical mean temperature profiles for West Geirinish, a., and Ft. Churchill, b.

5. Summary

The features which have been emphasized above are summarized in the vertical profiles of Fig. 11. Fig. 12 is a schematic drawing of the progression of the temperature changes in the stratosphere and mesosphere during a major midwinter warming at high latitudes outside of the regime of the Aleutian high. Referring to these two illustrations, the following statements can be made:

1) The changes which happen during a stratospheric midwinter warming are not limited to the stratosphere but extend *at least* into the upper mesosphere. If the whole layer is considered, the word "warming" is a misnomer. Rather, temperature changes of opposite sign take place at the same time at different levels, presumably linked with vertical motions.

2) The events begin outside the regime of the Aleutian high, with rising temperatures around a very high stratopause at ~60 km (profiles 1, Fig. 11).

3) The stratopause descends 20 km within several days while the temperature around it rises rapidly to a peak above 30C. At the same time the upper mesosphere, and often also the lower stratosphere, cool (profiles 2 in Figs. 11 and 12, 5–20 December).

4) After the peak, the stratopause descends further, and the upper stratosphere, now at 30–40 km, warms slowly whereas the upper mesosphere stays cold and the lower mesosphere cools (profiles 3 in Figs. 11 and 12, 20–28 December).

5) If the polar vortex breaks down (a major midwinter warming), the warming reaches the lower stratosphere (about 5 weeks after stage 1), the warm stratopause region is destroyed through cooling of the layer between 30–60 km, and the upper mesosphere

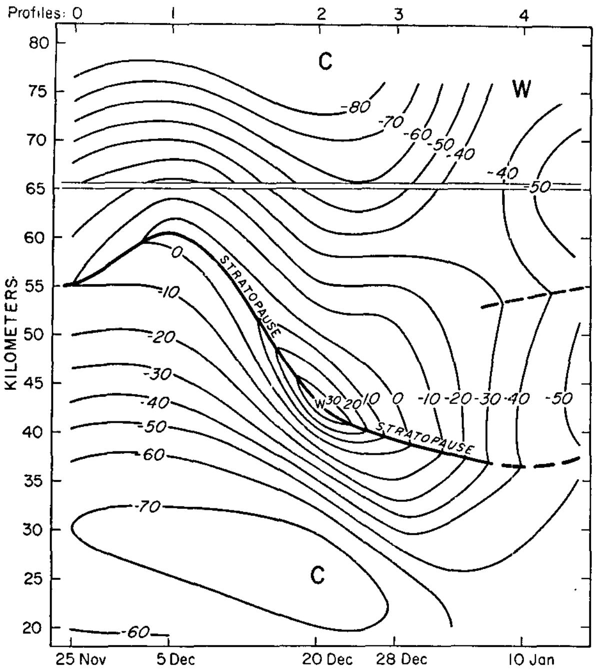

FIG. 12. Schematic vertical time section (20–80 km; time scale approximate) of the progression of a major midwinter warming at high latitudes outside the regime of the Aleutian high. Below 65 km the section is based on the rocketsonde profiles for West Geirinish (see Fig. 11a), above 65 km on the computations of Leovy (1964) and the rocket grenade data (Nordberg *et al.*, 1965; Quiroz, 1969).

warms (profiles 4 in Figs. 11 and 12 after 28 December).

6) The mean profiles in Fig. 11 support Quiroz' idea and Leovy's computations that the upper mesosphere is cold at high latitudes in early winter and again in late winter and that the warm upper mesosphere observed in late January–early February is an interval connected with the breakdown of the stratospheric polar vortex, i.e., stage 4.

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