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Climatology of the Stratosphere and Mesosphere

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Climatology of the stratosphere and mesosphere

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The use of all available radiosonde, rocketsonde and satellite data, has elucidated the climatology of the atmosphere up to the mesopause.

The seasonal variation of the temperature in the stratosphere and mesosphere will be described, mainly from monthly mean maps. Emphasis will be given to longitudinal and hemispheric differences.

During the winter season when, owing to the development of the cold stratospheric polar vortex, the winds in the stratosphere are mainly from the west, the planetary waves of the troposphere penetrate into the stratosphere, and even into the mesosphere during the northern winter. This results in longitudinal differences over both hemispheres, though the effect is stronger over the Northern Hemisphere.

The hemispheric differences are particularly large between the winters, as the stratospheric midwinter warmings are different over both hemispheres. As a consequence, the transition from the winter to the summer circulation also evolves differently. During summer, the southern stratosphere is warmer than the northern because of the difference in solar heating of ozone due to the ellipticity of the Earth's orbit.

1. Introduction

For the investigation of the lower and middle stratosphere radiosonde data have now been available for about 20 years (since 1958), i.e. since the International Geophysical Year. Above this level rocketsondes have been an important data source, especially for the fine structure of the atmosphere. Since 1969, remote temperature soundings from satellites provide data on a global scale to study the structure of the upper stratosphere and recently also of the mesosphere.

The information obtained from these data is very large and several climatologies and model atmospheres have been derived (e.g. *C.I.R.A.* 1972; Labitzke *et al.* 1972; Newell *et al.* 1972; van Loon *et al.* 1972; Newell *et al.* 1974; Knittel 1976). In the following only a few aspects of the climatology of the stratosphere and mesosphere will be pointed out.

2. Zonal mean temperatures

Zonal mean temperatures describe the gross structure of the temperature distribution, omitting the zonal asymmetries. In figure 1 the zonal mean temperatures (based on the radiosonde data of several years) are shown in a vertical meridional section for the January of the Northern Hemisphere. Typical features of the middle stratosphere are: the cold centre over polar latitudes, the warm region over middle latitudes and the cold tropical tropopause. In the upper stratosphere, near 10 mbar,† the pattern becomes simpler, as the temperature increases regularly from polar to low latitudes.

It must be kept in mind, however, that the stratospheric winter is a highly disturbed season and disturbances such as stratospheric warmings can destroy the polar vortex and alter the

† 1 bar = 10^5 Pa.

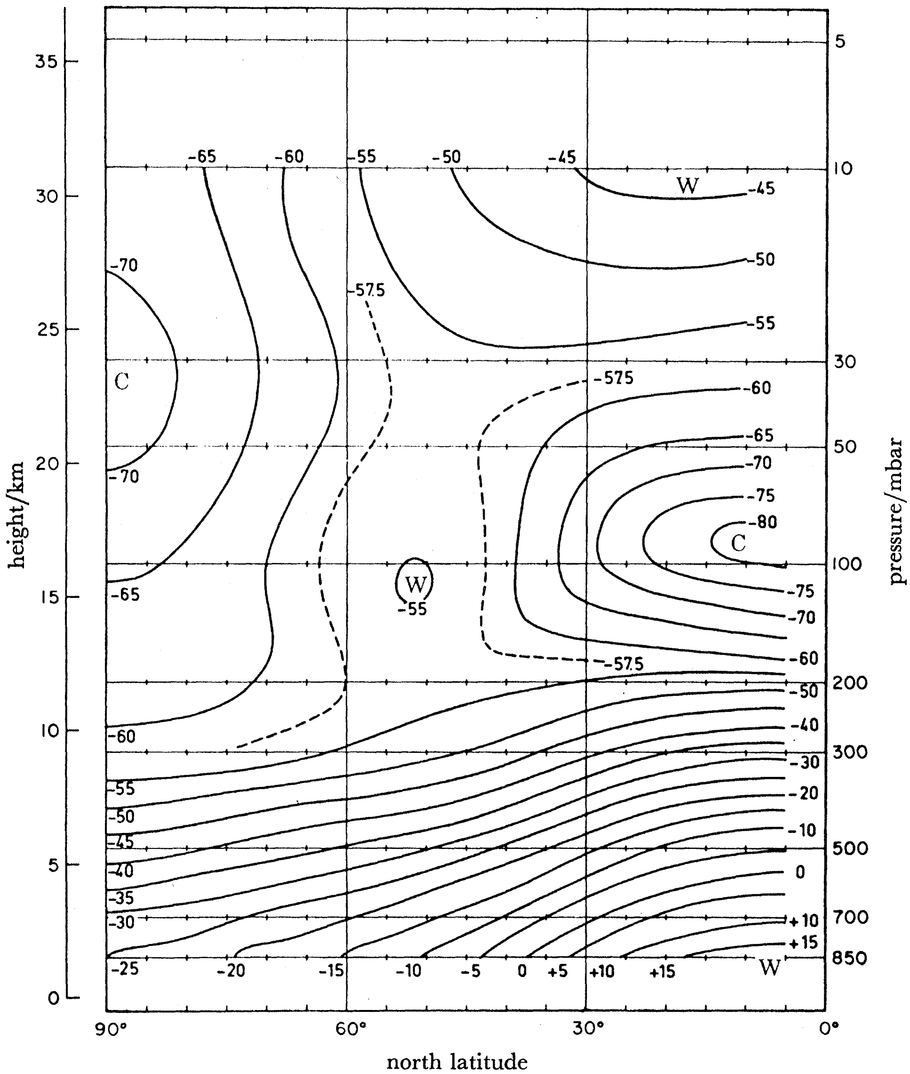

FIGURE 1. Vertical meridional section of zonal mean temperature (°C), for January, N.H. (from Labitzke *et al.* 1972).

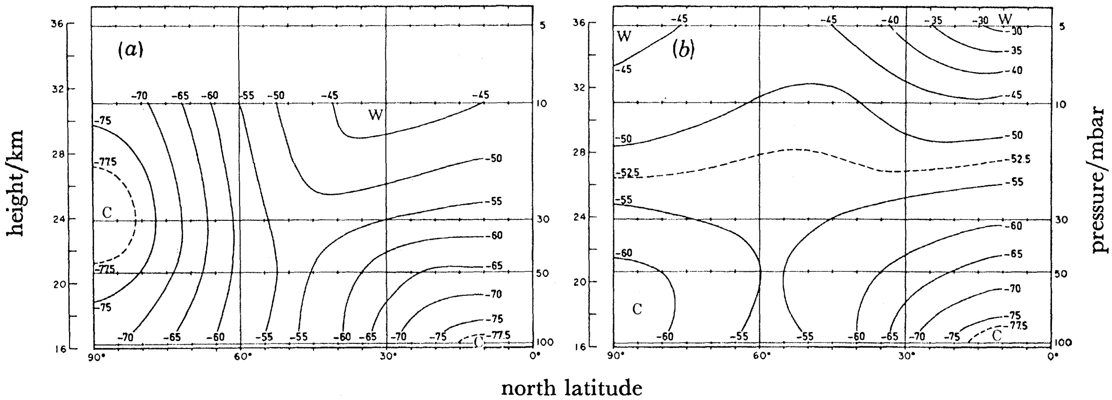

FIGURE 2. Vertical meridional sections of zonal mean temperatures (°C) (*a*) for a cold January and (*b*) for a warm January (from van Loon *et al.* 1972).

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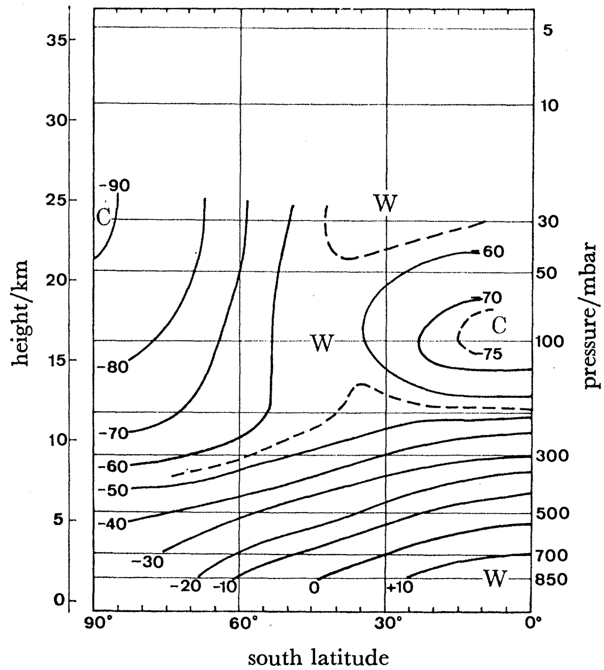

FIGURE 3. Vertical meridional section of zonal mean temperatures (°C), for July, S.H. (Data for the stratosphere from Knittel (1976); for the troposphere from Taljaard *et al.* (1969)).

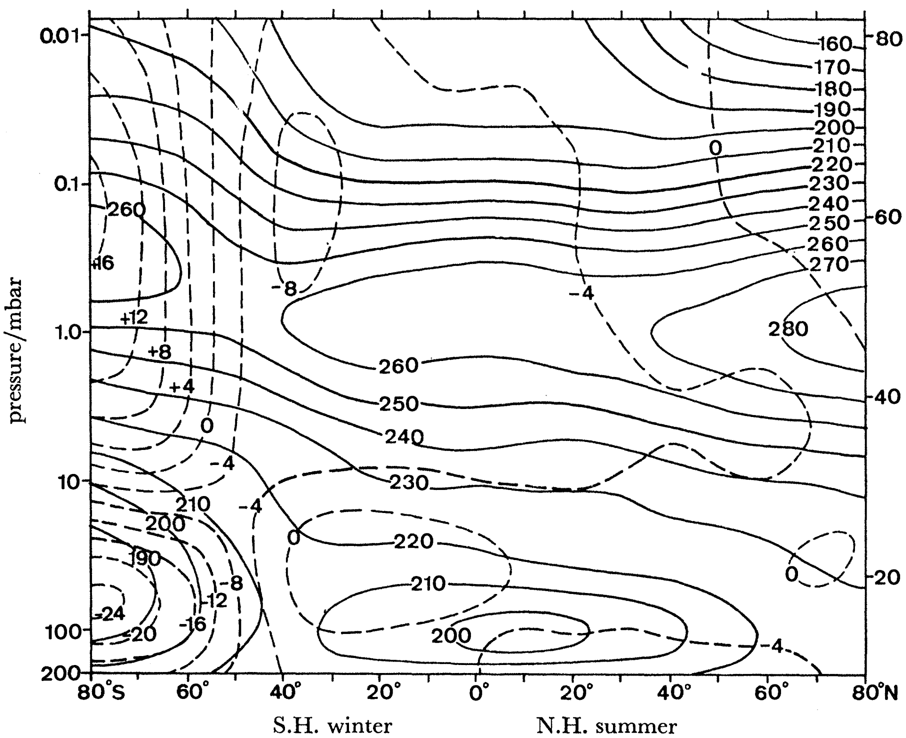

FIGURE 4. Vertical meridional section of zonal mean temperatures (K) for July. Dashed lines indicate deviations from *C.I.R.A.* (1972) (from Labitzke & Barnett 1978).

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temperature distribution of a whole month such that the temperature gradient is reversed over high latitudes. This is demonstrated in Figure 2, where the zonal mean temperatures of the 'cold' January 1967 are compared with those of the 'warm' January 1968.

The temperature structure of the middle stratosphere of the Southern Hemisphere winter, namely of July, is given in figure 3. Typically, the antarctic polar vortex is much colder than

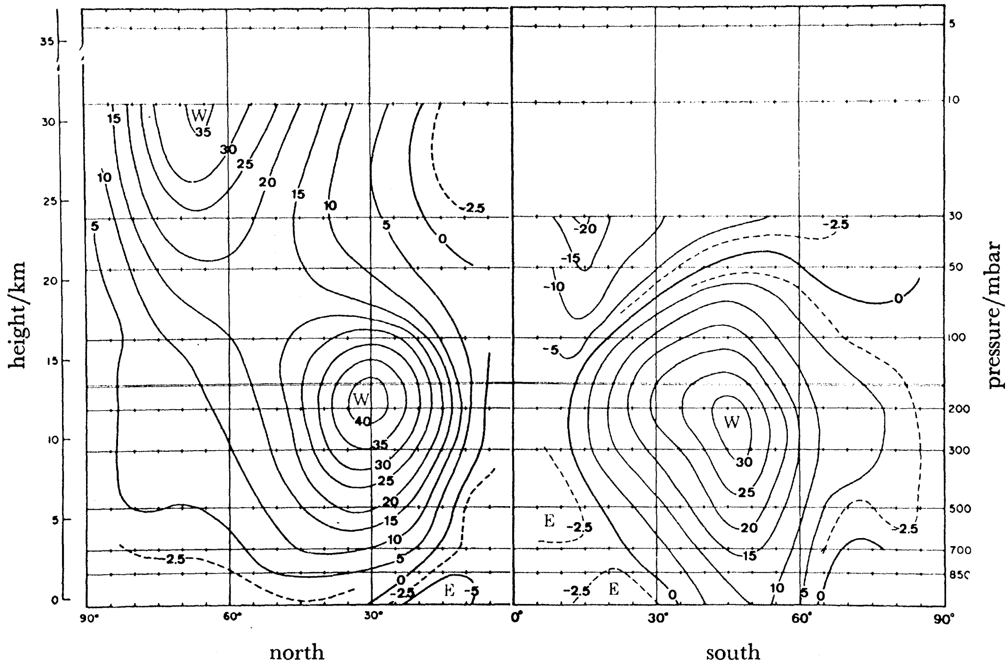

Figure 5. Vertical meridional section of zonal mean winds (in m/s) for January (from Knittel 1976).

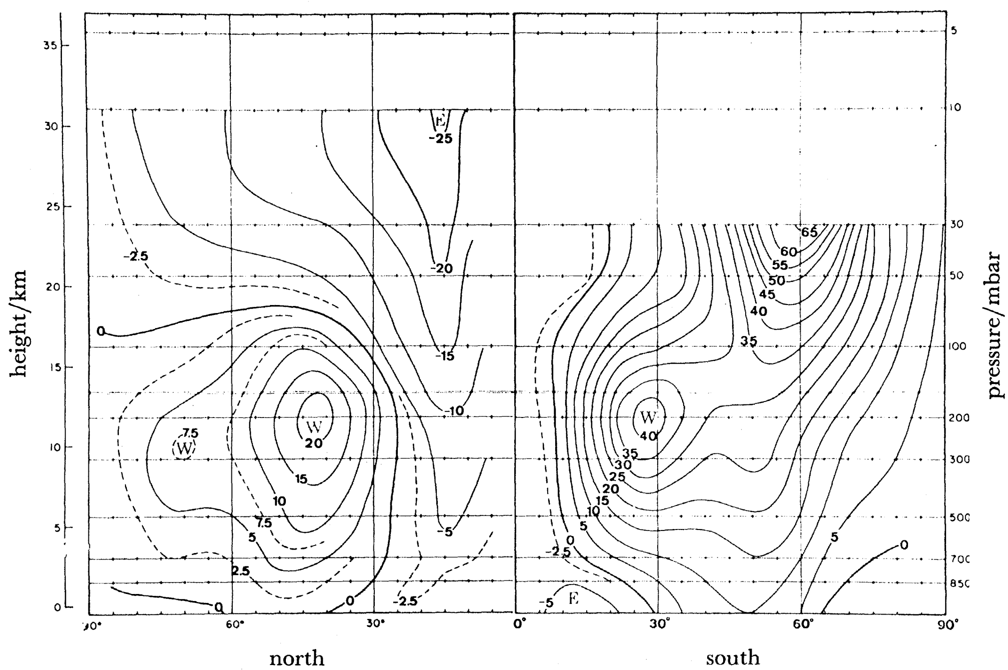

Figure 6. Vertical meridional section of zonal mean winds (in m/s) for July (from Knittel 1976).

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the arctic, and the warm region over middle latitudes is displaced about 10° latitude towards the equator.

Until recently the only way of studying the temperature structure of the upper stratosphere and of the mesosphere on a large scale was by using rocketsonde data. The distribution in time and space of these soundings was inadequate to establish a complete climatology. Today, different experiments on board satellites are capable of measuring the emitted thermal radiation of the Earth's atmosphere up to the mesopause region, daily on a global scale. With these new data it will be possible within the next years to get a complete analysis of the temperature structure of the atmosphere and of its changes up to the mesopause.

The zonal mean temperature cross section for July, figure 4, is based on retrieved temperatures from satellite measured radiances. Several years of data were available for the stratosphere, but only July 1975 for the mesosphere. The main features of the mesosphere are, however, well reflected: the very strong temperature decrease over high latitudes from the stratopause to the mesopause during summer and the reversed horizontal temperature gradient with temperatures increasing from the summer pole to the winter pole. Over the Northern Hemisphere the differences from the *C.I.R.A.* (1972) are below 4 K during this time of the year.

3. Zonal mean winds

In meridional sections from pole to pole the distribution of the mean zonal winds is shown in figure 5 for January and in figure 6 for July. In the stratosphere the polar night jet between 60 and 70° latitude is the main feature of the winter and this jet is more than twice as strong during the southern winter. During summer, winds from the east accompany the summer anticyclone. They reach further down over the Northern Hemisphere.

Over the tropics the direction of the winds depends on the phase of the quasi-biennial oscillation (review by Wallace 1973) and cannot be well reflected in a mean over several years.

4. Monthly mean maps

Monthly mean maps of temperatures or satellite measured radiances (which can be interpreted as mean temperatures over a certain layer) provide an excellent tool for showing longitudinal and hemispheric differences.

At first, the temperatures during early winter over both hemispheres (i.e. December, N.H. and June, S.H.) are compared. In the middle stratosphere (30 mbar) the antarctic region is much colder than the arctic (figure 7). This is valid for the whole winter. The well known warm region north of Japan, which is part of the standing wave 1 of the N.H., has only a weakly developed counterpart in the southern subtropics between the longitudes 170 W and 130 E. This warm region develops into an active region only in late spring (October) when the transition into summer conditions takes place. In the upper stratosphere (2 mbar), figure 8, the pattern of the temperature distribution is rather different over the two hemispheres: over the N.H. the strongly developed standing wave 1 slopes westward with height and the maximum of the temperature wave is found about 50° longitude further west in the 2 mbar level compared with that of the 30 mbar level; over middle and high southern latitudes the amplitude of the temperature wave 1 is again much smaller than over the N.H., and typically the temperature gradient is rather weak over the antarctic polar region.

The radiance data of channel 3000 of the p.m.r., figure 9, reflect the temperature pattern of the upper mesosphere with the warm polar region. The planetary wave number 1 is still evident during the northern winter but barely noticeable during the southern winter. These differences will be discussed further in § 5.

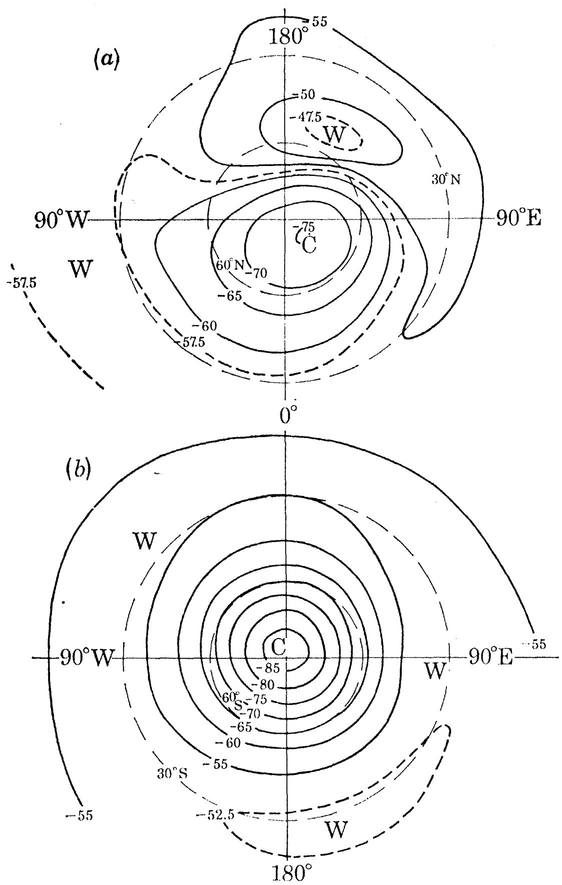

FIGURE 7. Monthly mean 30 mbar temperatures (°C), (*a*) December, N.H., and (*b*) June, S.H. (from Labitzke 1977).

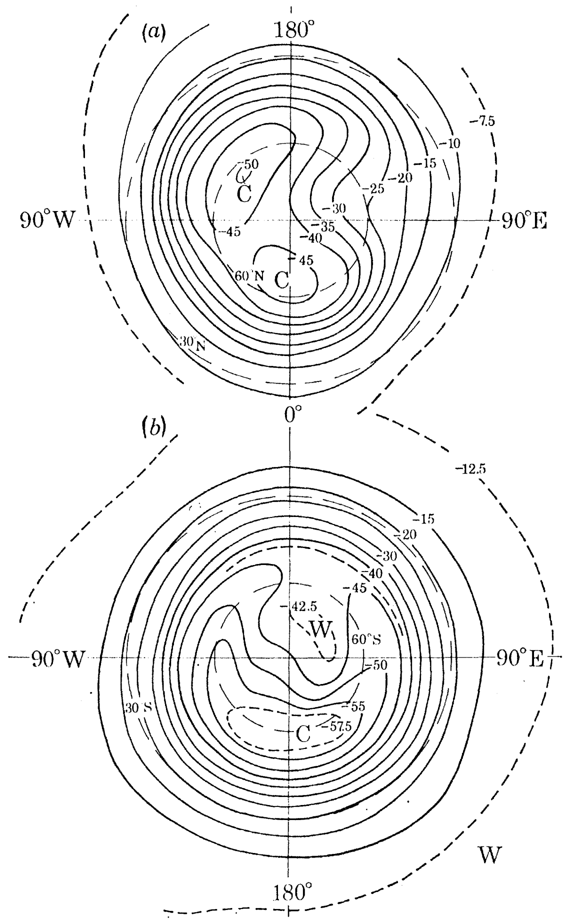

FIGURE 8. Monthly mean 2 mbar temperatures (°C), (*a*) December, N.H., and (*b*) June, S.H. (from Labitzke 1977).

In the upper stratosphere the transition from winter to summer has already started over Antarctica in early July, while a late winter cooling in high northern latitudes, caused by dynamic processes in connection with stratospheric warmings and typical of the northern winter, delays the transition to a summer pattern for about 2 months. Figure 10 shows mean maps of 2 years of radiances of the s.c.r. (A) for the spring season of both hemispheres. While the transition to summer is well in progress in September over the antarctic, no indication of a transition is noticeable in March over the arctic.

During summer the warm polar anticyclone is at its peak in the stratosphere. The isotherms of the 10 mbar level of the northern summer, figure 11*a*, indicate only a weak diurnal wave. As the analysis is based on radiosonde data of 00 U.T. the minimum is found during night over the Atlantic and the maximum during day over the Pacific. Together with the warm anticyclone, east winds prevail in the summer stratosphere (cf. figures 5 and 6) and lower

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mesosphere and prohibit the propagation of the planetary waves. The northern summer stratosphere is colder than the southern (Barnett 1974) because of the difference in solar heating of ozone. This is due to the ellipticity of the Earth's orbit, which produces a 6 % modulation of the solar input.

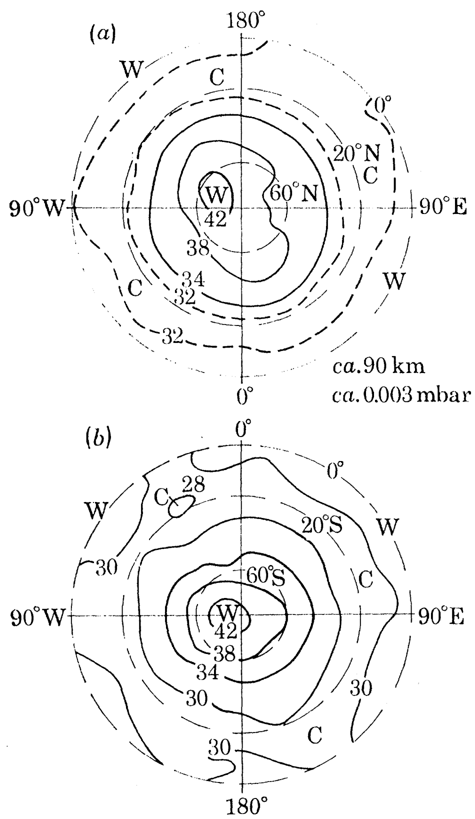

FIGURE 9. Monthly mean radiances [in mW/ (m² sr (cm⁻¹))] of the p.m.r. Channel 3000, (*a*) January 1976, N.H., and (*b*) July 1975, S.H. (from Labitzke & Barnett 1978).

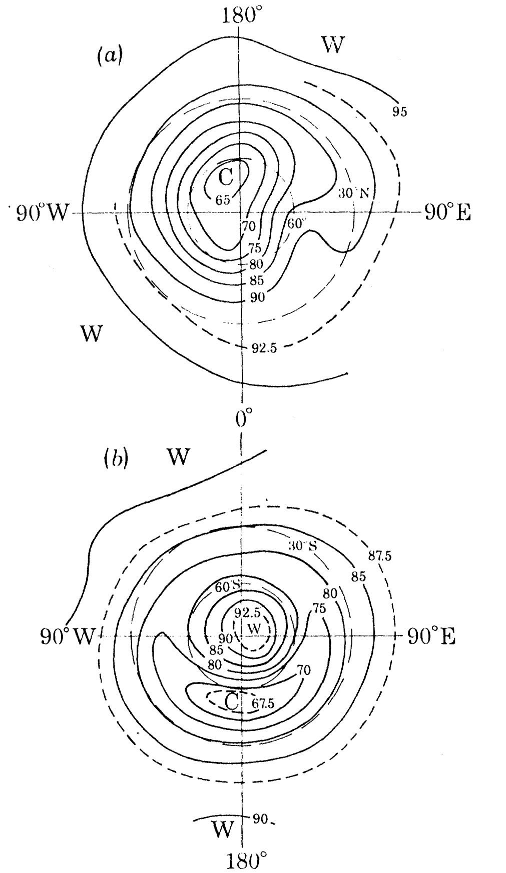

FIGURE 10. Monthly mean radiances [in mW/ (m² sr (cm⁻¹))] of the s.c.r. channel A, (*a*) March, N.H., and (*b*) September, S.H. (from Labitzke 1974).

The polar mesosphere is cold during summer, figure 11*b*, and the radiance data for the southern summer show no longitudinal differences because tidal oscillations cannot be observed as the data shown here are based on daily mean values of a 24 h period.

In figure 12, the temperature differences between the hemispheres are summarized for the lower and upper stratosphere and for high and middle latitudes. The timescale is arranged so that the same seasons in the two hemispheres can be compared directly. The most obvious feature is that in winter the difference over high latitudes, which amounts to 18 °C at the 100 mbar level vanishes in the upper stratosphere and reverses sign during spring, as discussed above. Also, the warmer southern summer values are clearly noticeable in all four sets of curves. Another interesting feature is the opposite behaviour between middle and high latitudes in the lower stratosphere during the winter half-year.

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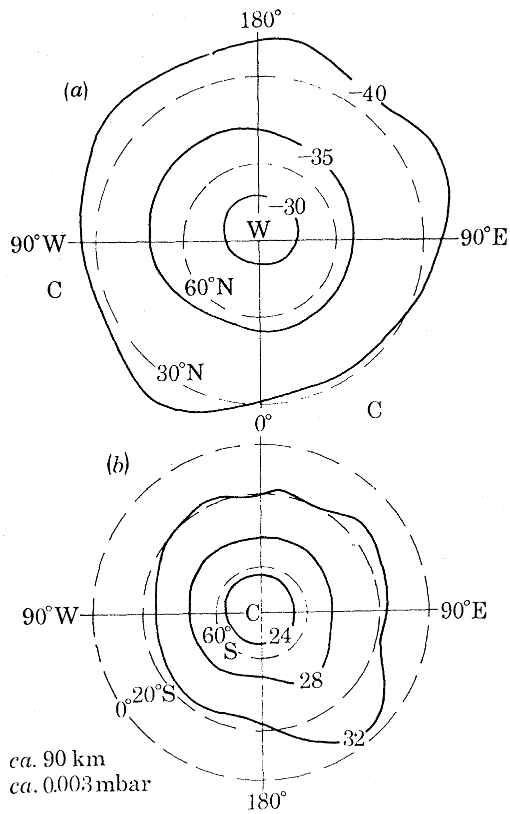

FIGURE 11. (a) Monthly mean 10 mbar temperatures (°C), July, N.H. (from Labitzke *et al.* 1972); (b) montl mean radiances [in mW/(m^2 sr cm^{-1})] of the p.m.r. channel 3000, January 1976, S.H. (from Labitzke Barnett 1978).

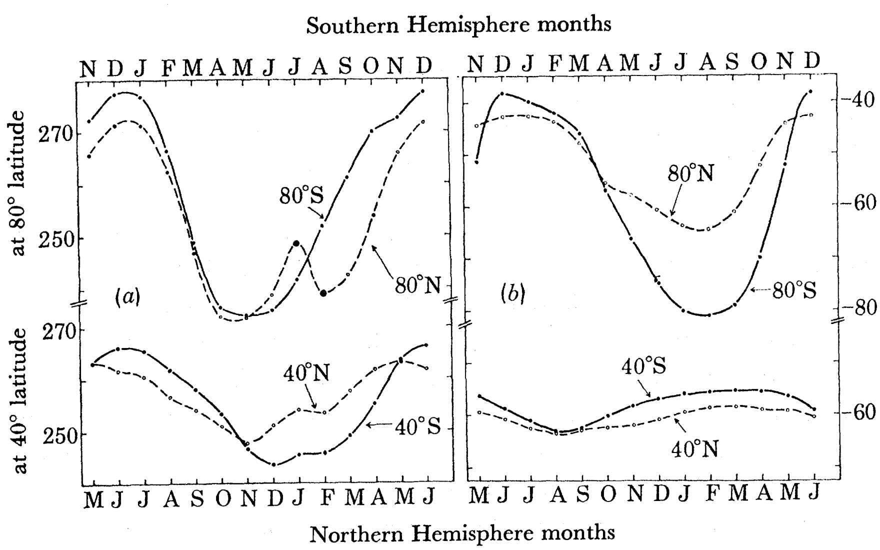

FIGURE 12. Annual march of monthly mean (a) *ca.* 2 mbar radiances of channel A of the s.c.r. (K), (b) 100 mbar temperatures (°C), both at 80° and 40° latitude (from Labitzke 1974).

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5. Planetary waves

As mentioned before, planetary waves, especially of wave numbers 1 and 2, play an important role in the general circulation of the stratosphere during winter, when the polar night jet is well developed. The quasi-stationary waves have their maximum amplitudes between 70 and 60° latitude, along the axis of the polar night jet.

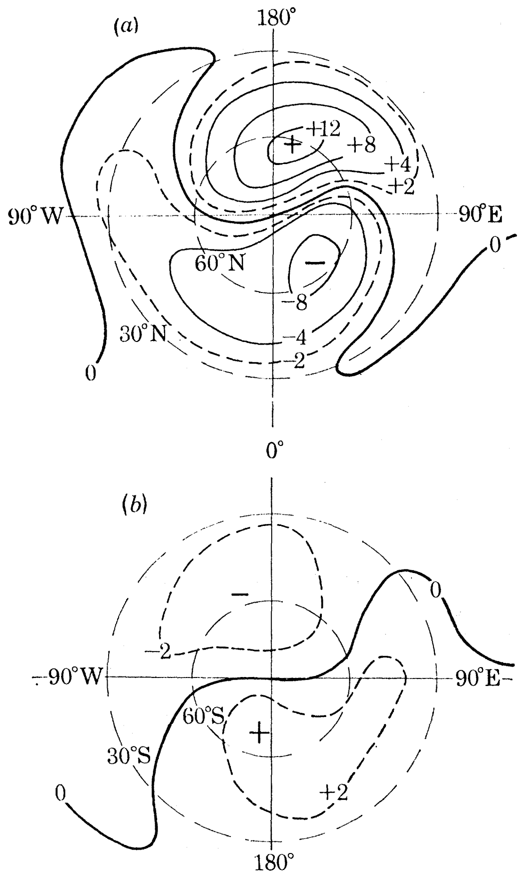

Figure 13. Latitude anomalies of the 30 mbar temperatures (°C) for (*a*) December, N.H., and (*b*) June, S.H. (data from Knittel 1976).

During winter the quasi-stationary waves are much stronger developed over the N.H. than over the S.H., as demonstrated in figure 13, where the deviations of the 30 mbar temperatures from the zonal means are analysed. A Fourier analysis for latitude 60° gives the following results: the amplitude of wave 1 is 10 °C at 60° N and 3 °C at 60° S, and the amplitude of wave 2 is 3 °C at 60° N and 0.1 °C at 60° S.

To give an indication of the slope of the quasi-stationary waves with height, figure 14 was constructed. It indicates at 60° latitude the deviations from the zonal mean temperatures in the middle stratosphere and the deviations from the zonal mean radiance data in the upper stratosphere and mesosphere (only one year of data available here). There appears to be not much difference in the vertical slope of the standing waves, but the amplitude of wave 1 remains two times larger also in the upper stratosphere and mesosphere during the northern winter.

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The transition to a summer circulation takes place during October in the middle southern stratosphere, in spite of the fact that the upper stratosphere has already warmed. This transition is brought about by an intense development of the quasi-stationary planetary waves which during this time of the year reach even larger amplitudes than they do during the northern winter (figure 15).

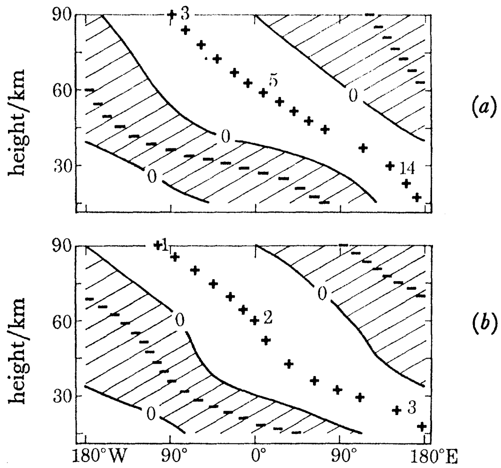

FIGURE 14. Vertical section along 60° latitude of the deviations of the temperatures (lower stratosphere) or of the radiances (upper stratosphere and mesosphere) from the zonal mean (*a*) December, (*b*) June. For selected levels the value of maximum positive deviation of radiances or temperatures is given. These values should be compared only between respective levels.

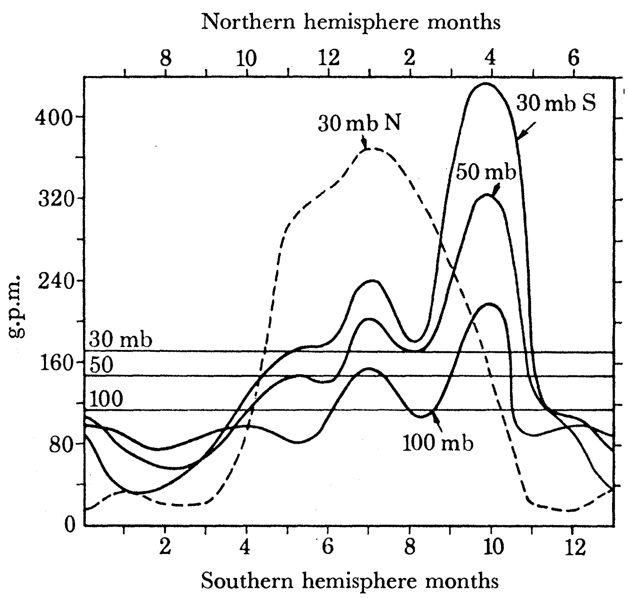

FIGURE 15. Annual march of amplitudes (g.p.m.) of planetary height – wave 1 at 60° S for the 100 mbar, 50 mbar and 30 mbar level, and at 60° N for the 30 mbar level (from Knittel 1976).

6. VARIABILITY

After a review has been given of the 'mean' state of the stratosphere and mesosphere, a short remark must be made on the natural variability of the stratospheric climate. In figure 16, monthly mean temperatures for the North Pole are shown from different sources. They indicate

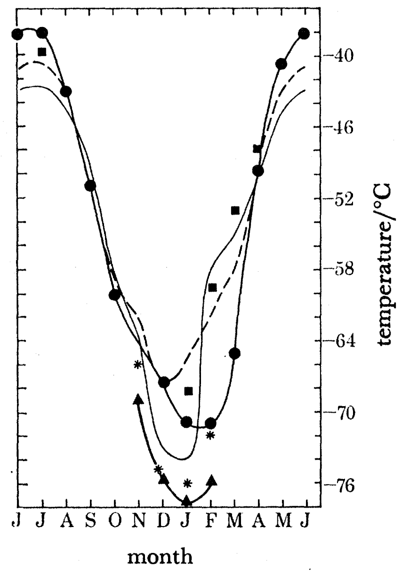

FIGURE 16. Monthly mean 50 mbar temperatures (°C) for the North Pole. Averages over different periods by different authors (partly by Labitzke *et al.* 1972). ▲, Berlin 1971/72+1973/74; --, Wege 1949–53; ●, Berlin 1964/7–1969/6; ——, Muench 1955/7–1959/6; *, Muench 1955/56; ■, Ebdon 1957–61.

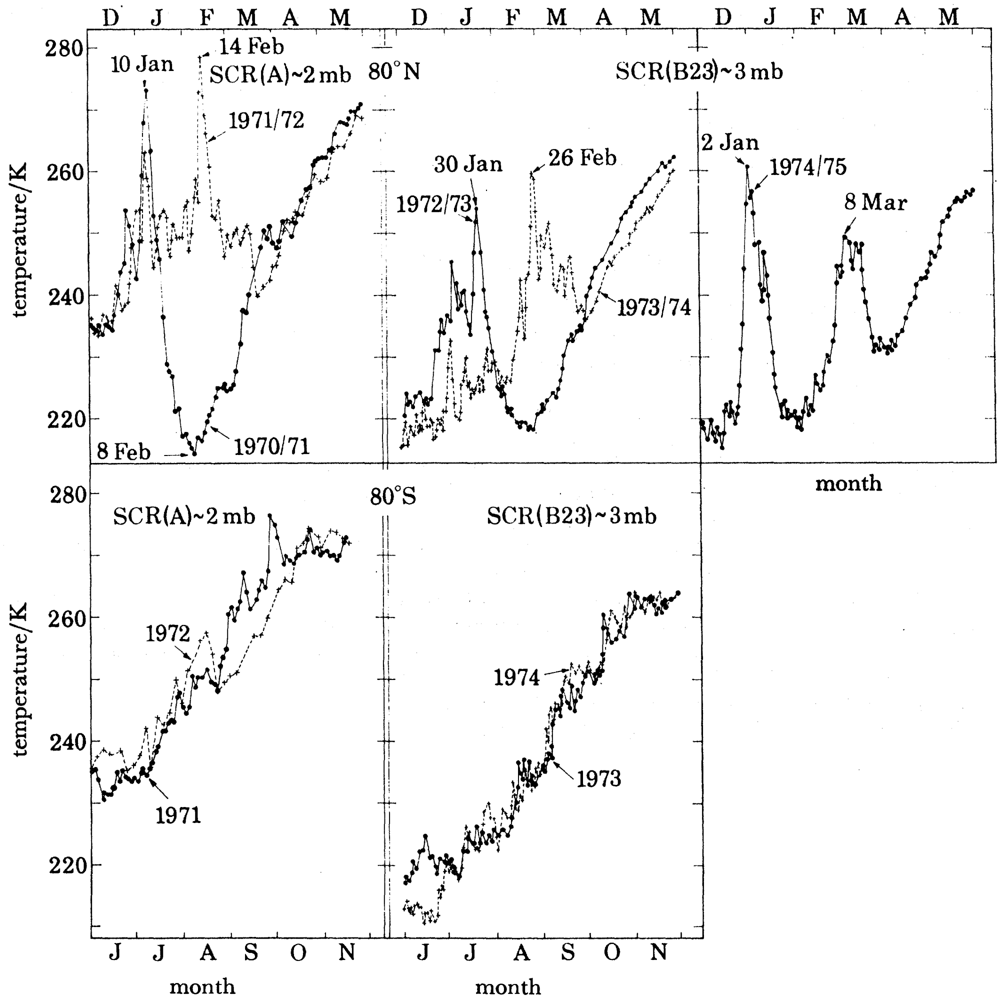

FIGURE 17. Daily zonal means at 80° latitude of radiances (converted into equivalent blackbody temperatures) of upper stratospheric channels of the s.c.r., flown on Nimbus 4 and 5 (from Labitzke 1977).

clearly that cold winters without major warmings result in much lower mean temperatures and, if an average is made during a period when several major warmings took place (such as during the period used by Ebdon), quite another value might be established as a mean. A connection with the solar cycle has been pointed out before (Kriester 1971; Kriester-Naujokat 1978; Labitzke *et al.* 1972). For a better comparison of the data of the middle stratosphere it has been suggested to derive mean data for the winter, using only the undisturbed winter months (Labitzke *et al.* 1972).

The satellite data have already clearly indicated (figure 17) that the upper stratosphere is highly disturbed during each northern winter, where a distinction can be made between winters with a late winter cooling period (usually following major warmings) and without. However, during the southern winters the temperature minimum is usually reached already during winter solstice and a rather regular warming trend towards summer values is obvious.

7. Conclusion

The material presented here showed clearly that the recent satellite experiments have largely increased our knowledge about the climatology of the stratosphere and mesosphere, though more years of data are needed to gain a representative climatology of the upper stratosphere and of the mesosphere. The discussion of the data pointed (*a*) to the effects of the planetary waves of the troposphere which penetrate into the stratosphere and even into the mesosphere, except during summer; these waves create longitudinal differences which should be treated in future model atmospheres; (*b*) to hemispheric differences which in winter have their origin in differences between the general circulation of the troposphere; and (*c*) to the interannual variability and possible variations within the solar cycle.

References (Labitzke)

Barnett, J. J. 1974 *Q. Jl R. met. Soc.* **100**, 505–530.

C.I.R.A. 1972 Cospar *International Reference Atmosphere*. Berlin: Akademie-Verlag.

Knittel, J. 1976 *Met. Abh. Inst. Met. Berl.* A **2** (no. 1).

Kriester, B. 1971 *Met. Rdsch.* **24**, 71–73.

Labitzke, K. *et al.* 1972 *Meteor. Abh. F. U. Berlin* **100** (no. 4).

Labitzke, K. 1974 *J. geophys. Res.* **79**, 2171–2175.

Labitzke, K. 1977 Cospar *Space Resarch*, **XVII**, 159–165, Oxford and New York: Pergamon Press.

Labitzke, K. & Barnett, J. J. 1978 Cospar *Space Research*, **XVIII**. (In the press.)

Naujokat, B. 1978 Paper presented at the S.T.P.-Symposium, Innsbruck, Austria.

Newell, R. E., Kidson, J. W., Vincent, D. G. & Boer, G. J. 1972 *The general circulation of the tropical atmosphere and interactions with extratropical latitudes*, vol. 1. Cambridge, Mass., and London: The M.I.T. Press.

Newell, R. E., Kidson, J. W., Vincent, D. G. & Boer, G. J. 1974 *The general circulation of the tropical atmosphere and interactions with extratropical latitudes*, vol. 2. Cambridge, Mass., and London: The M.I.T. press.

Taljaard, J. J., van Loon, H., Crutcher, H. L. & Jenne, R. L. 1969 *Climate of the upper air: Southern Hemisphere*, part 1. NAVAIR 50-1C-55, Chief of Nav. Oper., Washington, D.C.

van Loon, H., Jenne, R. L. & Labitzke, K. 1972 *Met. Abh. Inst. Met. Berl.* **100** (no. 5).

Wallace, J. M. 1973 *Rev. Geophys. Space Phys.* **11**, 191–222.

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