PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

# Mesospheric Temperatures and Winds during a Stratospheric Warming

A. F. D. Scott

*Phil. Trans. R. Soc. Lond. A* 1972 **271**, 547-557
doi: 10.1098/rsta.1972.0022

*Phil. Trans. R. Soc. Lond.* A. **271**, 547–557 (1972) [ 547 ]
*Printed in Great Britain*

# Mesospheric temperatures and winds during a stratospheric warming

By A. F. D. Scott
*Department of Physics, University College London*

## 1. Introduction

The distributions of mean temperature, pressure, density and winds are given in several model atmospheres (C.I.R.A. 1965; Groves 1969, 1970) as functions of altitude, season and latitude. The main features of the variations in the temperature profiles are that the stratopause temperature is greatest near the summer pole and decreases through the equator to the winter

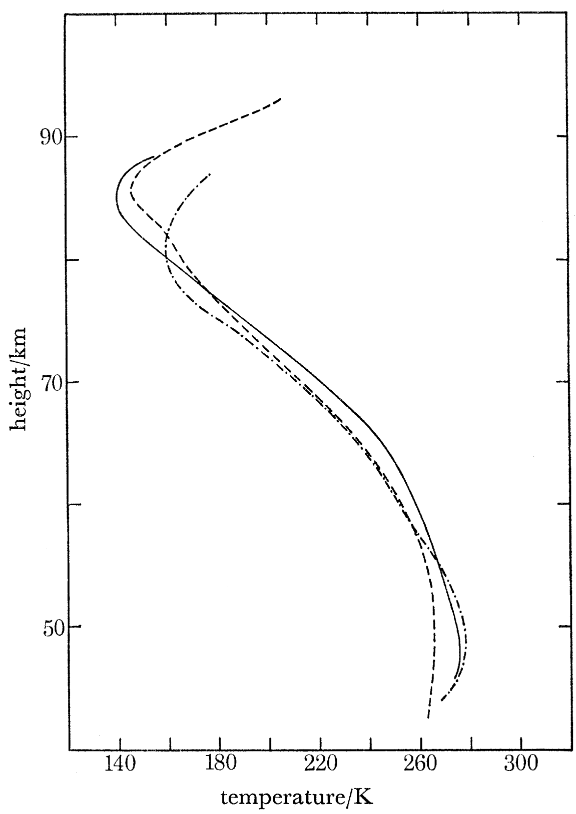


Figure 1. Summer temperature profiles from rocket grenade experiments at Kronogård, Sweden on: —, 29 July; –·–·–, 1 August; and – – –, 7 August 1963.

pole, and that at the mesopause the latitudinal temperature gradient is reversed, with highest temperatures towards the winter pole; the latter is contrary to calculations of temperature from radiational heating, and theories of chemical heating and energy transport by dynamical processes have been proposed to explain the anomaly. The wind systems are mainly zonal with meridional winds being small in comparison. At 50° N and at 60 km there is a maximum westerly wind during winter of about 80 m s$^{-1}$ and a maximum easterly wind during summer of about 60 m s$^{-1}$.

During summer the stratospheric circulation is symmetrical and centred over the pole. High-latitude temperature profiles are smooth up to 100 km and show little deviation from mean values (figure 1). However, at high latitude during winter the deviation from the mean is much greater and the mesospheric temperature profiles are highly structured (Theon, Nordberg, Katchen & Horvath 1967*a*).

Increases in temperature of 60 °C or more occurring in the winter stratosphere are known as stratospheric warmings and have been reviewed by Scherhag (1969). Major warmings may occur during mid-winter when the polar vortex splits into two southward moving parts; warm air replaces cold air over the pole and the latitudinal temperature gradient is reversed (Johnson, Miller & Gelman 1969). The westerly circulation collapses, to be replaced by weak easterly winds, but within a few weeks the wintertime circulation is restored. Minor warmings do not lead to a breakdown of the polar vortex and may occur several times in a winter period.

High-latitude disturbances of mesospheric winds and temperatures during a stratospheric warming will be examined with reference to a series of four rocket grenade experiments held at Esrange, Sweden, in January 1969.

## 2. Details of the experiment

The experimental objectives were to measure wind and temperature profiles in the stratosphere and mesosphere during a stratospheric warming. The joint experimenters were from the Goddard Space Flight Center (G.S.F.C.), the Institute of Meteorology at the University of Stockholm and University College London. The campaign was held at Esrange as a Swedish National Campaign in which the experiments were organized under a tripartite agreement between the National Aeronautics and Space Administration, U.S.A., the Swedish Space Research Committee and the British Science Research Council. Four Nike-Cajun rockets carrying grenade payloads were launched in an 8-day period after an I.U.W.D.S. stratalert was declared by the Free University of Berlin. Within the same period six similar launches were made by G.S.F.C. from Point Barrow in Alaska, Fort Churchill in Canada and Wallops Island, Virginia; two rockets were launched from each site. These launches were coordinated as far as possible with those from Esrange to examine the global extent of the disturbed atmosphere. At Esrange launch preparations and ground observations were carried out jointly by the Swedish Space Technology Group and University College London.

A stratalert was received on 16 January stating that a warming at 10 mbar† (about 30 km) over central and SE Europe had reached −28° C at its centre (stratalerts are initiated when temperatures at 10 mbar reach −30 °C). On 17 January rocket data from West Geirinish were received showing that, on 15 January, temperatures at 40 km were about 60 K above the C.I.R.A. 1965 values. Thus the first rocket was launched on 17 January into a warm stratosphere. It was expected that this would be a minor warming as the polar vortex at 10 mbar was strong and appeared little affected by the disturbance.

† 1 mbar = 100 Pa.

## 3. Temperatures

Figure 2 shows the four temperature profiles obtained at Esrange from which the following observations can be made.

(*a*) A stratospheric cooling of 57 K was measured at 39 km over a 6-day period starting 2 days after the warming was recorded at West Geirinish. This cooling was followed by a small warming recorded on the fourth launch. As the stratosphere cooled, the stratopause rose.

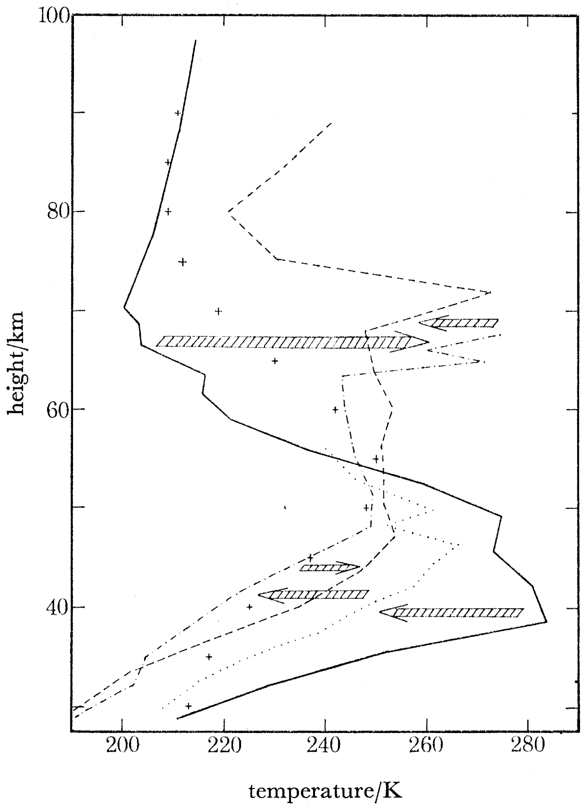


Figure 2. Temperature profiles from Esrange, Sweden on: —, 17; · · · ·, 19; —·—·, 23; and – – –, 25 January 1969 (Udin 1971); + + +, model (Groves 1970).

(*b*) At 54 km the temperature remained relatively constant with a change of only 8 K.

(*c*) At 65 km the mesospheric temperatures over the same 6-day period rose by 62 K and then cooled 23 K. These changes in the middle mesosphere were in a reverse sense to those in the stratosphere.

(*d*) The layer from 45 to 70 km was almost isothermal on 25 January, but on 17 January, when a warm stratopause occurred, the vertical lapse rate was 3.5 K $km^{-1}$. This is comparable with the average mesospheric lapse rates for the summertime profiles measured at Kronogård (figure 1).

(*e*) Evidence of wave-like structure was present in two of the three mesospheric profiles above 65 km. This is in direct contrast to the smooth summer profiles. On 17 January the profile is conspicuously smooth and free from wave-like structure.

Early studies of stratospheric warmings were confined to levels reached by balloons. With the



PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

increasing amount of data provided by rocket experiments, interest has been directed towards the level at which the warming is initiated. Finger & Teweles (1964) considered that their analysis of January 1963 data 'provided evidence of a maximum intensity of circulation change and sudden warming in the layer near 45 km. The circulation changes appear to initiate in this layer and then spread both downward and upward, eventually influencing the entire stratosphere and a portion of the mesosphere.' In January 1968 the first sign of a warming was observed at West Geirinish in the 45 to 50 km region and Johnson (1969) noted the anomalously high temperatures and wind speeds at high stratospheric and mesospheric levels. However, because of insufficient data he felt that no relation could be demonstrated between the warming in the middle stratosphere and events at higher levels.

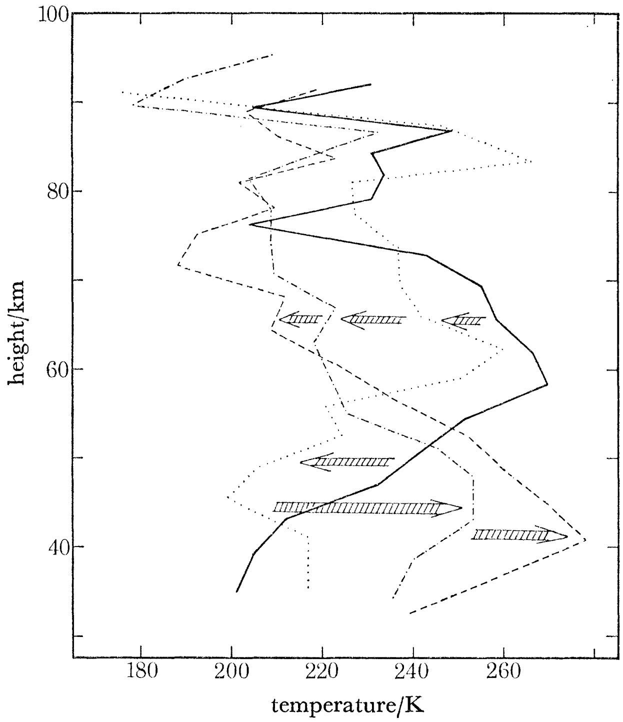


FIGURE 3. Temperature profiles from Point Barrow, Alaska on: —, 19; · · · ·, 26; –·–·–, 31 January; and – – –, 4 February 1969 (Smith *et al.* 1971).

In an examination of rocket grenade soundings at Fort Churchill, Quiroz (1969) showed that the data of January and February 1966 was compatible with the concept of a warming of the entire mesosphere penetrating down to the middle stratosphere.

From a similar analysis of rocket grenade data from Point Barrow in early 1969, Theon & Smith (1970) concluded that the relation between the gradual warming of the mesosphere at 80 km during December and the stratospheric warming in mid-January was not clear. Looking at a further stratospheric warming in late January they could not ascertain from the available data whether the several warm centres were independent events or merely a lower extension of the first warming. However, if their data are replotted as in figure 3, they indicate that the temperature of the region from 60 to 75 km is linked inversely with that of the level from 40 to 50 km. This is a similar conclusion to that reached for the Esrange data, that at high latitude in winter a warmer stratopause is linked to a colder middle mesosphere.

The upper mesosphere at high latitude is subject to short-term variations of 30 to 40 K per hour (Theon 1968), so the available data make it difficult to reach any conclusion about linkages with lower levels.

## 4. Horizontal winds

During all four launches the stratospheric winds were from the southwest, with little change of direction occurring. Examination of wind profiles from Fort Churchill and Point Barrow shows that during the campaign the polar vortex remained stable and so the warming was classified as minor.

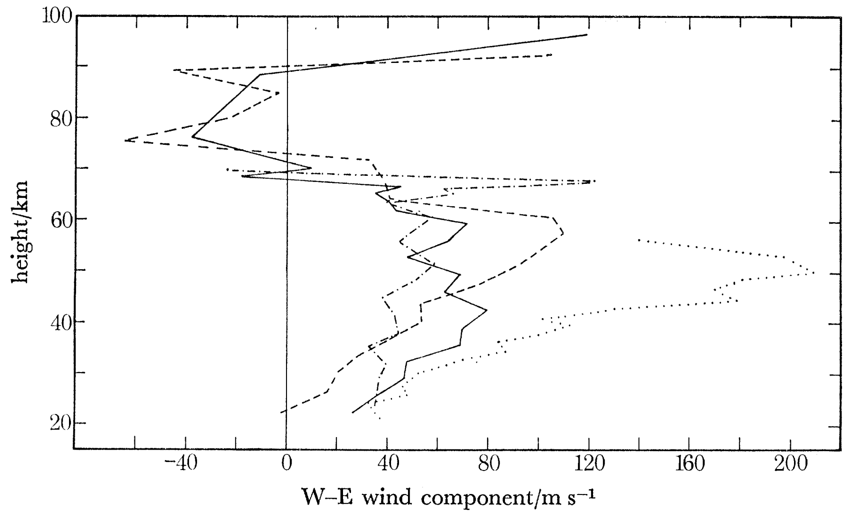


Figure 4. Wind profiles from Esrange, Sweden, on: —, 17; · · · · ·, 19; –·–·–, 23; and – – –, 25 January 1969 (Udin 1971).

A wind of 231 m $s^{-1}$ was recorded on 19 January (figure 4). This is comparable with the high wind measurements made using parachute tracking techniques near the time of a stratospheric warming, namely winds between 180 and 200 m $s^{-1}$ have been recorded at West Geirinish, Fort Churchill and Heiss Island between 6 and 9 days before the peak of a stratospheric warming (Quiroz 1969, World Data Center A 1968/9). Thus it is probable that if rocket launches had been continued at Esrange beyond 25 January, a further warming would have been observed. Later measurements from West Geirinish on 27 January confirmed that this happened – 8 days after the high wind at Esrange, stratopause temperatures reached +12 °C at West Geirinish.

Above the stratopause the westerly wind components declined and between 65 and 90 km easterly components were observed. This is consistent with the observed thermal structure in the mesosphere, where the latitudinal temperature gradient is the reverse of that in the stratosphere.

## 5. Vertical motion

The temperature increases during a stratospheric warming were thought to be due to downward motion and adiabatic compression. For example, in an analysis of the 1957 warming, Craig & Lateef (1962) computed that downward motion of a few centimetres per second was required to produce the observed warmings.

In the initial stages of a warming an anticyclone builds up in mid-latitudes and a system of warm air moves across the pressure contours towards higher latitudes. Recent data from the Nimbus 4 selective chopper radiometer (Barnett *et al.* 1971) show a warm region developing at 25° N before moving to about 75° N. As the pressure gradient increases and the warming builds up, high winds develop.

A reported wind speed of 198 m $s^{-1}$ at Heiss Island during the warming of February 1966 was verified by Quiroz (1969) using the thermal wind equation. The observed winds agreed reasonably well with the computed values. In the same paper Quiroz used the thermodynamic energy equation to calculate the vertical motion, with the horizontal advection of temperature being computed using the thermal wind equation and observed data. He found values of upward motion as high as 60 cm $s^{-1}$ but judged these to be accurate only to an order of magnitude. All the vertical motion values exceeding 10 cm $s^{-1}$ corresponded to large values of the wind speed and of the direction change with height (all were cases of veering). The horizontal advection term was several times greater than the local temperature increase and strong cooling from upward motion was necessary for balance to be achieved.

Similar calculations were carried out using the high wind measurements at Esrange. The change in wind direction with height was smaller than at Heiss Island with the wind backing very slightly. Cooling by advection was about the same as cooling due to upward motion of a few centimetres per second.

In contrast with the upward motion at Heiss Island during a warming, Craig & Lateef (1962) emphasized that the pattern of vertical motion was characterized by a very large area of uniformly downward motion. However, the situation must be examined over a wider area, since Finger & Teweles (1964) have shown that maxima of upward motion lay approximately north of downward maxima for the 1963 warming. Quiroz (1969) suggested that strong subsidence at some distance from Heiss Island could have created, through adiabatic compression, the source of warm air advected there. Further studies are required to elaborate the relative importance of horizontal advection and downward motion as mechanisms for producing stratospheric warmings.

## 6. Planetary waves

Planetary waves are deviations from symmetrical circulation patterns occurring in middle and high latitudes which have a time scale longer than a day. They have been shown to exist during winter months in the lower stratosphere over the Northern hemisphere, where the mean winter circulation is oval-shaped and displaced slightly from the pole. These departures from symmetry can be described in terms of Fourier wave components. Most of the variance of these departures from zonal symmetry is found in longitudinal wavenumbers one and two. The wavenumber one component represents much of the displacement of the vortex from the pole while the departure from spherical shape is largely given by wavenumber two.

The disturbances can be stationary throughout the winter season or transient with a duration of several days. An example of the standing eddy is the 'Aleutian High' which is centred over the Aleutian Islands and appears on the mean temperature and pressure charts throughout much of the winter. Transient eddies were shown in an analysis of the 1966 warming (Hirota 1969) when progressive waves of wavenumber two were discerned in the first half of January with a horizontal phase velocity of about 10 m $s^{-1}$ and a retrogressive wave of wavenumber one in the second half of January with a phase velocity of about $-17$ m $s^{-1}$.

Conditions for the propagation of planetary waves into the upper atmosphere were discussed


PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

by Charney & Drazin (1961), who concluded that conditions for upward propagation of planetary disturbances are most favourable at the equinoxes when there are weak westerly winds. Planetary waves should not propagate upwards from the tropopause in the presence of an easterly wind or a strong westerly wind in the stratosphere. The prediction that easterly winds cause total reflexion of upward propagating planetary waves is supported by the zonal symmetry of the summer circulation.

Later theoretical studies have used more realistic atmospheric models than the simple one adopted by Charney & Drazin and take into account the variation of wind with latitude and the inclusion of Newtonian cooling. Dickinson (1969) has shown that at the equinoxes, with weak zonal flow, there is strong damping of planetary waves by radiative processes which greatly reduces the possible upward vertical propagation. He has also suggested (1968) that planetary waves may be guided by horizontal wind shears, such as the mid-latitude stratospheric westerly jet, to form polar and equatorial wave guides in the winter hemisphere; these would facilitate upward propagation during the winter months.

Correlations between tropospheric and stratospheric disturbances have been discussed by several authors. For stratospheric warmings occurring over Europe, Labitske (1965) noted a blocking pattern appearing in the troposphere within 10 days of occurrence of the warming. Sawyer (1965) saw the existence of a significant relationship between tropospheric and stratospheric flow in January 1958 because of clear agreement in phase but little correspondence in amplitude for wavenumbers 2 and 3 for 500 and 50 mbar contours at 50° N. The geopotential height fields for January 1959 were analysed in terms of spherical harmonics by Boville (1967) to show the positions and amplitudes of the waves at various levels. He pointed out that the stationary waves all sloped westward with height from the troposphere through to the middle stratosphere and were a means of transporting energy and heat upward and northward. Correlations have also been reported by Deland & Johnson (1968) and Quiroz (1969).

Warnecke & Nordberg (1965) and Theon, Nordberg & Smith (1967*b*) have shown that these planetary scale disturbances can be traced up to levels of about 70 km. Above this level in the mesosphere a shortage of data and increased activity associated with gravity and tidal waves have prevented identification of planetary wave systems. However, at Sheffield (Müller 1966), observations of meteor winds have shown that variations of 10 to 15 m $s^{-1}$ in the prevailing components occur over a period of not more than a few days, indicating the propagation of waves of planetary type into the lower thermosphere.

## 7. Gravity waves

Temperature profiles in the high latitude winter mesosphere exhibit wave-like features which are commonly connected with changes of temperature of 30 to 40 K per hour and with large wind shears (Theon 1968). The vertical wavelength (10 to 15 km) and period (about 2 h) of the observed temperature fluctuations are consistent with the gravity-wave theory (Hines 1965). Possible sources for these waves may include tropospheric thunderstorms and frontal systems, instabilities in the jet stream, the effects of winds blowing over mountains and volcanic and nuclear explosions.

Similar wave-like structure is detected in the upper stratosphere by detailed analysis of falling sphere or parachute descent data. Webb (1965) showed that this structure can persist for up to 2 h. In an attempt to determine the spatial variation of the wave structure, Cole &

Kantor (1969) examined the wind profiles obtained using a series of Robin falling spheres launched from three sites. Small-scale oscillations with vertical wavelengths of 3 to 4 km and amplitudes of 4 to 12 m $s^{-1}$ were highly correlated over distances of 200 km and had an estimated horizontal wavelength of 1200 to 1600 km. Webb (1965) analysed the distribution with season of the vertical scale at different heights and suggested that there was a new local input of stratospheric detail structure in the winter data. He considered that, 'possibly this detailed structure input is locally generated by dynamic processes in the upper stratosphere'.

During the January 1969 launches from Fort Churchill a mesospheric temperature of 148 K was observed on 20 January (Smith *et al.* 1971). This is the lowest mesospheric temperature recorded in wintertime and it occurred one day after the high stratospheric wind of 231 m $s^{-1}$

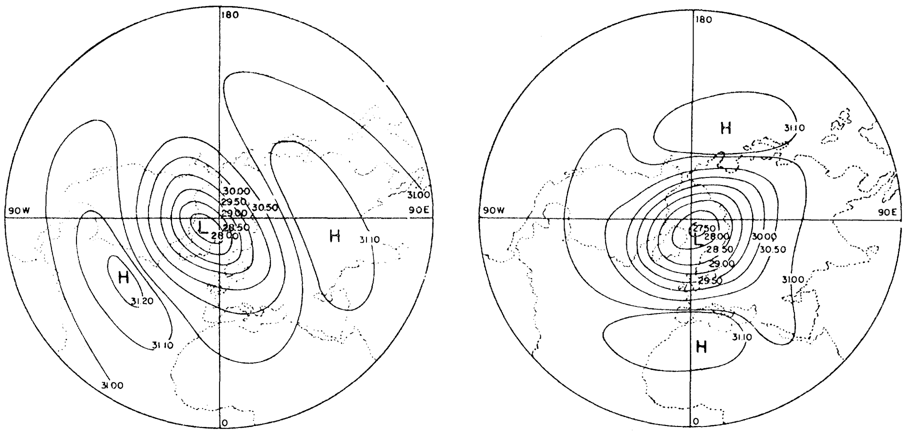


FIGURE 5. 10 mbar charts for 30 December 1963 (left-hand) and 4 January 1964 (right-hand) over the Northern hemisphere. Contour heights are in kilometres (Webb 1966).

was measured at Esrange. Perhaps this is an example of a stratospheric perturbation providing a source for gravity waves propagating into the mesosphere, where, by adiabatic cooling associated with the wave-structure, a very low temperature was reached.

During summertime high latitude mesospheric temperatures of about 140 K are recorded when noctilucent cloud displays are seen (Theon *et al.* 1967*b*, Witt, Martin-Löf, Wilhelm & Smith 1965). There has been one wintertime observation of noctilucent clounds made at Lerwick (60° N) on 5 January 1964 (Hamilton 1964). The clouds were at about 91 km (higher than the mean height of summertime n.l.c. which is about 82 km) and the observation was made after the Quadrantids meteor stream on 1 to 4 January.

It is interesting to assume that this n.l.c. observation on 5 January 1964 was associated with low mesospheric temperatures of about 140 K and to look for a possible source of such a disturbance in the stratospheric temperature structure.

The stratospheric circulation for December 1963 to January 1964 was described by Webb (1966) as a winter period without a major stratospheric warming. He noted that 'on 4 January 1964 the contour pattern at 10 mb presented a rather curious change, probably representing a dynamic change in shape of the high-latitude low-pressure system which rotated the previous principal axis very rapidly eastward across North America into the North Atlantic' (figure 5). This eastward motion of the low-pressure system may have provided the source for generation of the disturbance.

In order to examine the seasonal transition in the high-latitude mesosphere a series of twelve

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

acoustic grenade experiments was conducted from Point Barrow, Alaska, during the period September 1968 to February 1969. Theon & Smith (1970) examined the presence of the wave-like structure and noted that it appeared first in the high mesosphere in September and at successively lower altitudes during the remainder of the transition period. The rate of descent was approximately 9 km per month. When a stratospheric warming occurred, they observed that the warming either masked or prevented the formation of wave-like structure. Whereas their profiles show the lower boundary of the waves at about 40 km in early January 1969, during the warming, when stratopause temperatures were −4 °C, the boundary rose to about 65 to 75 km.

This phenomenon is seen much more clearly on the Esrange profile of 17 January when the stratopause temperature was +11 °C and wavelike structure was almost completely absent up to 96 km.

## 8. D-region absorption and mesospheric structure at mid-latitude

Sechrist (1967) suggested that temperature inversions in the mesosphere are associated with the winter anomaly in high-frequency radio absorption on certain winter days at mid-latitude. In an attempt to test this hypothesis, nearly simultaneous rocket measurements of D-region electron densities, neutral temperatures and winds were made on an anomalous winter day at Wallops Island (Sechrist, Mechtly, Shirke & Theon 1969). The rocket grenade temperature profile for the anomalous day revealed a strong temperature inversion at 70 km and a warm layer extending from the inversion to 84 km. The electron density profile showed that densities in the 70 to 80 km height range were about five times greater than on a normal winter day.

On the anomalous winter day there was a minor warming in the stratosphere around 45 km (+5 °C). This is consistent with the work of Shapley & Beynon (1965) who showed a correlation between moderate stratospheric warmings and an increase in the vertical incidence ionospheric absorption. At Wallops Island (38° N) there does appear to be a correlation between a minor stratospheric warming and a mesospheric warming at levels from 70 to 85 km – this is further supported by the profile of 17 January 1969 (Smith *et al.* 1971).

At high latitude sites such as Point Barrow it is difficult to see any similar correlation because of the influences of auroral absorption and gravity wave structure in the temperature profiles above 70 km.

## 9. Conclusions

High-latitude temperature profiles from Esrange and Point Barrow indicate that during mid-winter a warmer stratopause is linked to a colder middle mesosphere, such as to approach summertime conditions. The smooth mesospheric temperature profile characteristic of summertime was seen on 17 January 1969 at Esrange; at this time stratospheric temperatures reached +11 °C but the wind profile appeared normal. If the presence of a wave-like temperature structure is taken as evidence of gravity waves, the occurrence of a very warm stratopause would appear to inhibit gravity wave propagation upwards into the mesosphere.

Two cases of anomalous stratospheric circulation are noted as preceding extreme mesospheric conditions. The lowest mesospheric temperature in winter at high latitude (148 K) was recorded at Fort Churchill on 20 January 1969, one day after the very high stratospheric wind of 231 m $s^{-1}$

was measured at Esrange. A wintertime occurrence of noctilucent clouds on 5 January 1964 followed a dynamic change in shape of the high-latitude low-pressure system, which rotated very rapidly eastward across North America into the North Atlantic.

Disturbances in the tropospheric circulation are usually quoted as the possible sources for upward gravity wave propagation. Wind shears associated with the tropospheric jet stream and weather fronts are two examples. However, there has been an indication that stratospheric disturbances may also be considered as sources of gravity waves. Webb (1965) has analysed the wave-like wind structure obtained from detailed analysis of falling sphere descent data for the distribution with season of the vertical scale at different heights. He suggested that there was a new local input of wave-like structure in the winter data which was possibly generated by a dynamic process in the upper stratosphere. If the extreme mesospheric conditions noted above are caused by adiabatic cooling associated with gravity wave propagation, then it is suggested that the gravity waves may have been generated in the preceding stratospheric disturbances by mechanisms similar to those proposed for tropospheric sources. These conclusions require more data to confirm the few observations so far available.

Many people have made essential contributions to the experiments at Esrange. Among these, it is a particular pleasure to express gratitude to J. Martin-Löf of the Swedish Space Technology Group who acted as Campaign Director; to Professor B. Bolin and I. Udin of the Institute of Meteorology, University of Stockholm; to W. S. Smith and J. S. Theon of the Goddard Space Flight Center; to Dr K. Labitske of the Institute of Meteorology, Free University of Berlin; and finally to Professor G. V. Groves, whose interest and encouragement was invaluable.

The work carried out by University College London was supported by a grant from the British Science Research Council.

Throughout these studies the support of the technical, computing and scientific staff at University College London is gratefully acknowledged.

## References (Scott)

Barnett, J. J., Harwood, R. S., Houghton, J. T., Morgan, C. G., Rodgers, C. D., Williamson, E. J., Peckham, G. & Smith, S. D. 1971 *Nature, Lond.* **230**, 47.
Boville, B. W. 1967 *Space research VII* (ed. R. L. Smith-Rose), p. 20. Amsterdam: North-Holland.
Charney, J. G. & Drazin, P. G. 1961 *J. geophys. Res.* **66**, 83.
Cole, A. E. & Kantor, A. J. 1969 *Stratospheric circulation* (ed. W. L. Webb), p. 453. New York: Academic Press.
COSPAR Working Group 4 1965 *COSPAR International Reference Atmosphere.* Amsterdam: North-Holland.
Craig, R. A. & Lateef, M. A. 1962 *J. geophys. Res.* **67**, 1839.
Deland, R. J. & Johnson, K. W. 1968 *Mon. Weath. Rev.* **96**, 12.
Dickinson, R. E. 1968 *J. atmos. Sci.* **25**, 984.
Dickinson, R. E. 1969 *J. geophys. Res.* **74**, 929.
Finger, F. G. & Teweles, S. 1964 *J. appl. Meteor.* **3**, 1.
Groves, G. V. 1969 *J. Br. interplanet. Soc.* **22**, 285.
Groves, G. V. 1970 Air Force Surveys in Geophysics no. 218, AFCRL-70-0261, Bedford, Massachusetts.
Hamilton, R. A. 1964 *Met. Mag., Lond.* **93**, 201.
Hines, C. O. 1965 *J. geophys. Res.* **70**, 177.
Hirota, I. 1969 *Stratospheric circulation* (ed. W. L. Webb), p. 391. New York: Academic Press.
Johnson, K. W. 1969 *Mon. Weath. Rev.* **97**, 553.
Johnson, K. W., Miller, A. J. & Gelman, M. E. 1969 *Mon. Weath. Rev.* **97**, 565.
Labitzke, K. 1965 *J. appl. Meteor.* **4**, 91.
Müller, H. G. 1966 *Planet. Space Sci.* **14**, 1253.
Quiroz, R. S. 1969 *Mon. Weath. Rev.* **97**, 541.

Sawyer, J. S. 1965 *Q. Jl R. met. Soc.* **91**, 407.
Scherhag, R. 1969 *Annals of the IQSY* **5**, 33.
Sechrist, C. F., Jr. 1967 *J. atmos. terr. Phys.* **29**, 113.
Sechrist, C. F., Jr., Mechtly, E. A., Shirke, J. S. & Theon, J. S. 1969 *J. atmos. terr. Phys.* **31**, 145.
Shapley, A. H. & Beynon, W. J. G. 1965 *Nature, Lond.* **206**, 1242.
Smith, W. S., Theon, J. S., Casey, J. F., Azcárraga, A. & Horvath, J. J. 1971 NASA TR-R-360, Washington, D.C.
Theon, J. S. 1968 *Proc. 3rd National Conf. Aerospace Meteor*, p. 449. American Meteorological Society.
Theon, J. S., Nordberg, W., Katchen, L. B. & Horvath, J. J. 1967*a* *J. atmos. Sci.* **24**, 428.
Theon, J. S., Nordberg, W. & Smith, W. S. 1967*b* *Science, N.Y.* **157**, 419.
Theon, J. S. & Smith, W. S. 1970 *J. atmos. Sci.* **27**, 173.
Udin, I. 1971 Internal Report of the Institute of Meteorology, University of Stockholm.
Warnecke, G. & Nordberg, W. 1965 *Space research V* (ed. D. G. King-Hele, P. Muller and G. Righini), p. 1026. Amsterdam: North-Holland.
Webb, W. L. 1965 *Space research V* (ed. D. G. King-Hele, P. Muller and G. Righini), p. 997. Amsterdam: North-Holland.
Webb, W. L. 1966 *Structure of the stratosphere and mesosphere*, see pp. 190–194. New York: Academic Press.
Witt, G., Martin-Löf, J., Wilhelm, N. & Smith, W. S. 1965 *Space research V* (ed. D. G. King-Hele, P. Muller & G. Righini), p. 820. Amsterdam: North-Holland.
World Data Center A 1968/9 Data Reports of the Meteorological Rocket Network Firings, U.S. Department of Commerce, Asheville, N. Carolina.



PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES