Journal of Atmospheric and Terrestrial Physics, Vol. 49, Nos. 7/8, pp. 655–674, 1987.
Printed in Great Britain.

0021–9169/87 $3.00 + .00
Pergamon Journals Ltd.

Mean state and long term variations of temperature in the winter middle atmosphere above northern Scandinavia

D. OFFERMANN, R. GERNDT, R. KÜCHLER
Physics Department, University of Wuppertal, F.R.G.

K. BAKER, W. R. PENDLETON
Department of Physics, Utah State University, U.S.A.

W. MEYER, U. VON ZAHN
Institute of Physics, University of Bonn, F.R.G.

C. R. PHILBRICK
Air Force Geophysics Laboratory, Hanscom AFB, U.S.A.

and

F. J. SCHMIDLIN
NASA Goddard Space Flight Center, Wallops Island, U.S.A.

(*Received for publication* 14 *January* 1987)

Abstract—Stratosphere and mesosphere temperatures were measured during four winter months (November–February) at high latitudes (Andøya, ESRANGE) by means of numerous rocket flights during the Energy Budget Campaign 1980 and the MAP/WINE Campaign 1983–1984. They are compared to ground-based OH* measurements and SSU satellite data. The atmosphere was found to be very active, with several minor and one major stratospheric warming occurring. A harmonic analysis of the temperature oscillations observed is performed and found to be suitable to model the atmospheric disturbances (warmings) to a large extent by superposition of waves with appropriate periods. These periods are of the order of several days and weeks and are thus similar to those of planetary waves. Stratospheric warmings tend to be correlated with mesospheric coolings, and vice versa. This is reproduced by the model, giving details of the phase relationships as they depend on altitude. These are found to be more complicated than just an anticorrelation of the altitude regimes. Strong phase changes occur in narrow altitude layers, with oscillation amplitudes being very small at these places. These 'quiet layers' are frequent phenomena and are independently found in the data sets of the two campaigns. They are tentatively interpreted as the nodes of standing waves.

The time development of temperature altitude profiles shows strong variations that lead to peculiar features, such as a split stratopause or a near-adiabatic lapse rate in the mesosphere on occasion. The superposition model is able to reproduce these features, too. On one occasion it even shows super-adiabatic temperature gradients in the lower mesosphere for several days. Though this should be taken as an artifact, it nevertheless suggests a considerable contribution of the long period waves to atmospheric turbulence.

The many rocket data are also used to determine monthly mean temperature profiles. These are compared to reference atmospheres recently developed for the CIRA (BARNETT and CORNEY, 1985; GROVES, 1985). Fair agreement is found, which is much better than with CIRA (1972). This is not true for February 1984, because of the major warming that occurred late in that month. Before this warming took place, atmospheric preconditioning appears to have been present for more than two months.

INTRODUCTION

The middle atmosphere is known to be frequently and considerably disturbed in northern winter. Temperature retrievals by satellites may be unreliable under such conditions. Rocket experiments in the past were biased towards the American continent, especially as concerns the mesosphere. Two recent campaigns in northern Scandinavia therefore included quite a number of experiments for the determination of temperature and winds in the middle atmosphere: the Energy Budget Campaign was performed in November/December 1980 at ESRANGE (Sweden, 68°N, 21°E) and Andøya (Norway, 69°N, 16°E) and the MAP/WINE Campaign from December 1983 to February 1984 at Andøya and ESRANGE (OFFERMANN, 1985; VON ZAHN, 1986). Temperature data obtained on these occasions are analysed in the present paper.

The larger perturbations during winter are called 'stratospheric warmings'. The dynamical behaviour of the middle atmosphere during such a warming was studied in recent years by various authors (see, for instance, LABITZKE and GORETZKI, 1982; HAUCHECORNE and CHANIN, 1983). There were, however, very few measurements at high latitude which extended to higher altitudes on such occasions. This is an important deficiency, since a considerable anticorrelation between the temperature in the stratosphere and mesosphere is expected (see, for example, LABITZKE, 1972; HOUGHTON, 1978). During the Energy Budget Campaign 1980 a minor stratospheric warming occurred in November and early December 1980. In this period a total of 21 meteorological rockets were launched from ESRANGE to make measurements in the middle atmopsphere (PHILBRICK *et al.*, 1985; SCHMIDLIN *et al.*, 1985). Further rockets were launched from Heiss Island (80.5°N, 58°E; DANILOV *et al.*, 1983).

During the MAP/WINE Campaign three minor warmings occurred, at the end of December 1983, in mid January 1984 and during the first part of February 1984. A major warming developed around the end of February 1984. A total of 64 meteorological rockets were launched from Andøya during this period, which included the temperature rise of the major warming but not its decay.

The temperature results obtained from the rockets can be compared to satellite measurements in the lower part of the middle atmosphere. In the upper part (near the mesopause) they can be compared to and be supported by near i.r. measurements of the OH* emission that were performed by two ground-based instruments at Andøya and ESRANGE. Temperature data obtained at other places and resulting large scale structures are presented elsewhere (HAUCHECORNE *et al.*, 1987; PETZOLDT *et al.*, 1987).

The present analysis is restricted to medium and long term temperature variations. Therefore, short term variations, like gravity waves, etc., are removed by suitable filtering. Such features are discussed elsewhere (HASS and MEYER, 1987; RÖTTGER and MEYER, 1987; RÜSTER and KLOSTERMEYER, 1987). Medium term variations with periods of several days to several weeks are then analyzed in a first step. Thereafter, monthly mean temperatures are considered in a second step.

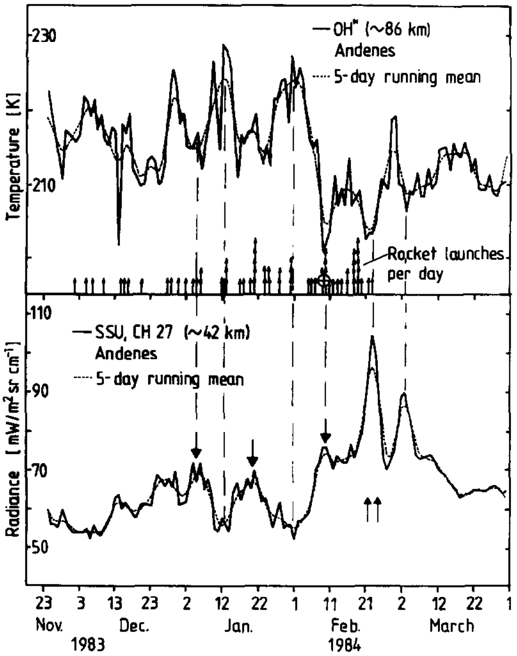


Fig. 1. Mesopause temperatures obtained from OH* at Andøya (Andenes) and stratospheric i.r. radiances representative of temperatures at 1.7 hPa from channel 27 of SSU on NOAA 7. Dashed curve gives 5 day running means. Circled cross is an OH* data point from ESRANGE.

DATA ANALYSIS

1. *Ground-based OH* measurements*

Near infrared emissions of OH* were measured by a ground-based grating spectrometer (University of Wuppertal) at ESRANGE and by a Michelson interferometer (Utah State University) at Andøya during the Energy Budget Campaign. The i.r. light (1–2 μm) is emitted by an OH* layer typically centered at 86 km and ±4 km wide. The layer shape is known from earlier measurements (BAKER *et al.*, 1985; BAKER and STAIR, 1986) and was confirmed by a rocket experiment during the MAP/WINE Campaign (ULWICK *et al.*, 1987). The ground-based instruments and the technique of temperature retrieval have been described by BAKER *et al.* (1985). These authors also present the results from the Energy Budget Campaign. During the MAP/WINE Campaign the same instruments were used, but the grating spectrometer was located at Andøya and the interferometer was at ESRANGE. The grating spectrometer was operated from the end of November 1983 until the beginning of May 1984. These data through the first of April are shown in Fig. 1, together with i.r. radiances measured by channel 27 of SSU (Stratospheric Sounding Unit) on the NOAA 7 satellite (courtesy of the Meteorological Office, Bracknell, U.K.). These radiances are representative of temperatures at about 1.7 hPa ($\sim$42 km). One OH* data point from ESRANGE is also included in Fig. 1. The stratospheric data clearly show the minor warmings mentioned above. They are indicated by arrows in Fig. 1. The strong major warming develops in the fourth week of February 1984 (double arrow in Fig. 1). The expected anticorrelation of mesospheric and stratospheric temperatures is quite obvious in Fig. 1. This is especially true if the five day running means are compared. Dashed vertical lines show some of the coincidences of minima at the mesopause with maxima in the upper stratosphere, and vice versa. In this context it is interesting to note that a decrease of OH* temperatures during the major warming is present, but it is much smaller than one might have expected from the strong temperature enhancement seen in the stratosphere. The lack of a fully developed anticorrelation or the absence of a correlation at all has already been observed on earlier occasions (LANGE, 1982; OFFERMANN *et al.*, 1983). It was attributed to phase shifts with altitude. In the present case it indicates that the temperature relations between stratosphere and mesosphere may be more complicated than a simple anticorrelation. This will be studied in detail below by means of rocket data. Rocket launches are indicated by small arrows in Fig. 1. Launch frequency is seen to increase towards the end of the campaign.

The smoothed temperature curves in Fig. 1 show regular oscillations, which strongly suggest that wavelike structures might have been present during the time period shown. A Fourier analysis (FFT) was therefore performed for the data presented in this figure. The resulting spectra of oscillation periods are given in Fig. 2. The coherence between the stratospheric and mesospheric oscillations and their phases are also given. (For details of the analysis see GERNDT, 1986.) The two spectra are remarkably similar if one considers periods of 9–10 days and longer. The most prominent periods that show up in the stratosphere and the mesosphere and that have high coherence between the two altitudes are the following: 9–10 days, 12 days, 16 days and 50–60 days. This is indicated by vertical broken lines in Fig. 2. All of these oscillations are found to be roughly in antiphase at the two altitudes. Several wave components thus appear to have been present in the atmosphere during this campaign, and these deserve further study. Similar oscillations were observed during the Energy Budget Campaign. A respective analysis can be performed using the many vertical temperature profiles measured by rockets during the two campaigns.

2. *Rocket measurements*

Energy Budget Campaign (*EBC*). Most of the rocket systems used during the Energy Budget and MAP/WINE Campaigns were datasondes and passive falling spheres (PHILBRICK *et al.*, 1985; SCHMIDLIN *et al.*, 1985). The measurements thus covered approximately the altitude range 20–90 km. Details of the launch dates and altitude ranges are given by KÜCHLER (1987). The analysis technique smoothes, to some extent, the temperature data at high altitudes. In the present analysis only long period temperature variations are considered. These long period features should not be influenced by such smoothing. A typical altitude profile from the Energy Budget Campaign (EBC) is shown in Fig. 3. The large amount of small scale structure observed in all profiles is attributed to short period gravity waves. This is concluded from the analysis of days with multiple rocket launches, which show respective phase changes of these structures on a time scale of hours. A smoothing procedure was used to remove these temperature perturbations and to arrive at mean daily profiles. The procedure used a filter which was wide at low altitudes and became more narrow towards higher altitudes. This was done in order not to lose important small scale, though permanent, features at lower altitudes, as for example the temperature changes near the stratopause. As Fig. 3 shows, this technique yields a reasonable mean of the measured profile (for details see KÜCHLER, 1987).

In case there was more than one rocket launch per day during the EBC, a mean of the individually smoothed altitude profiles was calculated and used as the temperature profile representative of that day. Nine altitude profiles were obtained in this way, which were nearly evenly distributed over a period of about three weeks in November/December 1980.

The time variation of temperatures at a fixed altitude during the Energy Budget Campaign was next analysed. This was done from 23 km to 89 km at altitude intervals of 1 km. Considerable periodic oscillations were seen in the data. The procedure used was therefore essentially to fit sine functions to the 9 data points at each altitude. Thus optimum oscillation periods (frequencies), amplitudes and phases were determined. A period of about 24 days and an additional shorter one of around 8 days yielded the best fit when it was required that the periods be the same throughout all altitudes (for details see KÜCHLER, 1987). Apart from these data, mesopause temperatures as derived from near infrared OH* emissions during the Energy Budget Campaign were analysed (BAKER *et al.*, 1985; OFFERMANN, 1985). These results also yielded a period

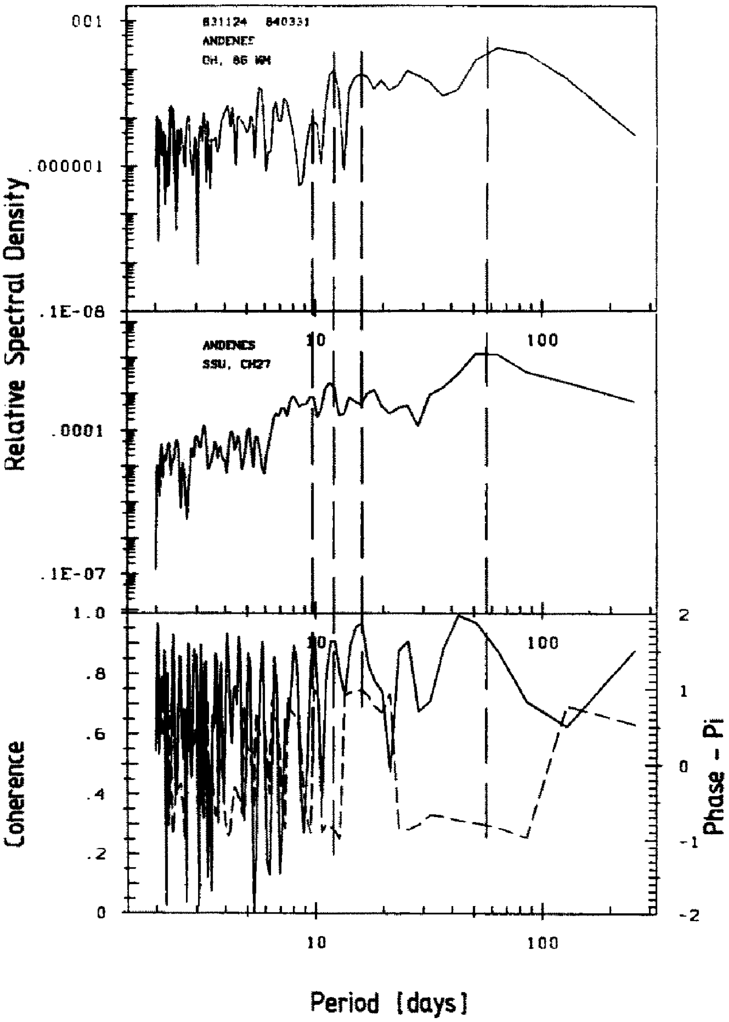


Fig. 2. Spectral analysis of the data shown in Fig. 1. Upper panel shows the results for the OH* temperatures at 86 km. Middle panel gives the spectrum of the radiances measured by channel 27 of SSU (42 km). Lowest panel shows the coherence and phase shift between the oscillations at the two altitudes.

of 24 days for the temperatures at around 86 km. The fit was therefore repeated with two oscillation periods fixed at 24 days and 8 days, which allowed the fitted amplitudes and phases of these two oscillations to be determined at all altitudes. The resulting values are given in Fig. 4. Figure 5 shows a superposition of the two oscillations at 2 km height intervals using amplitudes and phases from Fig. 4. To demonstrate the quality of the fit, the measured and smoothed data are compared in Fig. 6. It is obvious from the picture that the evaluation procedure described yields a reasonable fit to the data, though there are times and altitudes where considerable differences still exist. Thus the small scale structures seen in the amplitude and phase profiles in Fig. 4 must not be taken seriously. In addition, at high altitude the number of rockets available decreases and hence the quality of the fit may decrease. This was checked by comparing the fit to the above mentioned temperatures derived at 86 km ± 4 km from the OH* emissions. These data and the respective 24 day oscillation fitted to them by OFFERMANN (1985) are shown in Fig. 7, together with the main oscillation component (24 days) from the model developed here for 85 km altitude. The 8 day wave is neglected in this case, as its amplitude is small at this altitude (see Fig. 4). The two fitted curves cannot be compared directly, because the OH* data represent an average over an atmospheric layer 8 km thick. To facilitate comparison a bar is given, together with the fit to the rocket data of 85 km, which indicates

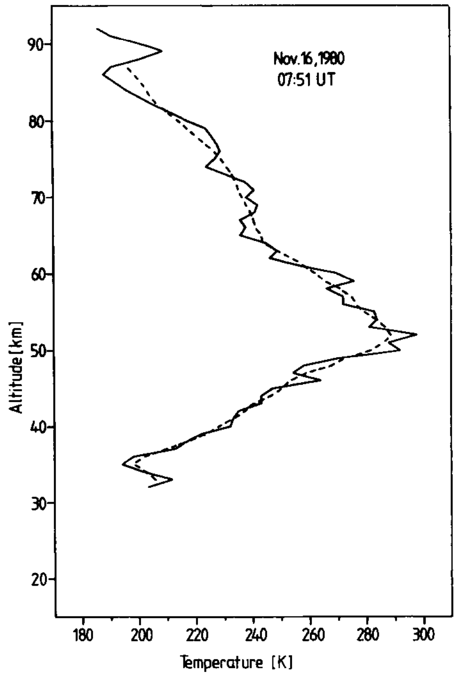


Fig. 3. Typical temperature profile measured by a passive falling sphere (solid curve). Dashed line is the result of a smoothing procedure described in the text.

the typical temperature variations seen in the layer 85 km ± 4 km. The temperatures obtained from the rocket data appear to be somewhat smaller (10K) than the OH* temperatures. This difference is, however, not significant if one takes into account the indicated variations in the 8 km atmospheric layer. The relative variations of the two data sets are rather

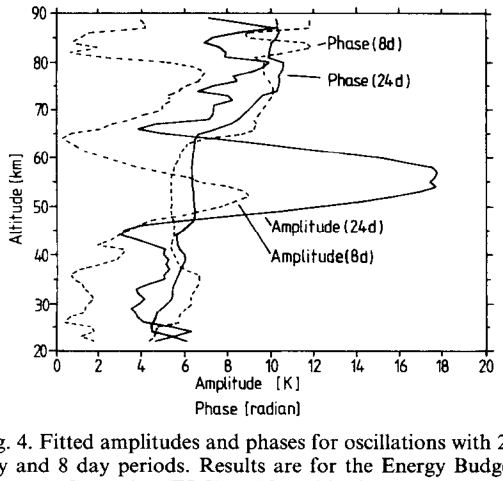


Fig. 4. Fitted amplitudes and phases for oscillations with 24 day and 8 day periods. Results are for the Energy Budget Campaign (EBC) at 1 km altitude steps.

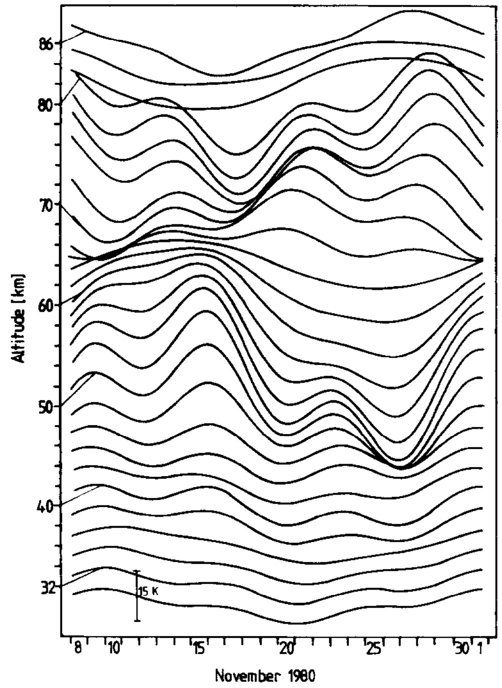


Fig. 5. Temperature variations during the EBC modeled by superposition of the 24 day and 8 day oscillations (at 2 km altitude steps).

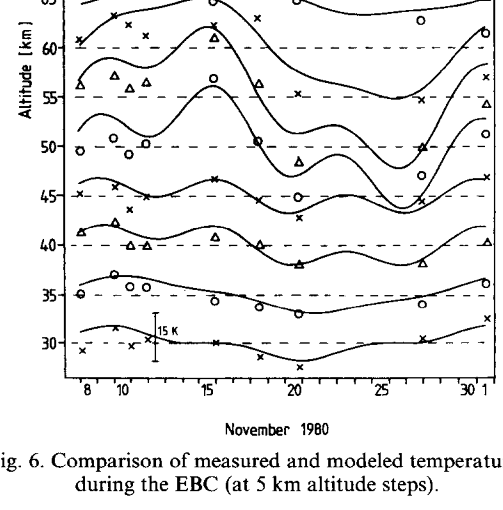


Fig. 6. Comparison of measured and modeled temperatures during the EBC (at 5 km altitude steps).

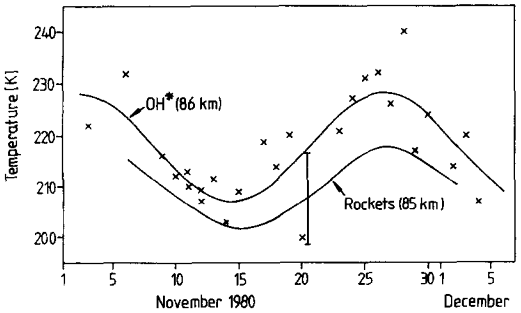


Fig. 7. Comparison of OH* temperatures (crosses and respective fitted curve) and modeled rocket temperatures (at 85 km) during the Energy Budget Campaign.

similar : the model amplitude is ±8K and that of the fit to the OH* data is ±10K. The agreement of the phases of the two curves is very good.

The temporal development of the modeled temperature altitude profiles is shown in Fig. 8. Kinks in the profiles are not in the measured data, but result from the method of analysis: the fit procedure is applied to the data at a given altitude and at altitude steps of 1 km. As successive layers are analysed independently, small deviations from a smooth vertical profile may result. They occur most frequently when the number of rockets available varies with altitude—as it does at the highest and lowest altitudes. The kinks thus give an indication of the quality of the fit procedure.

The time development of the vertical profiles shows strong movements. It sometimes even exhibits the very peculiar structure of a split stratopause. Here the temperature maximum at higher altitudes is ocassionally somewhat larger than that at lower altitudes. This may be an exaggeration by the model to some extent, which could be due to the limited time coverage by the rocket flights. It was, however, also seen in the raw data of the flight on 21 November 1980.

MAP/WINE Campaign. During the MAP/WINE Campaign from December 1983 to February 1984 many more meteorological rockets were launched than during the Energy Budget Campaign 1980. During the first part of this recent campaign, however, a difficulty was encountered with the passive falling spheres. They tended to collapse early during descent and hence the data coverage in the 70–90 km regime was poor in December 1983. Technical measures were taken and the situation improved towards the end of January 1984, and was good in February 1984. The data analysis is affected by this situation, especially in the 65–67 km regime, i.e. in the transition regime from the (more numerous) datasondes to the (fewer) passive spheres. As discussed above, kinks arise in the vertical model profiles and sometimes even steps and spikes, as will be seen below. These effects may have been enhanced by inappropriate smoothing of the temperature profiles obtained from many spheres. Thus, if a sphere collapsed early its data profile was too limited in altitude range (10–20 km) to apply the

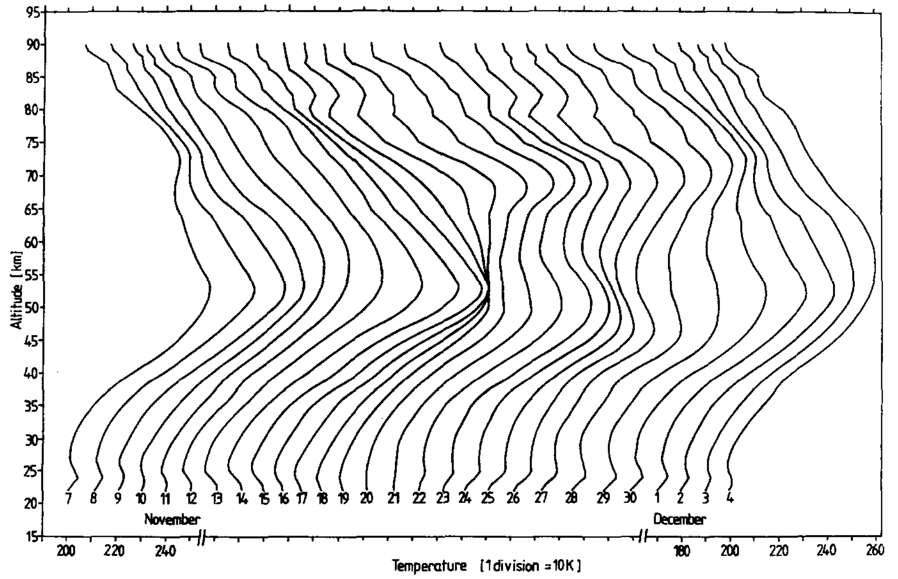


Fig. 8. Time development of modeled temperature altitude profiles for the Energy Budget Campaign. Profiles are given at 1 day intervals. They are shifted by 10K with respect to each other.

above described smoothing procedure. In such a case the temperature profile was approximated by a linear least square fit instead. This is a coarse method, especially if waves are present. It was feared, however, that more sophisticated approaches might introduce even more artifacts.

To derive temperatures from falling sphere measurements, before any smoothing an integration has to be performed that employs an upper boundary temperature value at about 95 km. The adoption of such a value is always arbitrary to a large extent. To reduce this uncertainty somewhat, it was decided to make use of the OH* temperatures shown above (Fig. 1), as such temperatures were found to be in reasonable agreement with the modeled rocket temperatures during the Energy Budget Campaign 1980. The upper boundary temperature values during the MAP/WINE Campaign were therefore chosen such that the altitude profiles approximately met the 86 km OH* temperatures.

Details of the MAP/WINE data coverage by the meteorological rockets, of the data evaluation, corrections applied and of the above normalization are described by MEYER *et al.* (1985). In summary, it must be remembered that the MAP/WINE rocket temperatures above 75–80 km are not an independent set of data and—with respect to the present analysis—suffer to some extent from inhomogeneous distribution and coarse smoothing.

Time variations of temperatures at fixed altitudes during the MAP/WINE Campaign were analysed in a similar way as for the previous campaign, i.e. harmonic functions were fitted to the data points at fixed altitudes. Because of the much more numerous measurements and the longer time interval covered, more oscillation periods were admitted to this analysis. Main wave components were initially determined at each altitude by carefully filtering the data. Tentative periods common to all altitudes were then estimated. These initial values were introduced into a least square analysis in which amplitudes and phases of all wave components at all altitude levels were free to adjust to a best fit. Also, the periods of the wave components were allowed to change during this procedure. It was, however, required that these periods be the same at all altitude levels. This analysis was performed at altitude steps of 400 m. All altitude levels were treated simultaneously, i.e. the sum of least square deviations at all levels was calculated and minimized.

Several tests were made to check the quality of this analysis and the stability of its results. In particular, the analysis was tested to see whether the periods obtained changed if the number of data (time interval) used was varied and how the periods depended on each other. For instance, an analysis with four basic periods (longer than 10 days) was repeated with a fifth period (9–10 days) added: the fit was considerably improved and the four original periods remained almost unchanged. It is therefore believed that the fit analysis gives stable results. Optimum periods obtained are: $\tau_1 = 144$ days; $\tau_2 = 54$ days; $\tau_3 = 17.4$ days; $\tau_4 = 13.3$ days; $\tau_5 = 9.6$ days. These were obtained when the data in the critical regime 65–67 km were omitted from the analysis for the reasons mentioned above. Introduction of a sixth (even shorter) period was considered. It was, however, felt that this would allow too many free parameters in the analysis as compared to the data available, though such an oscillation may well have been present in the atmosphere. It is furthermore questionable whether a short period oscillation would be continuously present for three months, as was tacitly assumed in our procedure. It appears likely that it would disappear after a while and be excited later again, possibly with a different phase. This caveat also applies to a certain extent to our periods τ_4 and τ_5. The influence of the length of the time interval used was checked by analysing the December/January data separately and comparing it with an analysis of the January/February data group. No essential differences were found. (This also pertains to the amplitude and phase analysis described below.)

The quality of the analysis was further checked by replacing the measured temperatures by random numbers. The results showed that the above derived periods cannot be artifacts of the analysis procedure, with one exception: if random numbers are used on the days of the rocket flights and, in addition, a constant temperature bias (deviation from the mean temperature) is assumed, the analysis tends to produce oscillations of very long periods. This is presumably due to the uneven distribution of rocket launches in the time interval analysed, with its strong bias towards February 1984. Since it is very difficult to be sure that the mean temperatures used are unbiased, it cannot be excluded that the longest period τ_1 obtained from our analysis is to some extent an artifact. Details of the filtering procedure, the tests and the checks of the analysis procedure are described by KÜCHLER (1987).

The periods τ_2–τ_5 obtained from the harmonic analysis of the rocket data are very similar to those found in the OH* tempeatures discussed above. As mentioned above, the rocket data at high altitudes were normalized to the OH* temperatures. This normalization will, however, influence the temperature profiles only down to one to two scale heights below the normalization level, i.e. down to 75–80 km. Thus the periods τ_2–τ_5 are mostly determined by data independent of the OH* measurements and the good agreement with the OH* FFT results supports the harmonic analysis of the rocket data.

Amplitudes and phases resulting from the harmonic analysis of the five waves τ_1–τ_5 are given versus altitude in Fig. 9a–e. The 65–67 km data have been omitted on the grounds mentioned above. As in the case of the Energy Budget Campaign (Fig. 4), the fine structure of the profiles is not real. The three short period oscillations are shown at various altitudes in Fig. 10a–c for the duration of the campaign. A superposition of all five wave components is given in Fig. 11. To show the quality of the fit, the superposition curves are compared to the measured temperatures at the respective altitudes in Fig. 12. As in the case of the Energy Budget Campaign, the fit yields reasonable results.

The temporal development of the modeled temperature altitude profiles during the MAP/WINE Campaign is shown in Fig. 13. January 1984 profiles are given as an example. Profiles of the other months are very similar. As mentioned above, the kinks and steps are artifacts of the analysis procedure. A set of smooth profiles was therefore developed instead. For

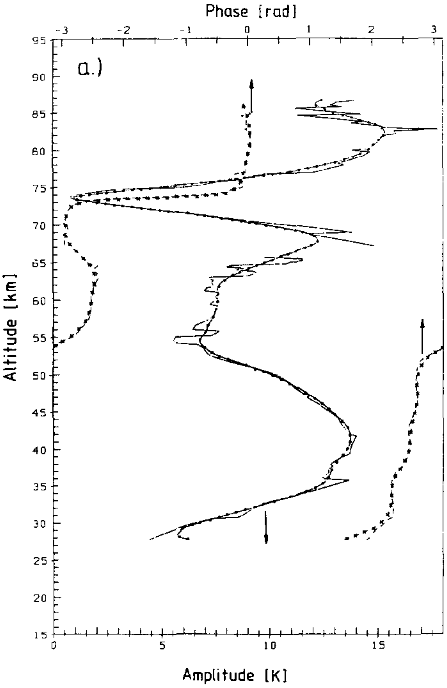
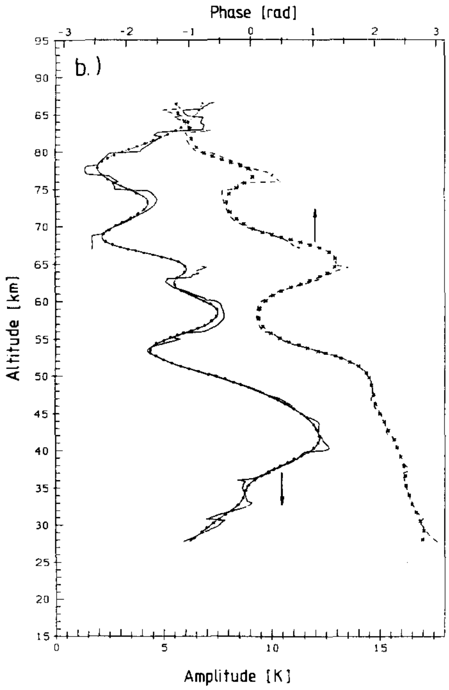


Fig. 9. Fitted amplitudes (solid lines) and phases (dashed lines) for oscillations present during the MAP/WINE Campaign. Curves with dots and crosses are for the smoothed model discussed in the text. (a) Oscillation period is 144 days.



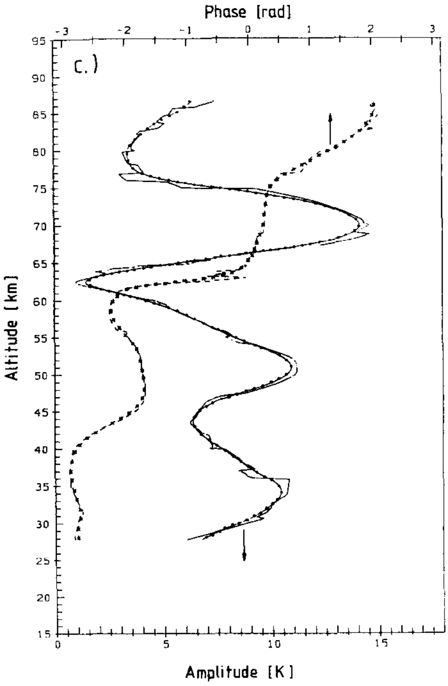


Figure 9 continued. (b) Oscillation period is 54 days. (c) Oscillation period is 17.4 days. (*Continued over.*)

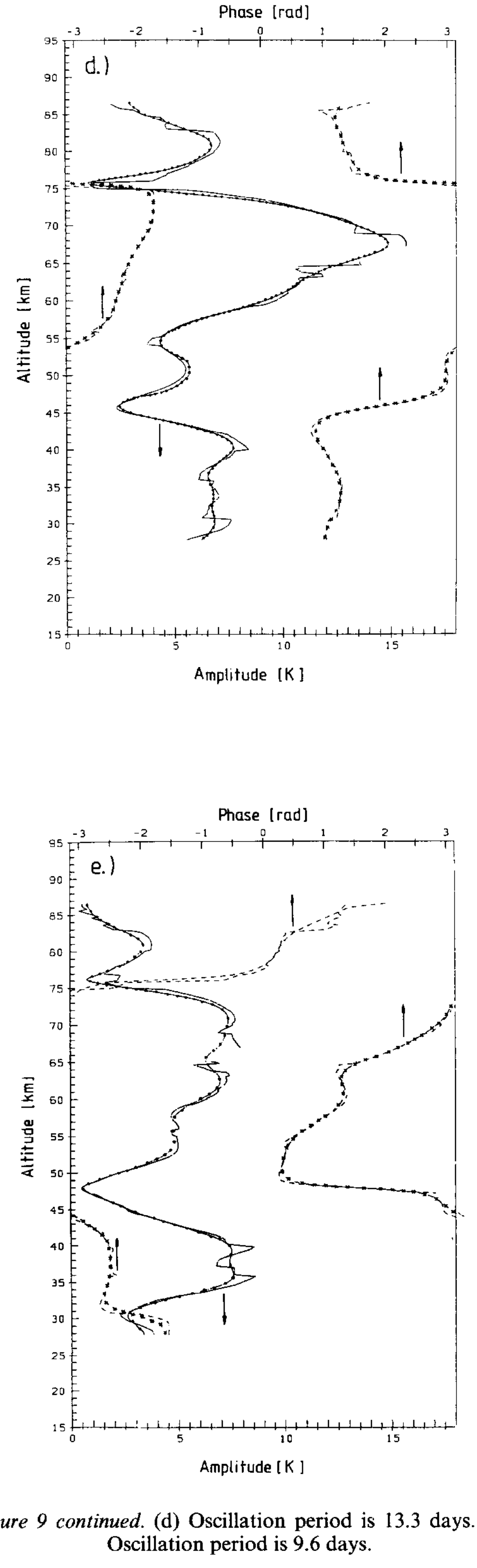


Figure 9 continued. (d) Oscillation period is 13.3 days. (e) Oscillation period is 9.6 days.

this purpose 48 profiles at three day intervals were selected from the total time period covered. They were smoothed by a low pass filter until the kinks and steps disappeared. The smoothed profiles were then treated like measured data, i.e. they were fed into our harmonic analysis procedure, using the periods τ_1–τ_5. Amplitude and phase distributions obtained in this way are included in Fig. 9. They are similar to the original ones, but very smooth now. They are also given in Table 1 at altitude steps of 1 km. (For more refined analyses they are available at 0.2 km intervals on request.) The time behaviour of the five oscillations in the smoothed version is very similar to that of Figs. 10 and 11, with maximum deviations of a few degrees. Considering this and the agreement of modeled with measured data shown in Fig. 12, it is believed that the smoothed model—though being an approximation—is able to demonstrate some essential features of atmospheric behaviour.

New vertical temperature profiles were obtained from the smoothed model. They are also very smooth now and deviations from the curves of Fig. 13 are a few degrees at most. Comparison to the untreated vertical profiles is also satisfactory. The temporal development of the smoothed vertical profiles is shown in Fig. 14 for the whole campaign. As in the case of the Energy Budget Campaign (Fig. 8), it shows strong movements. Very steep temperture gradients are observed occasionally. For instance, at the beginning of January 1984 the gradient above 65 km is even slightly super-adiabatic. It should be mentioned that in this altitude regime and time interval of the campaign the density of data is rather low. On the other hand, there are at least two measurements (on 31 Jan. 1984) that showed very similar temperature profiles with near adiabatic lapse rates (and indications of a split mesopause; MEYER *et al.*, 1985). It is interesting to note that the temperature model of Fig. 14, though it employs completely different frequencies to that of the Energy Budget Campaign (Fig. 8), also shows a split stratopause on occasions. This is most pronounced at the end of February/beginning of March 1984.

DISCUSSION

1. *Stratospheric warmings and temperature oscillations*

Stratospheric warmings are known to be accompanied by mesospheric coolings. They are further known to follow a characteristic pattern of time development. During a build-up phase the stratopause temperature increases and the altitude level of the stratopause decreases. During the recovery phase the upper stratosphere and a large part of the

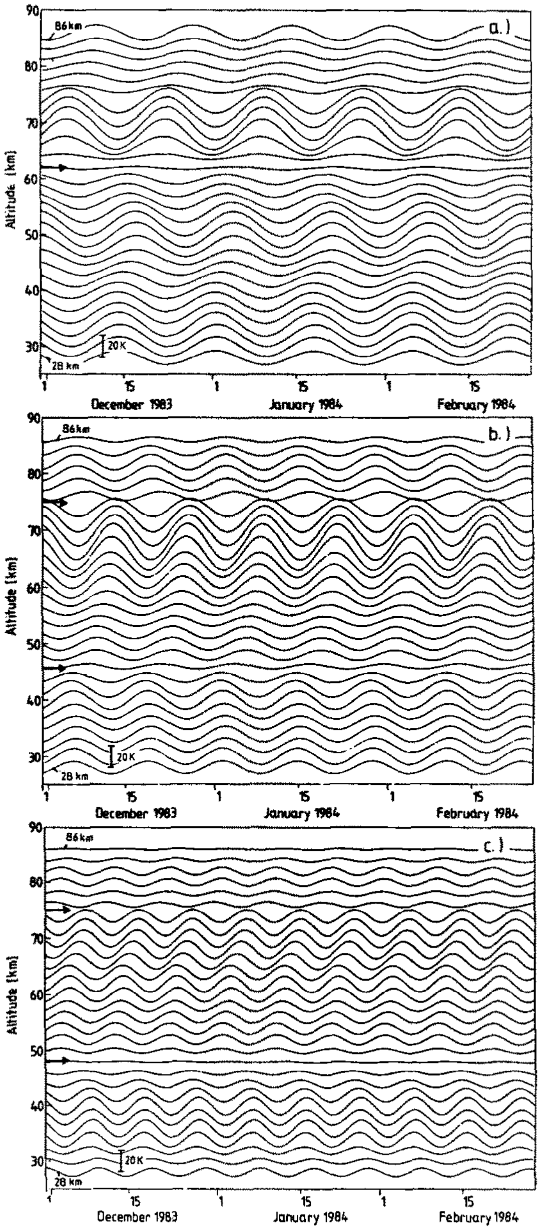


Fig. 10. Short period oscillations during the MAP/WINE Campaign vs. altitude. Temperatures are given for fixed altitudes from 28 to 86 km at 2 km intervals. Oscillation periods are (a) 17.4 days, (b) 13.3 days and (c) 9.6 days.

mesosphere tend to become isothermal. This pattern was modeled in four phases by COLE and KANTOR (1978). Both of these features are confirmed by the present analyses of the Energy Budget Campaign (Fig. 8), as well as the MAP/WINE Campaign (Fig. 14). It thus appears that the analysis presented here—though approximate—is able to model to a large extent stratospheric warmings and the related mesospheric coolings by suitable superposition of wave-like oscillations. It should be remembered that the emphasis of our analysis is on the minor warmings, as only part of the major warming in February 1984 was covered by the rocket experiments. As regards the periods of these oscillations, we note that planetary wave activity was analyzed for the Energy Budget Campaign by LABITZKE and BARNETT (1985). They found strong action of wave number 1 with an oscillation period of 20–30 days, which compares to the period of 24 days discussed here. HAUCHECORNE *et al.* (1987) performed a spatial analysis of temperatures measured during MAP/WINE at various places, with an interpretation in terms of planetary waves.

The detailed behaviour of a stratospheric warming appears to be much more complicated than is shown by the four phase model of COLE and KANTOR (1978). This is seen from Figs. 8 and 14, which show intermittent warmings in the stratosphere and mesosphere (with subsequent coolings). It is obvious from these pictures that heating periods in the stratosphere are correlated with coolings in the mesosphere, and vice versa. The altitude levels of these events are variable, however. It is also seen that an isothermal layer in the middle atmosphere after a warming event is not necessarily the end of the atmospheric disturbance. Occasionally it develops further and exhibits the peculiar feature of a split stratopause mentioned above: 21–30 Nov. 1980 in Fig. 8 and end of February/beginning of March 1984 in Fig. 14. It should be noted here that the last rocket of the MAP/WINE Campaign was launched on 23 February 1984. The profiles shown in Fig. 14 beyond that date are therefore an extrapolation of the second half of the main phase and of the decay phase of the major warming on the basis of the waves present in the weeks before.

Correlations between stratosphere and mesosphere are more easily shown by the temperature variations at fixed altitudes given in Figs. 5, 10 and 11. They are obvious from these pictures and exhibit interesting details. The two oscillations of the Energy Budget Campaign behave very similarly in two important respects: (a) the wave amplitudes show a very pronounced minimum at 64–65 km, with high values below and above this level; (b) phase changes are very considerable at and slightly above this level for both waves, whereas at lower and higher altitudes phase changes are rather small. Figure 5 shows that there is a 'quiet atmospheric layer' at about 65 km, with almost no oscillations visible, and strong variations above and below it, which are approximately in antiphase. The anticorrelation of stratospheric and mesospheric temperatures obviously originates from a transition

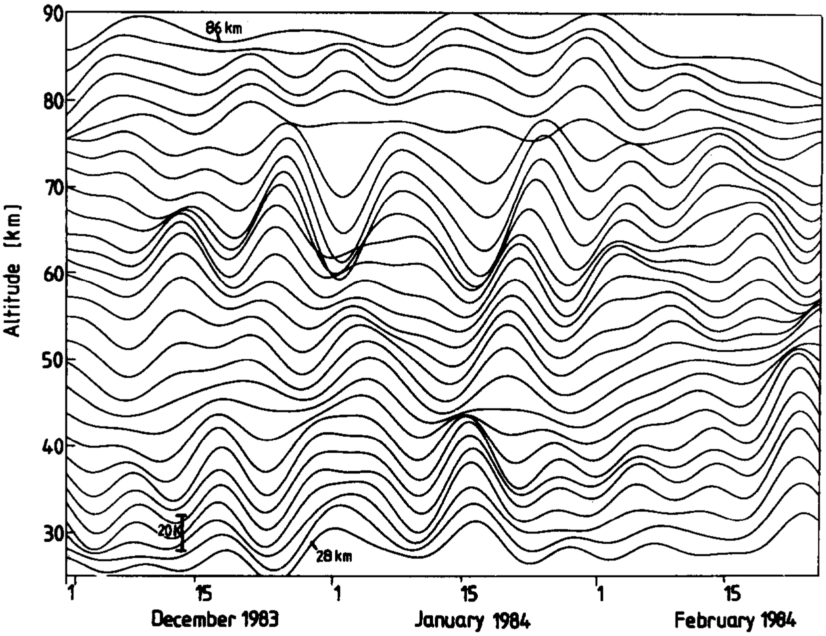


Fig. 11. Superposition of all five oscillations during the MAP/WINE Campaign. Temperatures are given at fixed altitudes from 28 to 86 km at 2 km intervals.

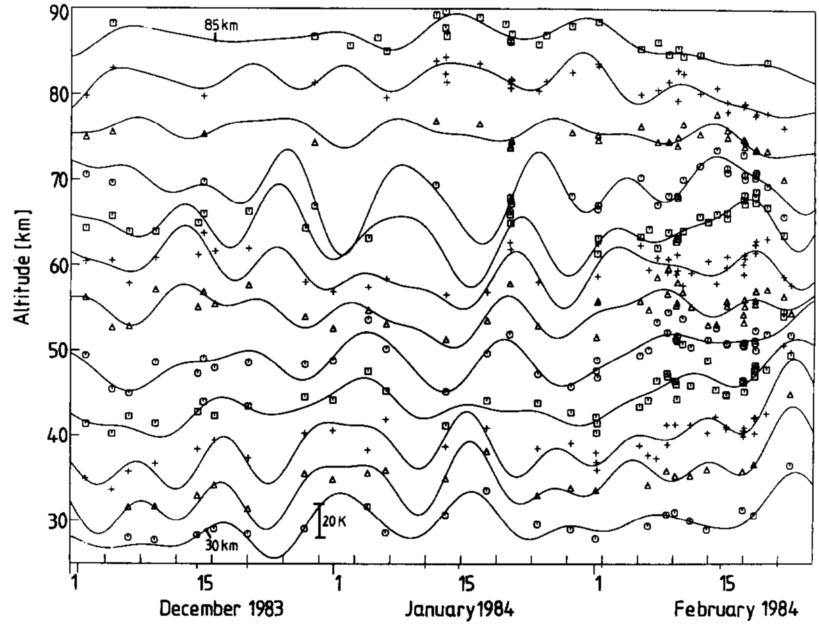


Fig. 12. Comparison of measured and modeled temperatures during the MAP/WINE Campaign (at 5 km altitude steps).

in a very narrow layer. This is, of course, also seen in the amplitude and phase distributions with height, as shown in Fig. 4. This picture furthermore indicates a second 'quiet layer' at about 45 km altitude.

These 'quiet layers' are again found in data of the MAP/WINE Campaign (Figs. 9–11). They are not so obvious in the superposition picture of the five oscillations (Fig. 11), though they are detectable in the upper mesosphere. This is because the five different oscillations τ_1–τ_5 have their respective layers at

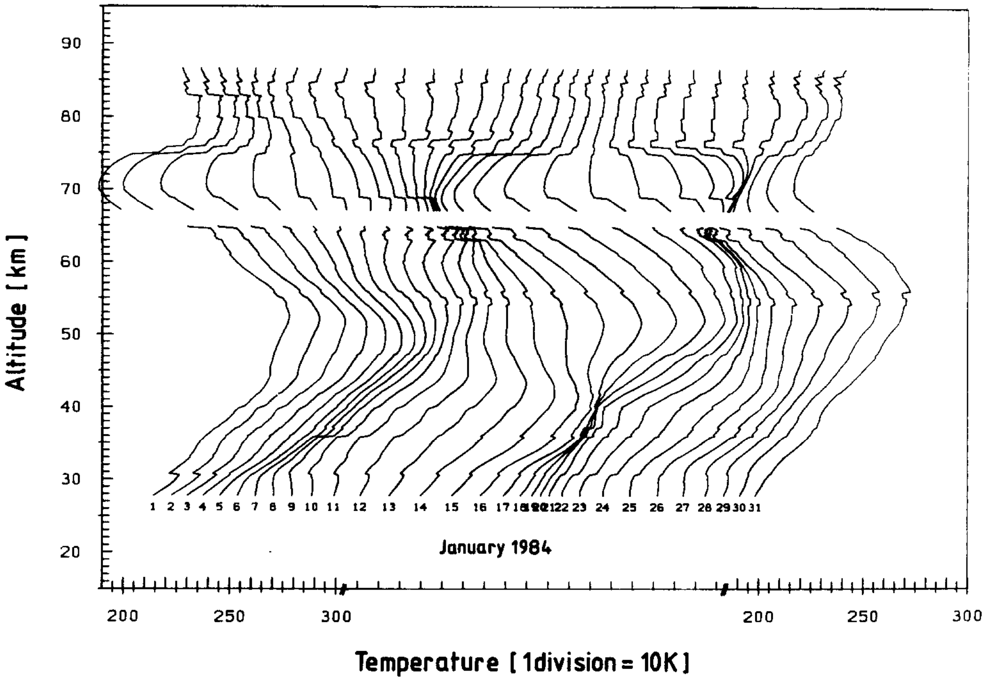


Fig. 13. Time development of modeled temperatures during the MAP/WINE Campaign. January 1984 is shown as an example. Profiles are given at 1 day intervals. They are shifted by 10K with respect to each other.

somewhat different altitudes. This is seen from Figs. 9 and 10, which show that the amplitude minima are very pronounced and the phase transitions very steep for all oscillations except τ_2 (arrows in Fig. 10). In this context it is interesting to note that on an earlier occasion an indication of an isothermal layer in the mesosphere was found during a minor stratospheric warming at much lower latitudes (Winter Anomaly Campaign 1975/1976, El Arenosillo, 37°N). This was discussed in the context of a stationary planetary wave of number 2 (OFFERMANN *et al.*, 1982).

It is, of course, tempting to interpret the amplitude minima and, especially, the steep phase transitions found in the present data as nodes of standing waves. Trapping and resonant conditions of Rossby waves in the lower and middle atmosphere were discussed by LINDZEN and TUNG (1979) in the context of stratospheric warmings. They find wave modes with one or two nodes to be a likely occurrence. Wave reflection and standing planetary waves in the middle atmosphere have also been discussed by PLUMB (1982) in connection with major warming build-up. In this paper nodes and reflection levels appear, however, to occur at much lower altitudes than the layers found here.

As standing and travelling planetary waves can be present in the atmosphere simultaneously, it is no surprise to see that not all oscillations analyzed here fit into the picture developed. Oscillation τ_2 behaves differently, as its amplitude profile (Fig. 9b) is not so strongly structured and its phase shift is on average much more gradual. This latter feature would rather indicate a travelling wave. It may have some bearing in this context that PETZOLDT (1985) analysed amplitude and movement of planetary wave no. 1 in the lower stratosphere during the MAP/WINE Campaign. The results show a travelling wave with a period of about 26 days and a rather low amplitude when the wave maximum was near to the rocket launch site. One may therefore speculate as to whether this wave is interpreted in our analysis as an oscillation with double period, which would be near τ_2 as derived here.

The mesospheric 'quiet layers' during the MAP/WINE Campaign also appear to be shown by the Fourier analysis of HAUCHECORNE *et al.* (1987). Earlier lidar data were presented by HAUCHECORNE and CHANIN (1983) (see also other references in that paper). Fourier analysis of that data yielded oscillations with periods similar to those found here and a minimum in wave amplitudes was also seen by these authors near the stratopause. They observed, however,

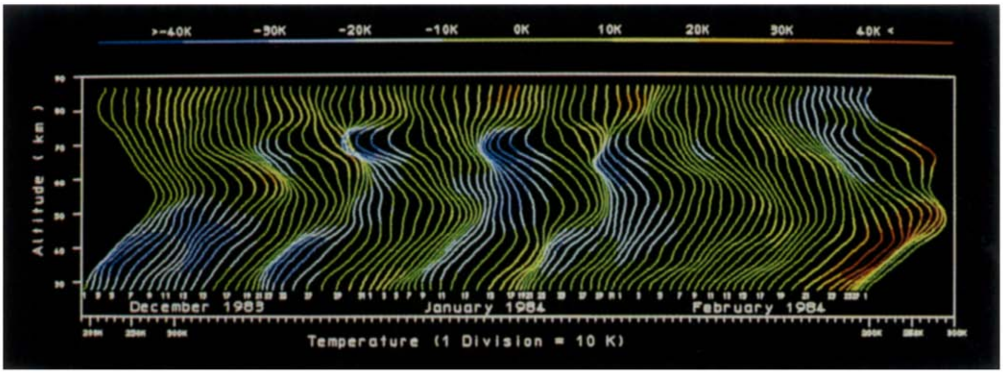


Fig. 14. Smoothed model temperature profiles for the MAP/WINE Campaign (28–86 km). Curves are given for 12:00 UT at 1 day intervals. They are shifted by 10K with respect to each other. Colour code indicates deviations from mean temperatures T_0: green = $T_0 + 10K/-10K$; sea-green = $T_0 - 10K/-20K$; blue = $T_0 - 20K/-30K$; dark-blue < $T_0 - 30K$; yellow = $T_0 + 10K/+20K$; orange = $T_0 + 20K/+30K$; red = $T_0 + 30K/+40K$; reddish-brown > $T_0 + 40K$. A numerical representation of the temperature wave field is given in Table 1.

Table 1. Amplitudes (A) and phases (P) of five harmonic oscillations during the MAP/WINE Campaign versus altitude z

z	$\bar{T}$	$A5$	$P5$	$A4$	$P4$	$A3$	$P3$	$A2$	$P2$	$A1$	$P1$
28.0	202.80	3.34	−1.627	6.29	1.004	6.87	−2.783	6.28	2.784	5.87	1.634
29.0	205.30	3.00	−1.697	6.65	1.039	7.65	−2.788	6.74	2.801	5.86	1.931
30.0	208.22	2.63	−1.942	6.84	1.084	8.51	−2.771	7.21	2.769	6.71	2.131
31.0	211.67	2.80	−2.340	6.78	1.146	9.25	−2.754	7.67	2.712	7.94	2.231
32.0	215.65	3.73	−2.567	6.70	1.205	9.80	−2.763	8.15	2.657	9.17	2.285
33.0	219.96	5.05	−2.607	6.74	1.244	10.20	−2.801	8.53	2.607	10.34	2.304
34.0	224.35	6.37	−2.579	6.78	1.262	10.40	−2.847	8.72	2.561	11.42	2.305
35.0	228.72	7.29	−2.544	6.68	1.265	10.25	−2.882	8.85	2.522	12.26	2.315
36.0	232.99	7.55	−2.517	6.54	1.246	9.74	−2.900	9.19	2.500	12.68	2.351
37.0	237.08	7.45	−2.505	6.57	1.200	9.78	−2.903	9.78	2.487	12.82	2.411
38.0	241.01	7.39	−2.503	6.90	1.135	8.62	−2.890	10.48	2.466	12.99	2.482
39.0	244.86	7.46	−2.511	7.36	1.062	8.14	−2.862	11.19	2.427	13.28	2.540
40.0	248.70	7.34	−2.538	7.67	0.985	7.62	−2.804	11.77	2.375	13.56	2.574
41.0	252.55	6.74	−2.603	7.56	0.911	7.11	−2.696	12.09	2.317	13.70	2.586
42.0	256.42	5.72	−2.718	6.94	0.862	6.68	−2.529	12.15	2.260	13.69	2.597
43.0	260.04	4.57	−2.883	5.80	0.869	6.40	−2.316	12.01	2.205	13.53	2.617
44.0	263.22	3.53	−3.076	4.34	0.980	6.37	−2.094	11.73	2.149	13.23	2.648
45.0	265.93	2.65	3.030	2.96	1.316	6.63	−1.911	11.30	2.089	12.86	2.685
46.0	268.21	1.83	2.877	2.46	2.004	7.21	−1.792	10.74	2.032	12.45	2.716
47.0	269.99	0.99	2.622	3.17	2.582	8.11	−1.733	10.07	1.992	11.97	2.727
48.0	271.32	0.50	1.319	4.21	2.840	9.19	−1.715	9.25	1.966	11.43	2.721
49.0	272.35	1.26	0.425	5.00	2.939	10.14	−1.720	8.29	1.938	10.83	2.715
50.0	273.20	2.27	0.306	5.41	2.967	10.74	−1.736	7.20	1.881	10.10	2.726
51.0	273.84	3.25	0.303	5.48	2.968	10.90	−1.755	6.07	1.767	9.17	2.770
52.0	274.19	4.08	0.326	5.25	2.988	10.63	−1.778	5.06	1.557	8.11	2.859
53.0	274.28	4.60	0.361	4.79	3.066	9.97	−1.816	4.42	1.225	7.23	3.014
54.0	274.07	4.81	0.424	4.39	−3.057	9.10	−1.879	4.47	0.821	6.81	−3.069
55.0	273.45	4.80	0.535	4.38	−2.844	8.22	−1.971	5.19	0.485	6.83	−2.879
56.0	272.28	4.73	0.694	4.85	−2.658	7.46	−2.078	6.18	0.273	7.06	−2.736
57.0	270.57	4.73	0.878	5.71	−2.521	6.77	−2.170	7.03	0.163	7.23	−2.639
58.0	268.54	4.93	1.063	6.85	−2.431	6.05	−2.227	7.45	0.124	7.39	−2.579
59.0	266.30	5.41	1.211	8.10	−2.372	5.21	−2.238	7.38	0.144	7.49	−2.547
60.0	263.90	6.06	1.293	9.20	−2.331	4.15	−2.204	6.84	0.230	7.56	−2.529
61.0	261.24	6.63	1.308	10.01	−2.292	2.83	−2.082	6.07	0.413	7.56	−2.506
62.0	258.36	6.92	1.284	10.55	−2.252	1.62	−1.635	5.52	0.713	7.67	−2.477
63.0	255.43	6.89	1.274	11.05	−2.219	1.77	−0.604	5.60	1.047	8.15	−2.470
64.0	252.54	6.57	1.359	11.76	−2.183	3.49	−0.191	5.98	1.276	8.93	−2.504
65.0	249.47	6.28	1.591	12.79	−2.133	5.91	−0.062	5.85	1.372	9.87	−2.592
66.0	245.86	6.42	1.923	13.94	−2.062	8.61	0.012	4.81	1.340	10.74	−2.721
67.0	241.98	6.85	2.220	14.72	−1.985	11.05	0.071	3.28	1.158	11.79	−2.845
68.0	238.11	7.11	2.460	14.79	−1.910	12.85	0.125	2.27	0.743	12.20	−2.918
69.0	234.57	7.21	2.668	14.24	−1.841	13.84	0.175	2.24	0.255	11.53	−2.943
70.0	231.57	7.31	2.839	13.38	−1.785	14.11	0.215	2.77	−0.059	9.76	−2.945
71.0	229.14	7.32	2.961	12.36	−1.749	13.79	0.241	3.42	−0.242	7.41	−2.933
72.0	227.06	7.07	3.039	11.13	−1.733	13.06	0.256	3.99	−0.349	4.73	−2.893
73.0	225.15	6.31	3.102	9.32	−1.733	11.85	0.268	4.26	−0.393	1.89	−2.668
74.0	223.46	4.83	−3.098	6.54	−1.775	9.95	0.287	4.04	−0.371	1.61	−0.512
75.0	221.92	2.69	−2.904	2.87	−1.990	7.47	0.332	3.35	−0.249	4.89	−0.181
76.0	220.66	0.82	−1.975	1.43	2.236	5.22	0.445	2.61	−0.048	8.10	−0.126
77.0	219.64	1.40	−0.368	3.81	1.663	3.95	0.649	2.10	−0.050	10.73	−0.083
78.0	218.78	2.26	−0.020	5.31	1.522	3.51	0.874	1.94	−0.149	12.59	−0.043
79.0	218.01	2.86	0.137	6.14	1.439	3.39	1.080	2.32	−0.521	13.78	−0.009
80.0	217.37	3.29	0.222	6.63	1.380	3.39	1.303	3.14	−0.788	14.49	0.016
81.0	216.88	3.37	0.300	6.72	1.334	3.58	1.532	4.07	−0.916	14.96	0.025
82.0	216.51	2.98	0.416	6.33	1.291	3.93	1.720	4.95	−0.968	15.26	0.025
83.0	216.41	2.27	0.610	5.48	1.240	4.35	1.855	5.64	−0.995	15.19	0.019
84.0	217.33	1.58	0.871	4.52	1.201	4.92	1.956	6.14	−1.074	14.16	−0.006
85.0	218.88	1.09	1.150	3.64	1.206	5.60	2.012	6.47	−1.163	12.91	−0.044
86.0	220.13	0.84	1.315	3.14	1.266	6.14	2.033	6.69	−1.219	12.07	−0.084

A in K; P in radians with respect to 1 Dec. 1983, 00:00 UT; z in km; wave periods τ are given in the text. Temperatures $T(z)$ are given by the equation

$$T(z) = \bar{T}(z) + \sum_{i=1}^{5} A_i(z)\cdot\sin(\omega_i t - P_i(z)).$$

a much more gradual amplitude and phase variation with height than is shown here in Figs. 4 and 9a, c–e. These figures demonstrate that a very good altitude resolution of the measurement and analysis method is needed to detect the variations in question. An altitude resolution of 4.8 km, as used by HAUCHECORNE and CHANIN (1983), may not be sufficient.

It was mentioned above that superposition of the five model oscillations occasionally yields very steep or even super-adiabatic temperature gradients. This is seen for instance at the end of December 1983 and beginning of March 1984. Unusually low temperatures at the end of December 1983 at other longitudes (same latitude) were also found for the lower mesosphere by PETZOLDT *et al.* (1987). It is not believed that the atmosphere had in fact an over-adiabatic temperature gradient for several days (Fig. 14). This should be considered an artifact of the model. The model demonstrates, however, that superposition of long term atmospheric waves can produce unstable situations which are favourable for the development of turbulence and which last for quite a while. It is an interesting question whether such wave–wave interaction can lead to a breaking of these long period oscillations. Very steep temperature gradients were also found and respective conclusions drawn by HAUCHECORNE and CHANIN (1983).

2. *Monthly mean temperatures*

The harmonic analysis presented here for the MAP/WINE Campaign contains periods of considerable length ($\tau_1 = 144$ days, $\tau_2 = 54$ days). This indicates that the respective data set which covers a time interval of three months may contain part of a seasonal variation. Seasonal variations of atmospheric temperatures are extensively modeled in terms of monthly means by Standard Atmospheres or Reference Atmospheres. It is therefore worthwhile to compare such reference profiles to monthly means obtained from our data set. For such a comparison monthly mean profiles can be calculated from the unfiltered 'raw' data. They extend to somewhat lower altitudes than the harmonic model presented here. Respective comparisons with CIRA (1972) (Part 2) and the reference atmospheres of COLE and KANTOR (1978) were performed by OFFERMANN *et al.* (1986) for the months November–February and the latitudes in question. Considerable and systematic discrepancies between the reference atmospheres and the present data were found. A much better agreement is obtained if the comparison is made with the reference atmospheres of BARNETT and CORNEY (1985) and GROVES (1985). These were prepared as inputs for the new CIRA and contain not only latitudinal, but also longitudinal temperature variations. The remaining deviations of our measured data from these new reference atmospheres are, on average, much smaller than from any of the other two discussed. Thus, on the basis of our data the new CIRA temperatures must be considered a real improvement in the middle atmosphere.

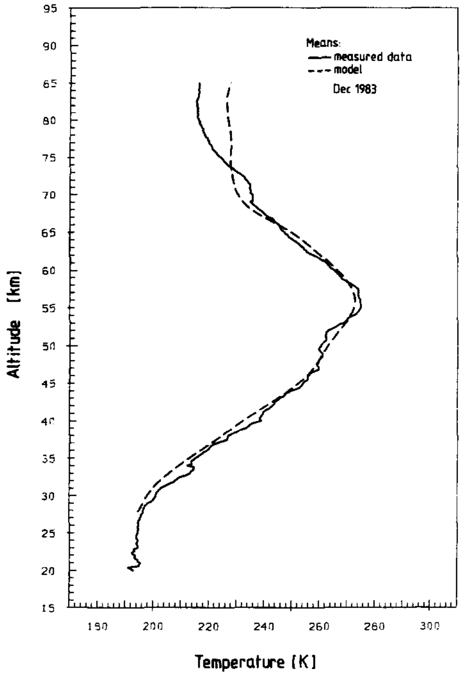


Fig. 15. Comparison of the means of measured 'raw' data and modeled temperatures for December 1983.

In the following analysis we shall restrict ourselves to these latter two reference atmospheres and compare them to the harmonic model developed for the MAP/WINE time period (December–February). For this purpose a mean is taken over the five oscillations discussed above during the months of December 1983, January 1984 and February 1984, respectively. The mean model profile for December 1983 is compared to the respective mean profile obtained from the unfiltered 'raw' data in Fig. 15. It is seen that the model curve is a good representation of the 'raw' data, except for the highest altitudes. A similar result is obtained for January 1984 and February 1984 (not shown here). This demonstrates the quality of the model developed.

A comparison of the monthly means of the modeled rocket data to the two reference atmospheres is shown in Fig. 16a–c. The agreement is very satisfactory for December 1983 and January 1984, especially in the stratosphere. In the mesosphere there are some devi-

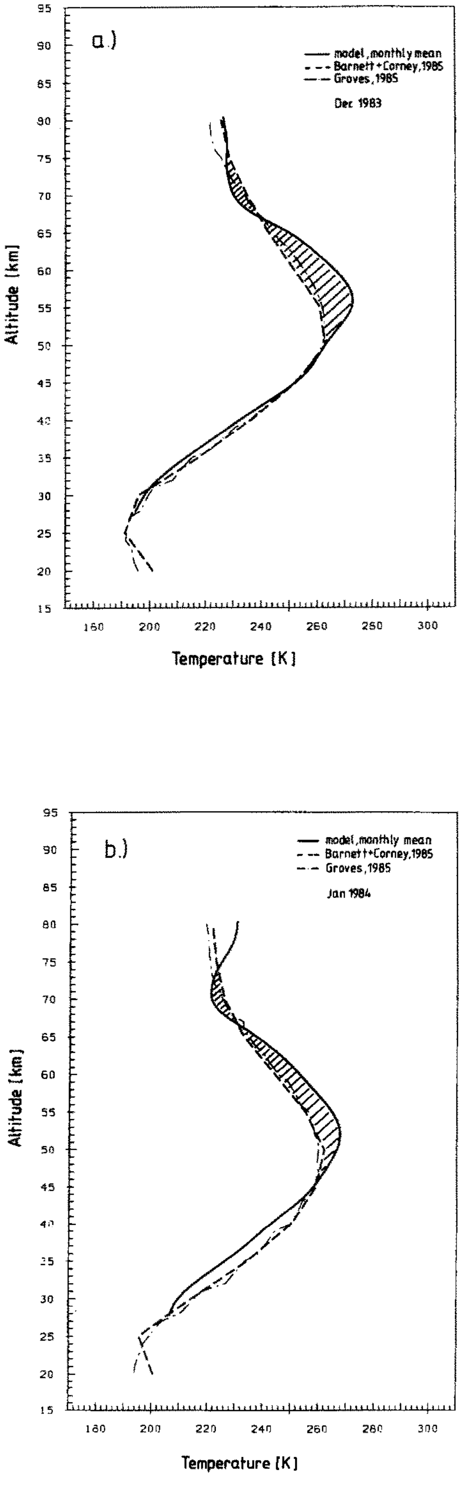


Fig. 16. Comparison of mean modeled temperatures to reference atmospheres during the MAP/WINE Campaign: (a) December 1983, (b) January 1984. (*Continued over.*)

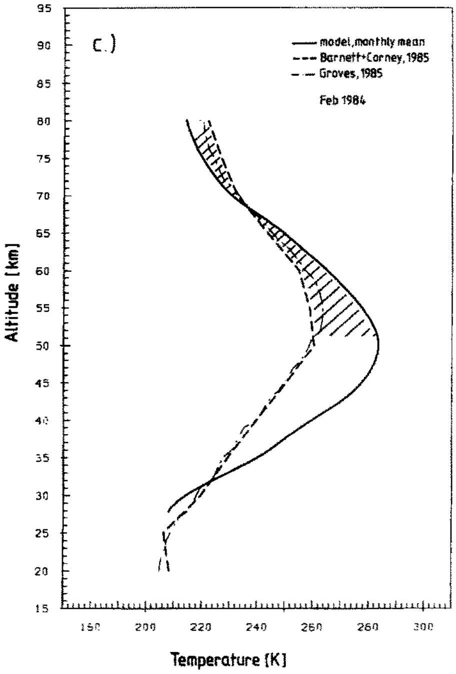


Figure 16 continued. (c) February 1984.

ations: the reference profiles tend to be higher in the upper mesosphere and lower in the lower mesosphere. This is also the case in February 1984. During this month the model profile is, however, not representative of a monthly mean, because the high stratopause temperatures show it to be strongly influenced by the built-up phase of the major warming which occurred in the fourth week of that month.

The good agreement between the rocket data and the new reference atmospheres obtained by OFFERMANN *et al.* (1986) and seen in Fig. 16 leads us to assume that the reference atmospheres represent the 'true' mean atmosphere. If this assumption holds, one has to understand the remaining deviations between the model means and the reference profiles in the mesosphere, which are indicated by the shaded areas in Fig. 16. It is important to note that these deviations are systematic and long term features which existed for more than two months. It should be stressed that they are not an artifact of our modeling procedure. Similar or even more pronounced deviations are found when comparing the means of the 'raw' data to the reference atmospheres (OFFERMANN *et al.*, 1986). A detailed check was made to see whether the deviations could be attributed to one specific oscillation out of our five model components, i.e. whether the omission of one component would bring the mean of the remaining ones into agreement with the reference

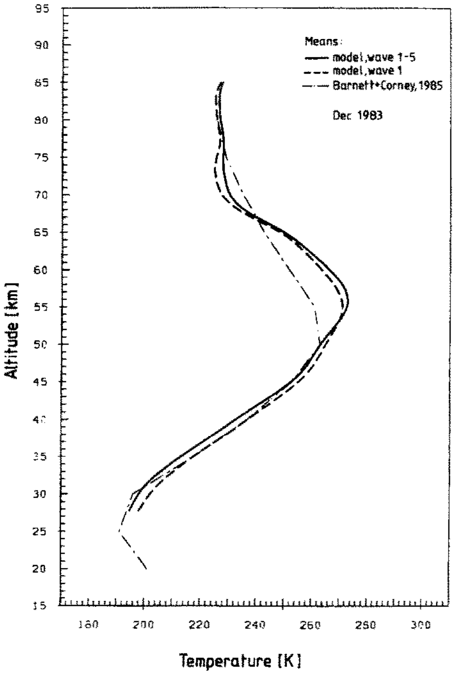


Fig. 17. Comparison of mean modeled temperatures obtained from the sum of all wave components τ_1–τ_5 and of the longest period $\tau_1 = 144$ days for December 1983. The reference atmosphere of BARNETT and CORNEY (1985) is also given.

atmospheres. The result was negative. During this analysis it was found, however, that the mean of the sum of all five model components was very similar to the monthly mean of the component with the longest period ($\tau_1 = 144$ days). This is shown in Fig. 17 for December 1983. The same result was obtained for January 1984 and February 1984 (not shown here). This finding supports the above conclusion that the deviations were long term features.

The deviations show temperatures too low in the upper mesosphere and too high in the lower mesosphere as compared to the reference profiles. Such a pattern is well known in the middle atmosphere, as it is typical of the build-up phase of a stratospheric warming. It is therefore not surprising to see this pattern prior to the major (final) warming during February 1984. It is, however, very interesting to see the same structure already in January 1984 and even in December 1983. It appears as if the major warming had precursors that were visible more than two months before the event itself took place. This result must be compared to the large scale dynamical analysis performed by PETZOLDT *et al.* (1987) for the MAP/WINE Campaign. Zonal wind data taken in the mesosphere at high latitudes and presented by these authors show considerable weakening long before the major warming and its associated flow reversal occurred. It has been suggested in the literature that a preconditioning process in the atmosphere is needed before a stratospheric major warming can occur (see, for instance, MCINTYRE, 1982; MCINTYRE and PALMER, 1983). In this context it is important that there were six major pulses of eddy heat flux at 30 hPa (40–70°N) during the MAP/WINE Campaign, which were observed between early December 1983 and the end of February 1984 at fairly regular time intervals (LABITZKE *et al.*, 1987).

CONCLUSIONS

Middle atmosphere temperatures measured during the Energy Budget Campaign (Nov./Dec. 1980) and during the MAP/WINE Campaign (Dec. 1983–Feb. 1984) showed wave-like oscillations if fixed altitude levels were considered. It was possible to model these oscillations with a reasonable degree of accuracy by superposition of a suitable number of harmonic functions. Optimum model oscillation periods were 24 days and 8 days in the case of the Energy Budget Campaign. The time interval covered by rocket measurements was three times as long during the MAP/WINE Campaign. A larger number of model periods was therefore used and optimum values were found to be 144 days, 54 days, 17.4 days, 13.3 days and 9.6 days. It is quite possible that even shorter periods were present in the atmosphere. It is, however, doubtful whether these would have been properly handled by our procedures. From these two harmonic analyses a number of results were obtained.

(1) The oscillation periods derived from the rocket data are in good agreement with those from OH* temperatures measured in the uppermost mesosphere during either campaign. An FFT analysis of SSU radiance data in the upper stratosphere (1.7 hPa) is also in line with the MAP/WINE results. Our MAP/WINE periods are also in general agreement with those obtained by HAUCHECORNE *et al.* (1987) from a Fourier transform calculation. They are similar to those for planetary waves.

(2) Several minor stratospheric warmings and one major (final) warming occurred during the time intervals discussed. The models reproduce these features reasonably well. They furthermore fit the corresponding mesospheric coolings and show the detailed phase shift with height for the various wave components.

(3) Amplitudes and phases of the oscillations exhi-

bit a very peculiar structure: there are 'quiet layers' in the middle mesosphere (and sometimes in the upper stratosphere) where the wave amplitudes become very small and their phases change strongly with height. A large part of the well known anticorrelation of stratospheric and mesospheric temperatures appears to occur in these narrow layers. Such a behaviour is found during both campaigns and is shown by six waves out of seven analysed. It is therefore believed that these 'quiet layers' are real atmospheric phenomena, which may indicate standing waves. This is an interesting result, as wave trapping, reflection and resonance have been theoretically treated in the context of stratospheric warmings by several authors.

(4) The harmonic model developed for the MAP/WINE Campaign (Fig. 14) shows very steep temperature gradients in the lower mesosphere on several occasions. In the beginning of January 1984 these gradients are even super-adiabatic for several days. Since it is unlikely that the atmosphere can be in such a state for an extended period, this must be an artifact of the model. It demonstrates, however, that superposition of long period waves can cause an unstable situation for quite a while, during which the development of turbulence would be supported.

(5) As a consequence of gravity waves, etc., a double (split) stratopause is occasionally observed for a short while. The present harmonic models for the Energy Budget Campaign, as well as for the MAP/WINE Campaign, exhibit such a split stratopause for several days.

(6) Monthly mean temperatures as modeled from the rocket data of the MAP/WINE Campaign have been compared to recently developed reference atmospheres prepared for the new CIRA (BARNETT and CORNEY, 1985; GROVES, 1985). Good agreement is found for December 1983 and January 1984. This is an independent check, as rocket data from the two Scandinavian campaigns were not used for the construction of the new reference atmospheres. Considerable differences are, however, found in February 1984. This is because of the major stratospheric warming which occurred in the last week of that month. Detailed analysis of dynamical, as well as temperature, data appears to indicate that this major warming was preceded by atmospheric preconditioning during January 1984 and even during December 1983.

Theoretical analyses of major stratospheric warmings mostly assume sudden and resonant increases of planetary waves 1 and 2 to be the origin of the event (e.g. MCINTYRE, 1982). If this is the basic reason for a *major* warming, our model analysis will not really apply to the February 1984 major (final) event. This is because our procedure uses fixed amplitudes (at a given altitude) for the five oscillations during the whole time interval covered (MAP/WINE Campaign). It thus simulates the final temperature increase by suitable adjustment of the oscillation phases, rather than by amplitude variations. It was mentioned above that our analysis has its emphasis on the *minor* stratospheric warmings. Furthermore, the fit was found to be quite satisfactory and it is therefore also a useful interpretation of the data for the major warming. This may be related to the fact that the amplitude maxima of wave number 1 during the minor warmings in winter 1983/1984 were not much different from those during the major warming (LABITZKE *et al.*, 1987). In summary, it is therefore concluded that the basic results of our analysis are valid and would remain essentially unchanged if a more sophisticated analysis were to be performed.

Acknowledgement—The rocket and ground-based experiments were supported by: Bundesministerium für Forschung und Technologie (BMFT), Bonn, through DFVLR/BPT, Köln; Deutsche Forschungsgemeinschaft (DFG), Bonn; U.S. Air Force Geophysics Laboratory (AFSC), Bedford; National Aeronautics and Space Administration (NASA), Washington.

REFERENCES

BAKER D. J., STEED A. J., WARE G. A., OFFERMANN D., LANGE G. and LAUCHE H. 1985 *J. atmos. terr. Phys.* **47,** 133.

BARNETT J. J. and CORNEY M. 1985 *Handbook for MAP* **16,** 47 and 86.

CIRA 1972 *COSPAR International Reference Atmosphere.* Akademie-Verlag, Berlin, G.D.R.

COLE A. E. and KANTOR A. J. 1978 Technical Report, AFGL-TR-78-0051, Air Force Geophysics Laboratory, Hanscom AFB, MA 01731, U.S.A.

DANILOV A. D., TULINOV G. F., ANDREEVA L. A., CHASOVITIN JU. K., DUDOLADOV JU. P., FEIGIN V. M., IVANOVA I. N., KASHIRIN A. I., KLUEV O. F., KOKIN G. A., POKHUNKOV A. A., SHCHUKA T. I. and TULINOV V. F. 1983 *Adv. Space Res.* **2**(10), 63.

GERNDT R. 1986 Doctoral Thesis, Physics Department, University of Wuppertal, F.R.G.

Groves G. V. 1985 Technical Report, AFGL-TR-85-0129, Air Force Geophysics Laboratory, Hanscom AFB, MA 01731, U.S.A.

Hass H. and Meyer W. 1987 *J. atmos. terr. Phys.* **49,** 705.

Hauchecorne A., Blix T., Gerndt R., Kokin G. A., Meyer W. and Shefov M. N. 1987 *J. atmos. terr. Phys.* **49,** 649.

Hauchecorne A. and Chanin M. L. 1983 *J. geophys. Res.* **88,** 3843.

Houghton J. T. 1978 *Q. J. R. met. Soc.* **104,** 1.

Labitzke K. 1972 *J. atmos. Sci.* **29,** 756.

Labitzke K. and Barnett J. 1985 *J. atmos. terr. Phys.* **47,** 173.

Labitzke K. and Goretzki B. 1982 *Handbook for MAP* **5,** 1.

Labitzke K., Manson A. H., Muller H. G., Rapoport Z. and Williams E. R. 1987 *J. atmos. terr. Phys.* **49,** 639.

Lange G. 1982 Doctoral Thesis, Physics Department, University of Wuppertal, F.R.G.

McIntyre M. E. 1982 *J. met. Soc. Japan* **60,** 37.

McIntyre M. E. and Palmer T. N. 1983 *Nature* **305,** 593.

Meyer W., Gerndt R., Philbrick C. R. and Schmidlin F. J. 1985 *Proceedings of the 7th ESA Symposium on Rockets and Balloons*, p. 41. ESA SP-229, ESTeC, Noordwijk, Netherlands.

Offermann D. 1985 *J. atmos. terr. Phys.* **47,** 1.

Offermann D., Brückelmann H. G. K., Barnett J., Labitzke K., Torkar K. M. and Widdel H. U. 1982 *J. geophys. Res.* **87,** 8286.

Offermann D., Gerndt R., Lange G. and Trinks H. 1983 *Adv. Space Res.* **3,** 21.

Offermann D., Gerndt R. and Küchler R. 1986 *Adv. Space Res.* (*in press*).

Petzoldt K. 1985 *Proceedings of the 7th ESA Symposium on Rockets and Balloons*, p. 33. ESA SP-229, ESTeC, Noordwijk, Netherlands.

Plumb R. A. 1982 *J. atmos. Sci.* **38,** 2514.

Petzoldt K., Lenschow R., Hauchecorne A., Kokin G. A., Meyer W., O'Neill A., Schmidlin F. J. and Thomas R. 1987 *J. atmos. terr. Phys.* **49,** 621.

Philbrick C. R., Schmidlin F. J., Grossmann K. U., Lange G., Offermann D., Baker K. D., Krankowsky D. and von Zahn U. 1985 *J. atmos. terr. Phys.* **47,** 159.

Röttger J. and Meyer W. 1987 *J. atmos. terr. Phys.* **49,** 689.

Rüster R. and Klostermeyer J. 1987 *J. atmos. terr. Phys.* **49,** 743.

Schmidlin F. J., Carlson M., Rees D., Offermann D., Philbrick C. R. and Widdel H. U. 1985 *J. atmos. terr. Phys.* **47,** 183.

Tung K. K. and Lindzen R. S. 1979 *Mon. Weath. Rev.* **107,** 735.

Ulwick J. C., Baker K. D., Baker D. J., Steed A. J., Pendleton W. R. Jr, Grossmann K. U. and Brückelmann H. G. 1987 *J. atmos. terr. Phys.* **49,** 855.

von Zahn U. 1987 *J. atmos. terr. Phys.* **49,** 607.

Reference is also made to the following unpublished material:

Baker D. J. and Stair A. T. Jr 1986 XXVI COSPAR (Toulouse), STP Symposium, Paper STP 4–5.

Küchler R. 1987 Scientific Report, Physics Department, University of Wuppertal, F.R.G.