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MID-LATITUDE LIDAR OBSERVATIONS OF PLANETARY WAVES IN THE MIDDLE ATMOSPHERE DURING THE WINTER OF 1981-1982

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Abstract. A quasi-continuous survey of the stratospheric and mesospheric temperature was performed, between June 1981 and April 1982, using the lidar station of the Observatory of Haute-Provence (44°N, 6°E). During the period of easterly winds in the lower stratosphere (i.e., from June to September), the variability of the temperature is observed to be very low. As long as prevailing winds are westerlies, from October to March, temperature profiles are continuously perturbed by planetary waves, with a maximum of amplitude in January 1982, before the 'strong minor warning' of the winter. Spectral analysis of the data indicates the presence of a well-defined 18-day wave interpreted as a free Rossby wave and the existence of large perturbations with periods of 25 to 40 days which are tentatively explained as a succession of minor upper stratospheric warmings due to the interference of the 18 day traveling Rossby wave and a stationary wave.

Introduction

Ground-based lidar measurements of stratospheric and mesospheric density and temperature have been performed since 1978 at the Observatory of Haute-Provence (44°N, 6°E). The density is obtained above 30 km from the light of a pulsed laser beam backscattered by air molecules, and the temperature is deduced from the density measurements assuming that the atmosphere obeys the ideal gas law and is in hydrostatic equilibrium, which are standard assumptions [Hauchecorne and Chanin, 1980]. During the period of the two major warmings of the winters 1979-1980 and 1980-1981 [Labitzke, 1982], lidar profiles showed clearly a stratospheric warming and an associated mesospheric cooling. [Hauchecorne and Chanin, 1981, 1982]. This may be surprising, considering the relatively low latitude of the lidar station, but it should be noticed that because of its longitude the station is only 25° to 30° south of the average position of the center of the polar depression. During the winter of 1980-1981, a variation of the temperature profile with a period of about 20 days was observed and was attributed by the authors to the propagation of planetary waves. To study these planetary waves, a quasi-continuous survey of the nighttime temperature profile has been performed from June 1981 to April 1982. In this paper, the series of 82 profiles obtained during this period is used to study the local temperature variations and their interpretation in terms of planetary waves propagation.

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Experimental Results

The main characteristics of the lidar measurements reported here are, on the one hand, the fact that they are performed locally above the station (with a fixed zenith pointing) and, on the other hand, that they cover with a good height resolution and a very accurate altitude definition the range from 30 to 80 km, which is not not covered by radiosondes, and measured with a degraded resolution by satellites. Then the events that will be referred to will be obviously local, unless mentioned otherwise.

The temperature profiles have been integrated for each night during the whole period of measurements, that is, during 2 to 10 hours depending on weather conditions. The vertical resolution is 0.6 km on the rough data but has been degraded to 4.8 km to improve the temperature accuracy. Furthermore, this choice of temporal and spatial resolutions helps to remove short period fluctuations and short vertical wavelength structures induced by gravity waves [Chanin and Hauchecorne, 1981].

Seven temperature profiles obtained between September 1981 and April 1982 and representative of typical situations are presented in Figure 1. For each experimental profile are indicated the ±1 standard deviation and the Cira (1972) model for the appropriate month and latitude (44°N). The profile of September 13 (night of September 13-14) is typical of the summer period. It is very close to the Cira (1972) model and does not present any large perturbation. On November 22 the perturbation of the profile by planetary waves is clearly visible, with a cooling of about 10 K between 50 and 60 km and a secondary maximum of temperature at 74 km. The four profiles of January 1982 have been obtained during the more disturbed period of the winter, just before the 'strong minor warming' of the lower stratosphere occurring at the end of January [Naujokat et al., 1982]. A definite warming becomes noticeable near 50 km on January 2, then increases and moves downward to reach a maximum value of 30 K above the Cira model at 40 km on January 13. During the same period a strong mesospheric cooling descends from 70 to 58 km. A minimum value (45 K below the Cira) is observed at 62 km on January 6.

The perturbation of these three profiles is characterized by a vertical wavelength of about 40 km. This vertical structure is visible both on the density and on the temperature profiles as it is shown on Figure 2 for January 2, 1982. Such vertical wavelengths of about 40-50 km, have already been observed in the winter of 1975-1976 [Offermann et al., 1979] and of 1980-1981 [Hauchecorne and Chanin, 1982]; they seem to be a general feature of the disturbed winter profiles. Owing to these structures the vertical temperature gradient may reach a mean value of -7 K km^{-1} from 50 to 60 km when the upper strato-

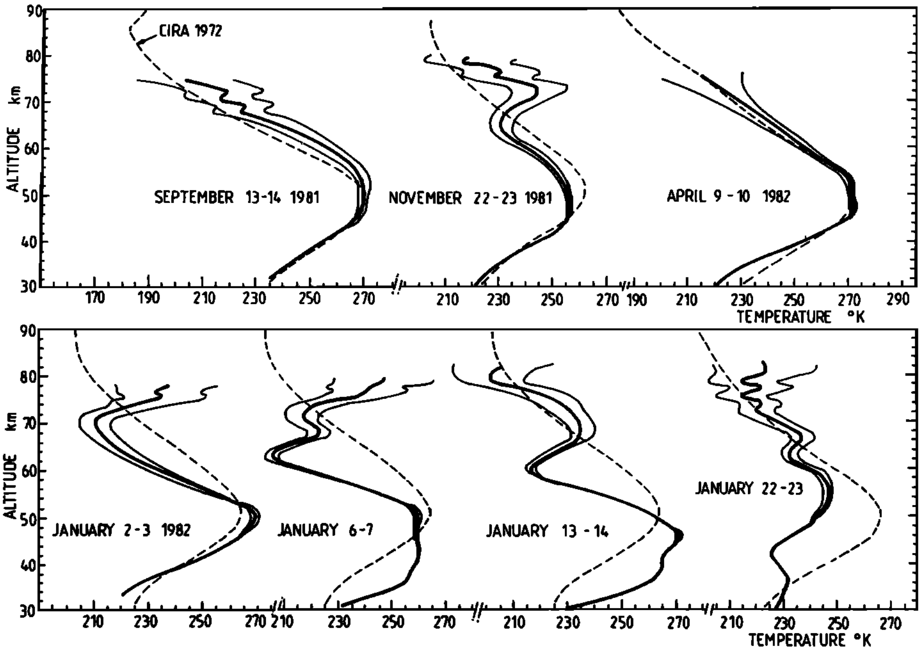

Fig. 1. Series of 7 Lidar temperature profiles obtained from September 1981 to April 1982. The dotted line represents the Cira (1972) model for the corresponding month and latitude. The standard deviation ($\pm\sigma$) is indicated.

sphere is warm and the mesosphere cold. Then, if gravity waves are present, the temperature gradient may be locally amplified up to the adiabatic gradient of -9.8 K km^{-1}, and unstable layers with subsequent turbulent dissipation may then appear in the lower mesosphere.

On January 22 the warming has moved down into the lower stratosphere and is not visible on the lidar data but appears at the end of January on the radiosonde data both locally and globally, as we will see later. The temperature profile is near isothermal from 30 to 80 km with a very cold stratopause about 20 K colder than its mean value. The profile of April 9, 1982, shows the return to a summer quiet situation without any perturbation induced by planetary waves but with a stratosphere colder than indicated by the Cira model.

The complete series of temperature profiles obtained from June 1981 to April 1982 has been used to study the temporal variation of the stratospheric and mesospheric temperature during these 10 months. The quality and the density of data is not homogenous during that period. To obtain a continuous determination of the temperature and to eliminate possible fluctuations due to the variations in the data accuracy, the temperature at each height level has been approximated and interpolated by use of spline functions with a mean least square criterion proportional to the standard error of each of the temperature measurements. Temperature profiles have been extended below 30 km, using the radiosonde data of the two nearby stations of Nîmes (44°N, 4°E) and Lyon (46°N, 5°E).

The time-height section of the temperature from 20 to 70 km is represented on Figure 3 together with the mean zonal wind from 0 to 30 km obtained from the data of the same two radiosonde stations. During summertime, from June to September 1981,the temperature isopleths are nearly horizontal, corresponding to very little time variation in the temperature profiles. During that period, easterly winds are present in the lower stratosphere, a situation that prevents the propagation of planetary waves into the stratosphere [Charney and Drazin, 1961]. At the beginning of October the change over from easterly to westerly winds occurs in the lower stratosphere. The planetary waves may then propagate into the middle atmosphere, and a succession of large perturbations in the temperature profiles appears in the upper stratosphere and in the mesosphere. The maximum amplitude of these perturbations is observed in January after a period of strong westerly winds and just before the 'strong minor warming' of this winter. In February and March the zonal wind is locally easterly or moderately westerly and the amplitude of the perturbations decreases. A

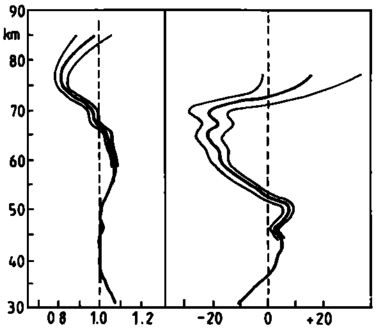

Fig. 2. Density and temperature profiles for the night of January 2-3, 1982, compared with the Cira (1972) model. The standard deviation is indicated.

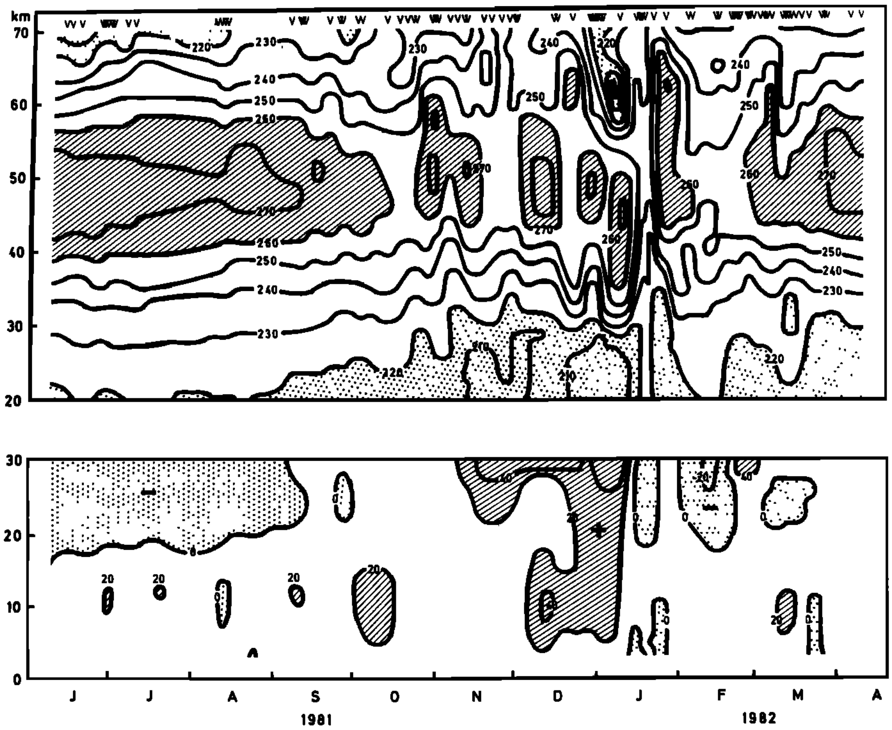

Fig. 3. (Top): Time height section of Lidar and radiosonde temperature (K). The contour lines are plotted in steps of 10 K. The arrows above indicate the days when Lidar data were recorded. Shaded areas correspond to temperatures above 260 K, dotted areas to temperatures below 220 K. (Bottom): time height section of the radiosonde zonal wind (m s^{-1}) Westerly winds are >0 and represented by the shaded area; easterly winds are <0 and represented by dotted area. Contour lines are plotted by steps of 20 m s^{-1}.

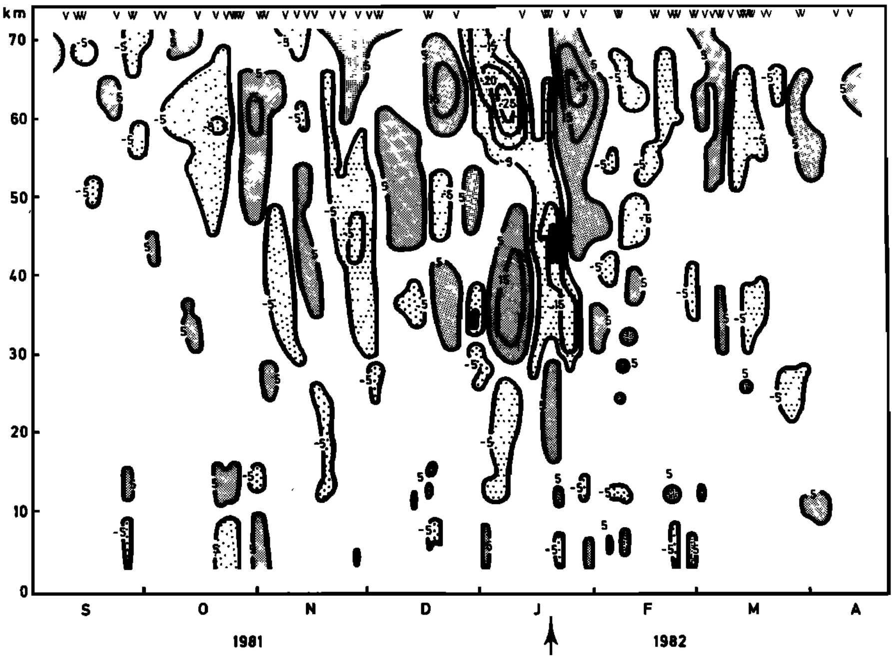

Fig. 4. Time-height section of the temperature deviation from a 45 days running average. Contour lines are plotted in steps of 10 K. Gray areas correspond to a warming. Dotted areas represent a cooling from the average value. The large arrow indicates the time of the strong minor warming.

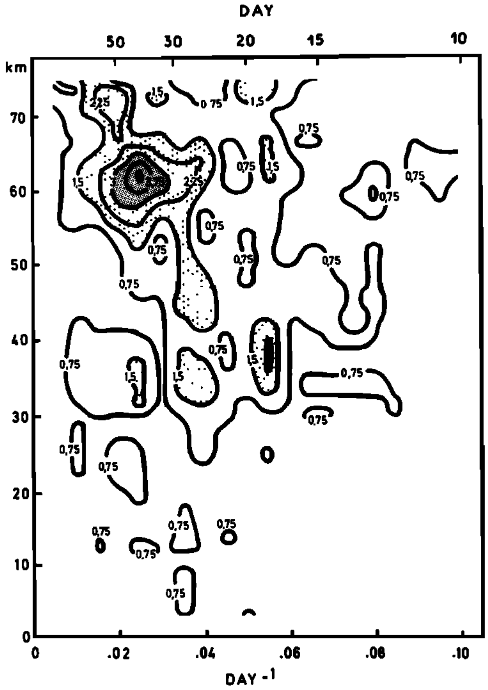

Fig. 5. Frequency-height section of the amplitude of the temperature oscillations (in K/0.005 day $^{-1}$) during the period from September 13, 1981, to March 31, 1982. Contour lines are plotted in steps of 0.75K/(0.005 day $^{-1}$).

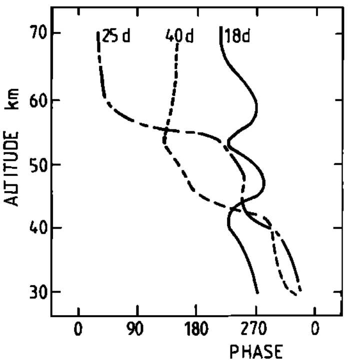

Fig. 6. Phase ϕ of the temperature oscillation T(f,t) as a function of height, defined as $T(f,t) = T_0(f)\cos[2\pi f(t-t_0)-\phi]$ for the three frequencies f = 0.025 day^{-1} (period 40 days), f = 0.040 day^{-1} (25 days) and f = 0.055 day^{-1} (period 18 days). The origin of time t_0 is set on September 12, 1981. A negative slope indicates a downward propagation of the phase. The period of analysis is the same as in Fig.5.

return to the quiet summer situation is observed at the beginning of April.

Data analysis

Time analysis of the experimentally observed temperature disturbances has been performed by two complementary analysis. The same type of treatment has also been applied to the pressure values deduced from the density profiles:

1. Temperature : To study the characteristics of the temperature perturbation, the difference between the daily temperature and the mean temperature has been considered. This mean temperature is obtained by applying to the data obtained for each night of observation a running average with a triangular filter of 45 days half width. These temperature deviations from the mean value are presented in Figure 4 for the period of September 1981 to April 1982. From this representation it appears that a regular succession of coolings and warmings is observed in both the stratosphere and the mesosphere. Furthermore, each warming is associated with a cooling occurring about 20 km above or below. This corresponds to the 40 km vertical wavelength already mentioned. Such vertical structures are responsible for the anticorrelation observed in the temperature variation between the upper stratosphere and the lower mesosphere. The periodic variation of these structures does not appear to be due to the propagation of a single planetary wave.

A spectral Fourier analysis of the temperature data has been performed on the data from September 13 to March 31 to study possible periodicities. Figure 5 presents the frequency-height section of the amplitude of the temperature oscillations. In the stratosphere, three main periods are observed: 18 days, 25 to 29 days, and 40 days (herein 18D, 25D, and 40D respectively), with a maximum amplitude near 35-40 km for these three periods. It should be noticed that the stratopause level corresponds to a minimum of amplitude of the temperature variations. In the mesosphere, near 60-65 km, the 18D is still present, but the two longer periods have merged to produce a broad maximum. The maximum amplitudes occur for the 18D in the stratosphere and for the 25 to 40 day periods in the mesosphere. The phase of the 18D, as defined in Figure 6, is nearly constant with altitude, while The phase change of the 25D and 40D indicates a

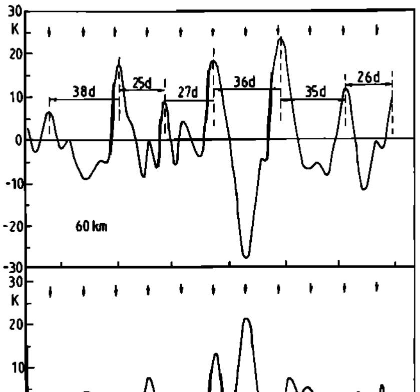

Fig. 7. Deviation from the mean temperature measured at 35 and 60 km. The arrows indicate the dates of the maximum of the 18D wave computed from the phase shown in Figure 6.

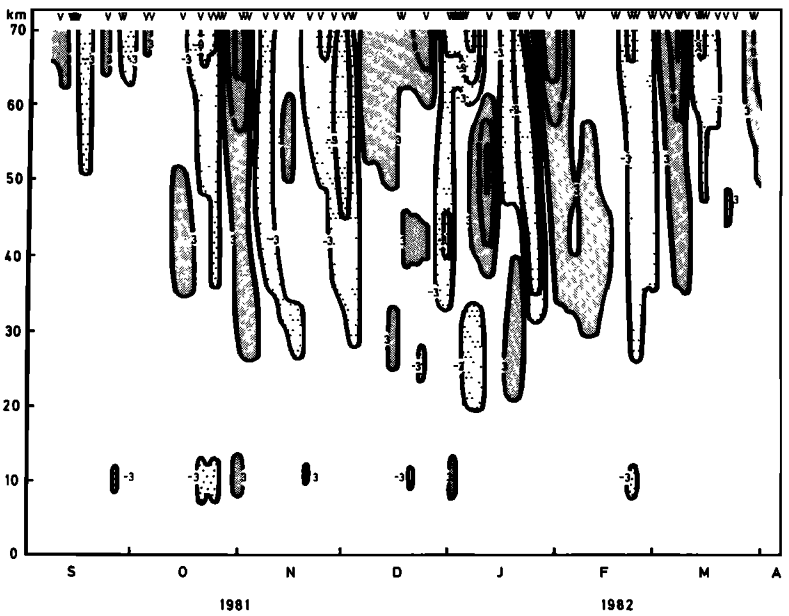

Fig. 8. As in Figure 4 except for the relative difference in percent between the measured pressure and a 45-day running averaged pressure. Contour lines are plotted in steps of 6%.

downward propagation. The 18D is probably the same as the 16-day traveling wave observed by Madden and Labitzke [1981] and attributed by them to the H_4^1 Hough mode of a free Rossby wave. As expected from theoretical considerations, its phase is observed to be constant with height. This 18D wave is present in the stratosphere during the whole 6 month period from September 1981 to April 1982. At 35 km (Figure 7) it is possible to observe each maximum of that wave, except at the end of January, while the strongest warming of the winter is going on. At 60 km, the 18D wave is observed most of the time. On the other hand, the two longer periods are not observed simultaneously, as it can be seen near 60 km where they dominate the temperature variations. The seven successive maxima of temperature occurring from September 25 to March 31 are separated by 38, 25, 27, 36, 35, and 26 days, respectively. Three of these periods are near 25-27 days, and the three others near 35-40 days. The succession of these two periods broadens the temporal spectrum and explains the merging of the 25D and 40D in the mesosphere.

2. Pressure. From the radiosonde profiles that extend up to 30 km and from the lidar density profiles from 30 to 70 km, it is possible to trace the pressure behavior up to 70 km. The deviation of the average daily pressure from the 45 days running average pressure has been evaluated for the period under study (Figure 8). The regular succession of low and high pressures appears clearly above 25 km with a dominant 18D period and a quasi vertical structure. These features are explained by the fact that the phase of the 18D temperature wave is constant with altitude, giving a cumulative effect of the temperature perturbations on the pressure perturbations at all levels. On the other hand, the 25D and 40D temperature oscillations are out of phase in the upper stratosphere and lower mesosphere so their contributions to the pressure perturbations are, if not canceled, at least decreased. Thus, the quasi vertical structure observed in the pressure perturbations is easily understood.

A spectral Fourier analysis of the pressure variation confirms the prevailing role of the 18D

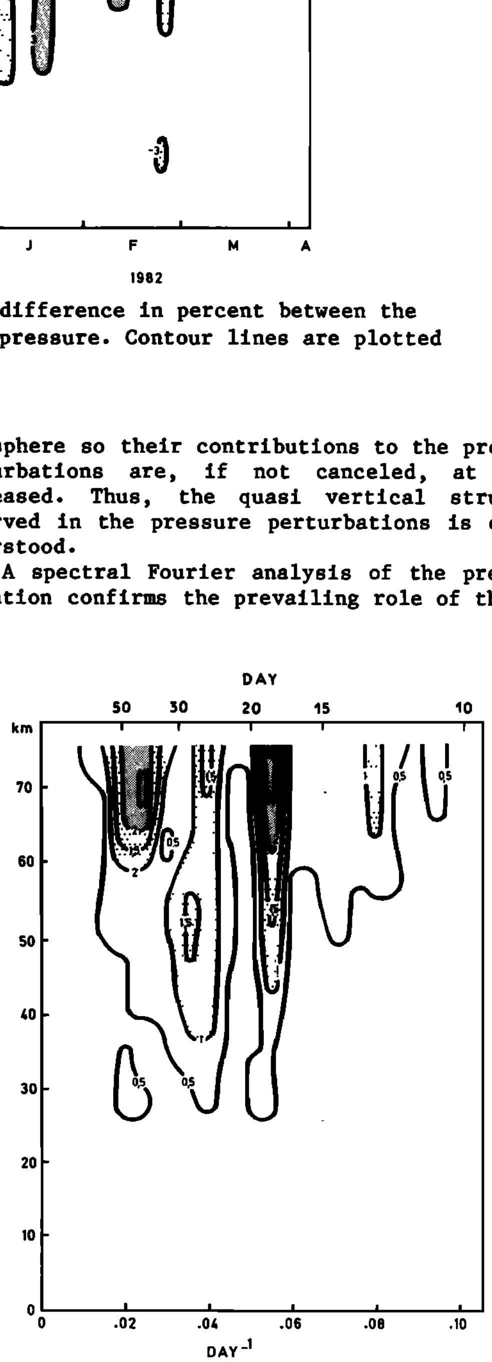

Fig. 9. As in Figure 5 except for the amplitude of the pressure oscillation (in percent /0.005 day^{-1}). Contour lines are plotted in steps of 0.5 % /0.005 day^{-1}.

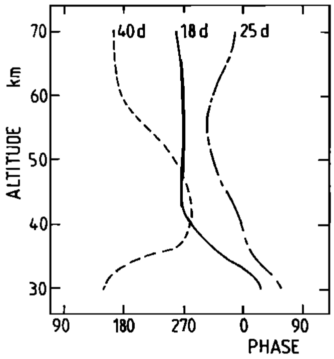

Fig. 10. As in Figure 6 except for the pressure oscillations.

wave as shown in Figure 9. Its period is very well defined (±1 day), and its amplitude reaches quite high values in the mesosphere (3% at 70 km for the average value over 6 months). The two other larger periods are still present around 25 and 40 days, but with a broader spectrum and a smaller amplitude. The 25D wave appears to be present at all levels above 25 km, while the 40D wave is only present above 55 km but with a slightly larger amplitude. The phase of the 18D is constant above 40 km, while its amplitude is increasing, but it decreases slightly with altitude between 30 and 40 km. The phases of the 25D and 40D are decreasing with height between 40 and 60 km, which indicates a downward propagation as for the temperature perturbations. The phase change of the 40D below 40 km should not be considered as real, the period not being well defined in this altitude range.

Concluding Remarks

Lidar observations of stratospheric and mesospheric temperature has allowed us to perform a local and continuous survey of the atmosphere in the altitude range 30-80 km during the winter of 1981-1982. Such a study performed with a height resolution not available from satellite data has shown detailed structure in the temperature profiles under the influence of planetary waves during the period from October to March when such waves can propagate. On the other hand, during the period of easterly winds, from June to September, the propagation of planetary waves is blocked and then the temperature is observed to be very stable.

The main features observed during the winter are the anticorrelation of the mesospheric and upper stratospheric temperature perturbations (indicating a vertical wavelength of 40 km in the temperature profiles) and the succession at constant level of warmings and coolings reaching a large amplitude in January. A spectral analysis of the observed perturbations has shown the presence of three main periods. The 18D wave with a phase constant with height is attributed to the H_4^1 mode of a free Rossby wave. This represents the first observation of the 18D Rossby wave in this altitude range and suggests the permanent presence of this wave during the winter period. The two longer periods of about 25 and 40 days are not observed simultaneously, which may indicate the existence of a single variable period. Owing to the large amplitudes associated with these long periods in the mesosphere and to their phase change between the mesosphere and the stratosphere, six main sequences, presenting locally the characteristics of minor warmings, are observed during the winter.

With the usual definition of a 'major warming' [Labitzke, 1982] this specific winter (1981-1982) presented only one 'strong minor warming' at the end of January. As seen by the Lidar, locally at 44°N, 6°E, six warmings are observed and among them is one of major importance in January. Its temporal relationship with the 'strong minor warming' observed a few days later on a global basis does not appear fortuitous. The existing models are able to explain the vertical structure and the downward propagation of each of the individual warming, whether they are minor or major, by taking into account the interaction between a stationnary wave and the zonal wind [Matsuno, 1971]. To explain the repetitive perturbations in the lower atmosphere (or the so-called vacillations in a zonally averaged flow), Lindzen et al. [1982] developed a theory involving the interference of a stationary wave with a Rossby wave. The recurrent variations reported in this article might also be explained with such an interference, but no model existing today has led to their prediction.

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