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LONG-TERM VARIATION OF THE TEMPERATURE OF THE MIDDLE ATMOSPHERE AT MID-LATITUDE: DYNAMICAL AND RADIATIVE CAUSES

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Abstract. Temperature of the middle atmosphere has been measured since 1979 at the Observatory of Haute-Provence (France, 44°N, 6°E) using the Rayleigh lidar technique. More than 500 temperature profiles in the height range 35-75 km have been used in that study. The main results are the following: temperature trends of opposite sign have been observed in the mesosphere (-20°K at 65 km) and in the stratosphere (+20°K at 40 km) between 1981 and 1985; but while the trend in the stratosphere is only found in winter, the tendency in the mesosphere is observed all year around. These temperature changes exhibit a highly significant correlation with the solar flux (represented by the radio flux at 10.7 cm) in the mesosphere and an equally significant anticorrelation in the winter stratosphere. On the other hand, the temperature at the 50-km level does not present any long-term variation. These results are interpreted as due to a superposition of a direct response of the mesosphere to the increase of the UV flux and a second effect, mainly present in winter, which affects all height ranges. This effect may or not be related to the 11-year solar cycle, but its height dependence and its sign can only be interpreted by a change in the planetary wave activity.

Introduction

The attempt to detect any possible trend in the middle atmosphere structure and composition has induced a tremendous effort by both modelists and experimenters. In order to separate solar-induced variations (whether they are direct or indirect) from a possible anthropogenic effect in interpreting the observations, different models have attempted to evaluate the direct effect of solar UV variations on the composition, temperature, and dynamics of the stratosphere. The results of these models have been strongly dependent upon the assumed amplitude of the UV flux variability; the earlier ones, based in part on the estimates of Heath and Thekaekara [1977], had a tendency to overestimate the solar variability. Only the more recent models, which use a more realistic estimate of the UV flux variation, will be used for reference [Brasseur and Simon, 1981; Garcia et al., 1984]. The predicted influence of the 11-year cycle on the stratospheric temperature is then reduced to a few degrees at most around the stratopause.

Models taking into account the direct UV response of the atmosphere underestimate systematically the amplitude of the variations as they have been observed in stratospheric ozone [Keating et al., 1981] and temperature [Angell and Korshover, 1978; Quiroz, 1979]. Furthermore, the few observations of solar-related variations not only disagree with the models, but they are far from agreement with each other; they differ not only in the amplitude of the effect but also in its sign.

The altitude range concerned in this paper includes both the upper stratosphere and the mesosphere. This region has been traditionally studied by rocket techniques, from which most of the published data have been obtained. Satellite data in the stratosphere suffer from possible instrument drift and from a too short lifetime and have not been used for study of long-term variation.

In this study we present the results of a long-term temperature survey performed at middle latitude using a Rayleigh lidar; this technique provides absolute temperature profiles unaffected by any instrumental drift. We first summarize the results obtained on temperature trends before presenting the lidar data and their interpretation. We then show how this interpretation can explain most of the observations.

Brief Summary of Observed Temperature Trends and Their Relationship With 11-Year Solar Cycle

Most studies of long-term trends of the middle atmosphere temperature have been conducted having in mind a possible solar cycle relationship. To mention first the mesosphere, where the results are the least confusing, we refer to the more recent and more extensive study by Mohanakumar [1985]: the analysis concerns the height range 50-80 km and is based on rocket data from four stations ranging from 81°N to 69°S: Heyss Island (81°N, 58°E), Volgograd (49°N, 44°E), Thumba (8°N, 77°E), and Molodezhnaya (69°S, 46°E). A clear positive correlation is observed between the solar activity measured by the Zurich sunspot number Rz and the mesospheric temperature with a maximum amplitude of about 10°K around 65-70 km for all seasons. This result is in general agreement (independently of the number of the solar cycle) with the earlier results of Kokin et al. [1981] at 81°N, Von Cossart and Taubenheim [1987] at 49°N, and Devanarayanan and Mohanakumar [1985a] at 8°N. But surprisingly, the data collected by Devanarayanan and Mohanakumar [1985b] between 28°N and 34°N, during the preceding solar cycle, did not indicate any definite correlation in the height range 50-65 km.

In the stratosphere the situation is more complex. Until 1982 all of the authors, with the exception of Kokin et al. [1981], reported a positive response of the stratosphere to the solar activity [Schwentek, 1971; Zlotnik and

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Roswoda, 1976; Angell and Korshover, 1978, 1983; Quiroz, 1979; Schwentek and Elling, 1981]; the data were all concerned with solar cycle 19 and 20. The more extensive study, and the one more often mentioned, is that of Quiroz [1979] who used a large set of rocket data from seven sites. A first disagreement with these results came with the paper of Kokin et al. [1981], who found a negative response in winter at the altitude of 45 km above Heyss Island. Later, Schwentek and Elling [1984], analyzing the Berlin radiosonde data for the period 1970-1982 (cycle 20-21), did not confirm the results obtained for the period 1958-1971, and they put into doubt their own results published earlier. More recently, Devananayanan and Mohanakumar [1985a, b] found opposite results at 8°N and 28°-34N°. The confusion observed in the stratosphere from the data obtained by rockets was lately tentatively explained by the fact that a change occurred in 1970 in the corrections applied to the rocket data; as a consequence, Watson et al., [1986] recommended that those data should not be used to infer long-term variations.

In the lower stratosphere the radiosonde network has been largely used for detecting climatologic trends. A decrease of temperature of the order of 0.3° per decade around 20 km has been found on a global basis [Labitzke et al., 1986; Oehlert, 1986]. They attributed this cooling to the increase of CO_2, as it was apparently not related to any solar activity effect. More recently, radiosonde data have been studied to detect local changes which may be associated with the Antarctic ozone hole, and large changes of temperature have been found to occur locally [Newman and Schoeberl, 1986].

Description of the Data Set

The experimental data used for this study were obtained at the Observatory of Haute-Provence, France (44°N, 6°E) during the period 1979-1985, using the Rayleigh lidar technique. The measurement technique is based on the backscattering of a pulsed laser beam by atmospheric molecules; the temporal analysis of the echo by time-gating provides the vertical profile of the atmospheric density. The method is described in detail in several publications [Hauchecorne and Chanin, 1980; Chanin and Hauchecorne, 1984], and only relevant indications will be given here. The downward limit of the atmospheric density measurements is imposed by the aerosol upper limit, which is usually 30 km but was raised to 35 km during the El Chichón posteruption period. The upward limit is given by the sky background level and has been pushed up from 75 km in 1979 to 95 km since 1985. In order to use an homogeneous set of data, we chose to limit our study to the height range 35-75 km.

The temperature deduced from the density profile, using the hypothesis of a perfect gas in hydrostatic equilibrium, is given in absolute value. It does not require any calibration, and the data are free of any long-term intrument drift. The data are acquired with good time and vertical resolutions, which are superfluous when looking at long-term variation. Time integration for the whole period of measurement during the same night (~3 hours) and reduction of the height resolution to 3 km help to improve the accuracy and to get rid of most of the short-period gravity waves. Under these conditions the absolute accuracy is 1°K at 70 km since 1985; in the early phase of the measurements, the accuracy was always better than 1°K at 50 km and below.

The period covered by this paper extends from 1979 to 1985 and includes 519 temperature profiles. The temporal coverage depends upon meteorological conditions. In the recent years and more specifically since 1982, when the station started to be operated on a routine basis, an average of more than 100 nights of data is obtained each year.

Analysis of the Lidar Temperature Data

In order to separate clearly long-term from short-term variability, a study of the day-to-day variability was performed successively for each year of data. Unless the gap in the series of data was too large (>10 days), individual data were interpolated to provide a set of one profile per day. The variance was calculated at each level for each individual profile as the deviation from the 45-day running mean. The results were then smoothed with a Blackman window to suppress all variation with periods less than 20 days, which were mostly due to planetary waves. The yearly maps of variance were shown to have the same characteristics from year to year, therefore justifying the decision to compile several years to provide a mean seasonal variation of the variance. These data were already published up to 1984 as part of the lidar contribution to the new CIRA model by Chanin et al. [1985]. The more recent results for the period 1981-1985 are given in Figure 1. Because of intense planetary wave activity, the winter period corresponds to a much larger variance than the summer. One also notices a systematic difference between the equinoxes, the mesosphere in autumn being already disturbed with planetary wave activity. Furthermore, in the winter period a region of low variability exists around 50 km between two well-defined maxima situated around 70-65 and 35-40 km. Those maxima correspond to variation of opposite phase associated with the stratospheric warmings and mesospheric coolings. We will come back to that point later in the discussion. But this preliminary study suggests that, in order to look for a long-term trend, one should study separately the data for the different seasons, since, at first thought, the large day-to-day variability in winter could hide any trend. Thus the data were considered by group of 3 months each : December-January-February (DJF) for winter, March-April-May (MAM) for spring, June-July-August (JJA) for summer, and September-October-November (SON) for autumn. The reason for separating both equinoxes in the study was the asymmetry observed in the short-term variability.

To get rid of another possible source of short-term variability, which may come from the solar rotation, we average the data over a month; this method of averaging is more convenient to use for comparison between successive years than the 27-day average, and we checked to see that it did not affect the final results. The behavior of these monthly averaged temperature values as a function of time is presented in Figure 2, from 40 to 65 km, with a step of 5 km. A running

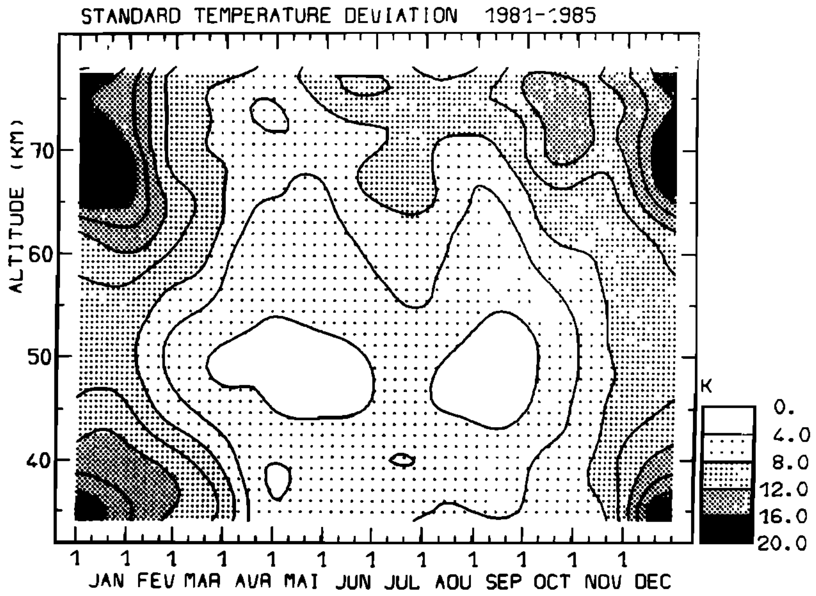

Fig. 1. Contour maps of the standard deviation observed in the day-to-day temperature variability for the years 1981 to 1985.

average over 1 year has been calculated and is superimposed on each graph in order to smooth out the seasonal variation. The monthly mean solar flux at 10.7 cm has been plotted for comparison on Figure 2, as it will be of use in the discussion.

Without further analysis several features can be readily seen. Two well-defined trends are visible above and below 50 km, starting around the end of 1981: an increase of 20°K at 40 km and a decrease of the same magnitude at 65 km. Independently of the sign, the magnitudes of the observed changes are much larger than predicted by models (~1°K). On the other hand, the smoothed temperature is observed to be quite stable at 50 km.

As indicated earlier, the study is performed separately for each season; furthermore, in order to take into account the seasonal variation of the temperature, the quantity which is considered is the deviation of each monthly averaged value from the corresponding monthly mean. This quantity is plotted as a function of time successively for the different altitudes from 35 to 75 km, with a step of 5 km, and for each season; Figures 3 and 4 show representative examples of the different behaviors observed at 40, 50, and 65 km for winter and summer conditions. These altitudes are selected because they correspond to either a maximum or a minimum of variability. The opposite trends in the mesospheric and stratospheric temperatures are very well observed in winter; Figure 3 shows clearly that the changes at both levels only start after the winter of 1981-1982. The absence of variability at 50 km is confirmed. The situation during the summer (Figure 4) is slightly different at 65 km, even though the decrease of temperature is almost as large as in winter, but the drop in temperature is already visible in 1981. The trends observed at 40 km and 50 km in summer are below the significant level.

The linear regression coefficient (Rc) has been calculated and its value in degrees per month is given on each plot of Figures 3 and 4. From this coefficient one can evaluate the magnitude of the temperature change over the 6-year period as a function of altitude and season. Those results are presented in Figure 5, which summarizes the height distribution and the seasonal variation of the observed trends. Several features should be pointed out: in the mesosphere, the summer, autumn, and winter effects are of about the same amplitude, while the amplitude for spring is much smaller. Furthermore, the effects for both winter and autumn are more sharply peaked (at 65 km) than for summer and spring, for which the maximum extends up to 70 km. In the stratosphere the only period for which the effect is of the same order of magnitude as in the mesosphere is the winter, with a maximum sharply peaked at 37 km; the effect in autumn is weaker, while in summer and spring it is barely significant.

The observed opposite variations in the stratosphere and mesosphere could induce a change in the height of the stratopause. We plotted in Figure 6 the average height of the stratopause calculated by fitting the temperature profiles with a parabolic shape. Even though the scattering of the data is quite large, mainly for the first period 1979-1982, it clearly shows that the altitude of the winter stratopause has been going down during the period 1979-1985.

Relationship With Solar Cycle

The fact that the changes observed in the temperature took place mostly after the start of the decreasing phase of the solar flux cannot be ignored (cf. Figure 2). Even though the data set is far too short to establish a solar-induced relationship, we investigate further a speculative possibility: Figure 2 seems to indicate that locally the atmosphere is responding positively to solar activity in the mesosphere and negatively in the stratosphere.

The best parameter to characterize the solar

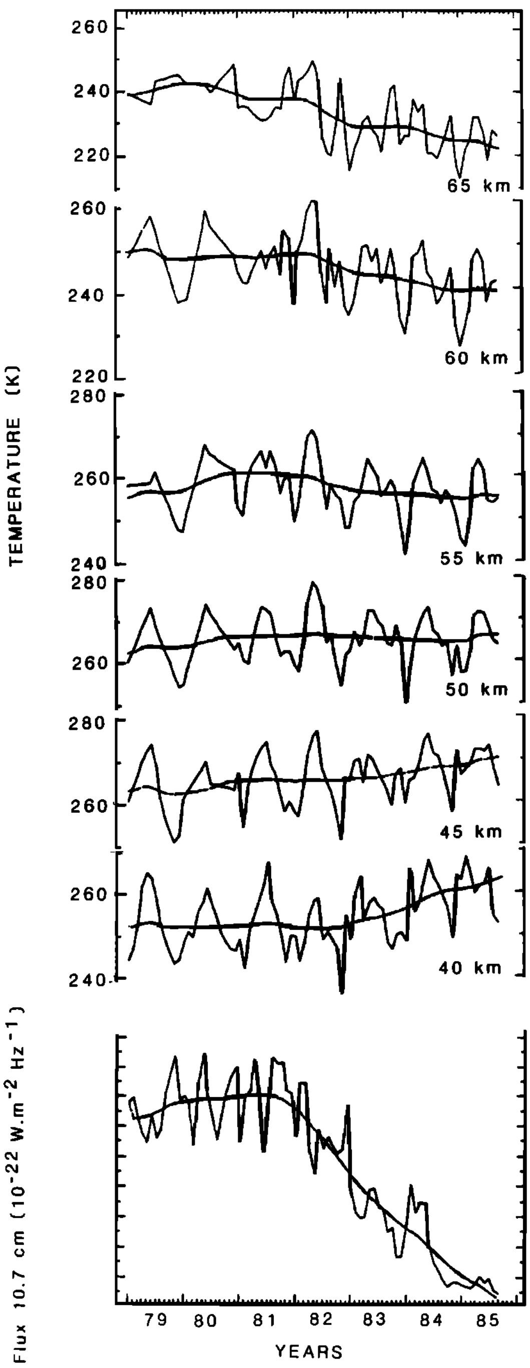

Fig. 2. Monthly mean of the temperature measured by lidar between 40 and 65 km and monthly mean of the 10.7 cm solar flux during the period 1979-1985. A running mean over a year is superimposed on each set of data.

activity which may influence the middle atmosphere behavior would be the UV flux around 200 nm. At the time when this study was performed, no such data set was available for the whole period of 1979 to 1985: the SME data started to be available in October 1981. The Solar Backscattered Ultraviolet (SBUV) data were only available until 1983 (D.F. Heath, private communication, 1986) and the index based on the Ca plage was only calculated for 1 year-data. There was no question of limiting our period of observation, which was already quite short; therefore we decided to use the 10.7-cm radio flux, which has been shown to be reasonably well correlated with the solar UV flux, when looking for long-term variation [London et al., 1984].

The correlation coefficients have been calculated for the four seasons and are presented in Figure 7. The 95% confidence limit and the 99%

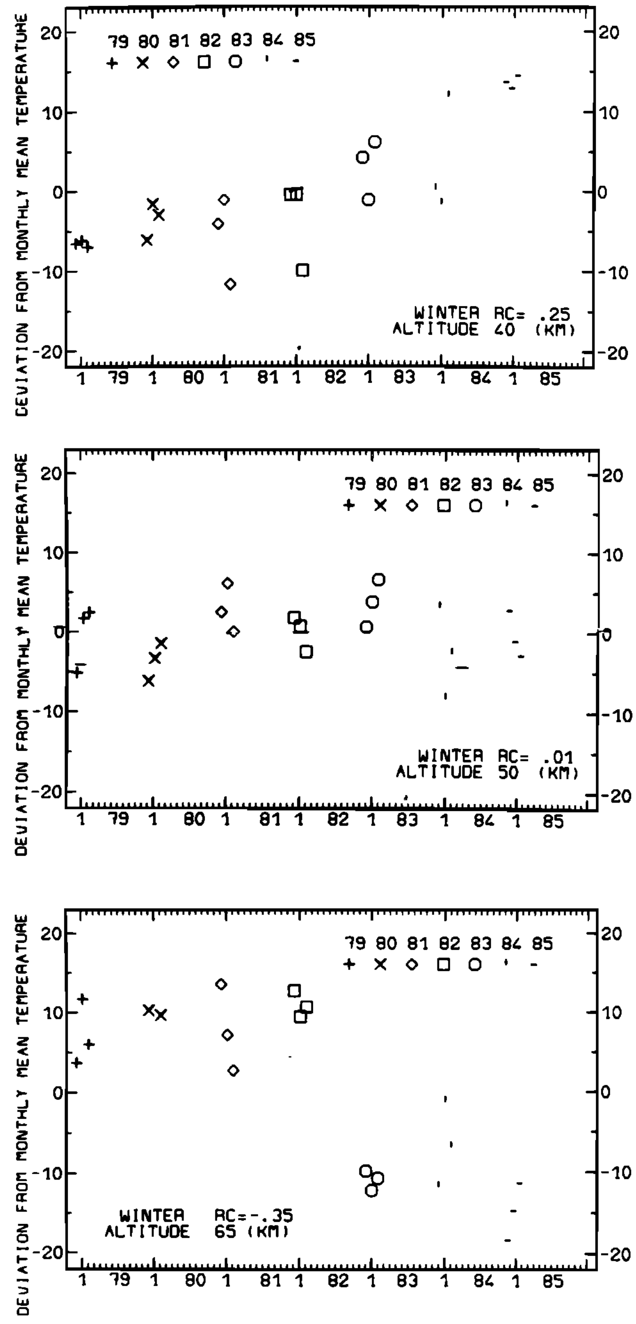

Fig. 3. Temperature deviation from the monthly average of the individual monthly mean values for the period 1979-1985, as a function of time. The individual points are given for the three winter months (DJF) of each year at three different altitude levels 40, 50, and 65 km. The value of the regression coefficient R_c is given in degrees per month for each altitude.

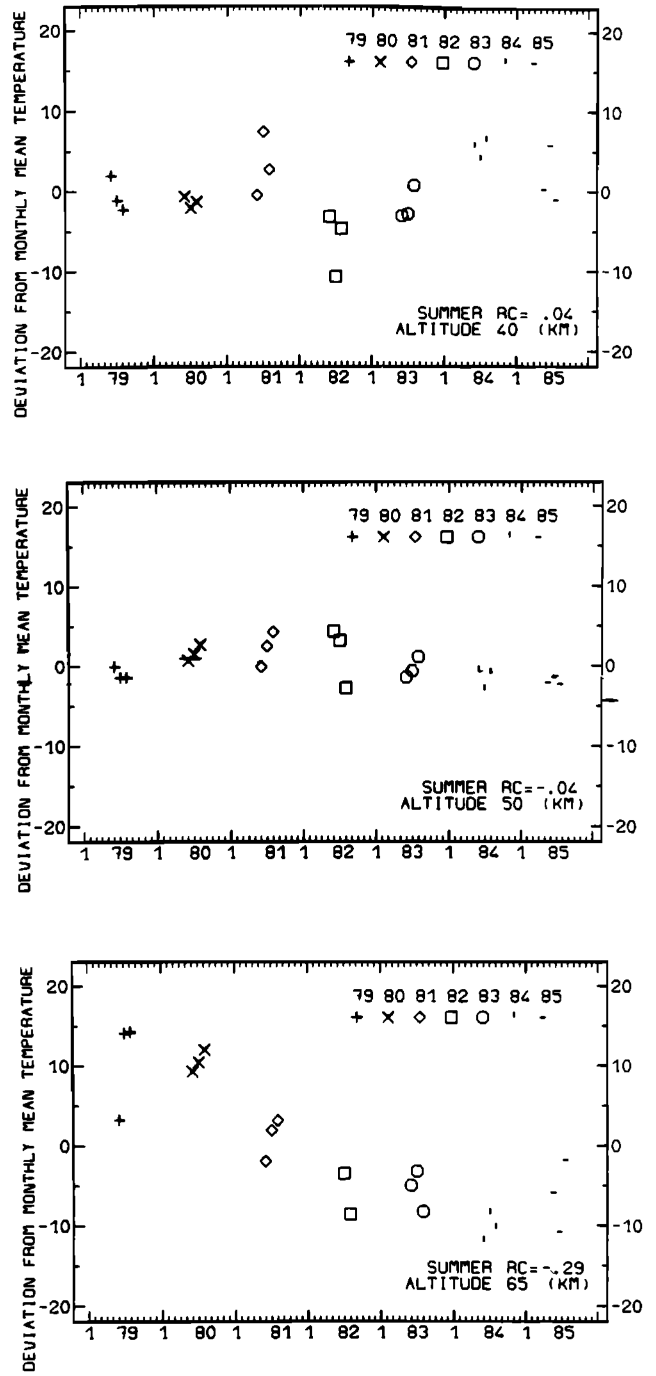

Fig. 4. Same as Figure 3, except for summer months (JJA).

significant level are represented. It was assumed that the data under study are normally distributed. Looking first at the mesospheric range, one can state that for all seasons, the atmospheric response to solar activity is positive and significant. The maximum correlation coefficient is observed in winter at 65 km, where it reaches 0.8; it is only slightly less in summer, but then it extends on a much wider altitude range (50-70 km). The stratospheric behavior is drastically different: whereas the negative correlation is very significant in winter and slightly less during equinoxes, the result is not significant in summer. Calculation of the regression coefficients confirms the results observed earlier: the maximum amplitudes are situated at 65 km for all seasons and at 37 km in the winter stratosphere. The presence of a minimum of variability around 50 km is observed all year around.

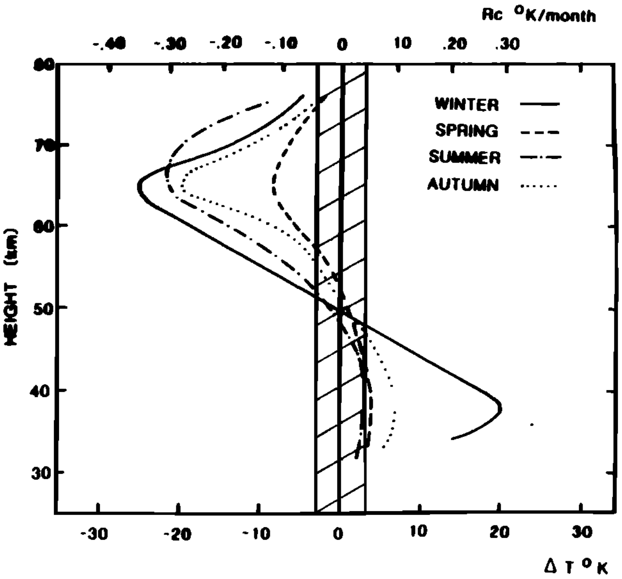

Fig. 5. Amplitude of the observed temperature variations as a function of altitude for the period 1979-1985, deduced from the regression coefficient calculated with a step of 5 km ($\Delta T = R_c \times 6 \times 12$°K). The hatched area corresponds to the region where data are below significant level.

Interpretation

We will discuss separately the results concerning the mesosphere all year around from those relevant to the whole middle atmosphere in winter.

The cooling of the mesosphere between 1979 and 1985 is observed for all seasons and with significant amplitudes. This effect, being in phase with the solar cycle, leads to a highly significant correlation with the solar activity

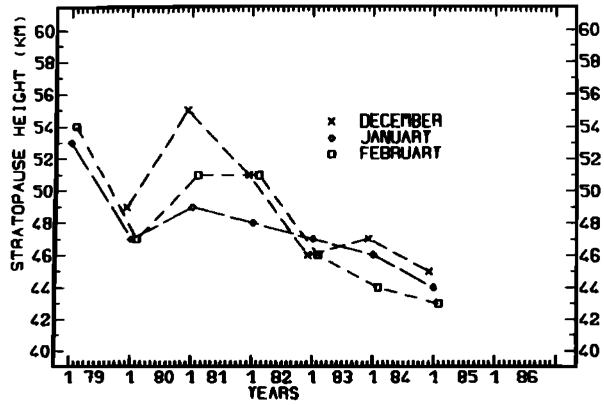

Fig. 6. Mean stratopause height as a function of years for the three winter months.

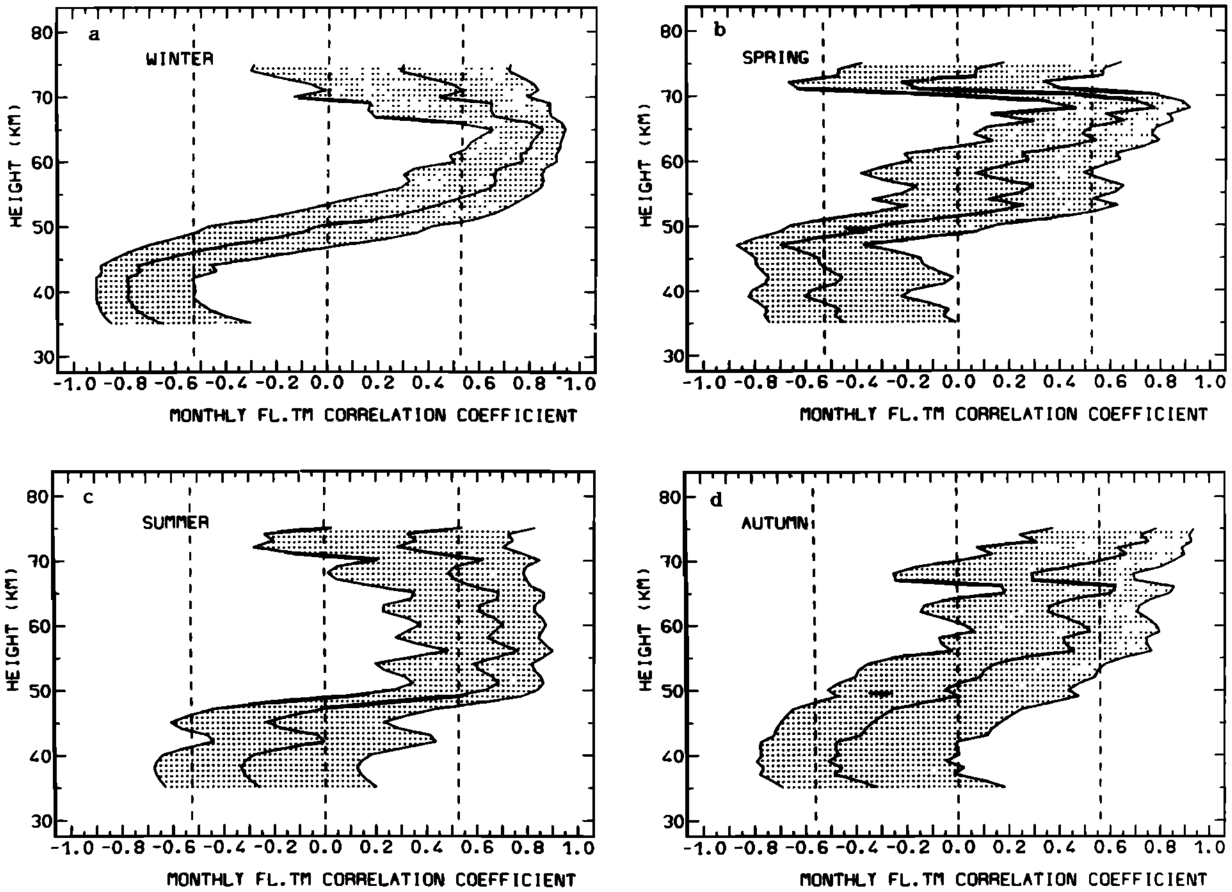

Fig. 7. Correlation coefficient (with ±95% confidence limits) between the monthly mean values of temperature and solar flux at 10.7 cm for (a) winter (DJF); (b) spring (MAM); (c) summer (JJA); and (d) autumn (SON). The significant level of 99% is indicated by the extreme vertical dotted lines.

maximizing around 65-70 km. Such a response of the mesosphere to variation of the UV solar flux is mostly the result of UV absorption by molecular oxygen around 200 nm and is expected to decrease with decreasing altitude, as a result of the smaller variability of the UV flux at the longer wavelengths which penetrate deeper into the atmosphere. This is in agreement with the decrease of the effect from 65 to 50 km, as observed in Figure 5. The presence of a maximum of variability around 70 km can be explained by the fact that around that altitude 20% of the total heating is due to the Lyman α radiation, whose variability is much larger than in the 200-nm range [Brasseur et al., 1986]. However, if the sensitivity to solar radiation is observed at the altitude where it is expected to occur, the observed amplitudes are much larger than those calculated by the models.

Furthermore, the response to solar UV should be the strongest in summer. If the seasonal variation reflects the variation of the absorbed UV flux at mid-latitude, then we would expect a minimum in the winter and intermediate response during the equinoxes. The amplitude of the summer effect (ΔT_{max} = -21°K) is, in fact, observed to be larger than during spring (ΔT_{max} = -9°K). On the other hand, both the winter and autumn effects (ΔT_{max} = -25°K and -19°K, respectively) are much larger than expected and do not present the same height dependance. We interpret the large values found in winter and autumn as due to the superposition of two separate effects of different nature, the weaker effect being the direct influence of the solar UV variation just mentioned.

The second effect, mainly observed in winter, leads to a response of 18°K in the stratosphere and close to 20°K in the mesosphere (if one subtracts from the observed value the expected radiative response of a few degrees K). This behavior is displayed in Figure 5, with two maxima of similar amplitude but opposite signs sharply peaked around 65 km and 35 km, with a minimum at 50 km. This feature is identical to the one we have described in the short-term temperature variability in winter, under the influence of planetary waves, and displayed in Figure 1 (even though the opposite sign between stratospheric and mesospheric temperature deviation does not appear on this figure, since the quantity represented is the square root of the variance). We also noticed in Figure 1 that the upper mesosphere is quite disturbed in autumn and this may explain why the long-term behavior of the temperature in autumn is so similar in amplitude and height distribution to the winter one in the mesosphere, while it differs in the stratosphere.

It has been shown (A. Hauchercorne and M. L.

Chanin, Planetary waves-mean flow interaction in the middle atmosphere: modelization and comparison with lidar observations, submitted to Annales Geophysicae, 1987) that the variability represented in Figure 1 is clearly related to planetary wave activity and can be understood completely in terms of planetary wave propagation. So we conclude that the long-term variability observed in wintertime is being induced by planetary waves. Furthermore, the highly significant correlation with the solar cycle in both the stratosphere and the mesosphere in winter may give a strong indication that the atmospheric response to solar flux variation involves an indirect mechanism producing a change in planetary wave activity, only seen in winter when planetary waves can propagate upwards in the middle atmosphere.

A very important consequence of a long-term change in planetary wave activity, whether or not it is induced by the solar variability, is that the observed trends will be strongly latitudinal dependent and their local amplitudes may differ largely from what is observed on a zonal mean.

Discussion

The results presented earlier are now compared with other observations and with model expectation. We will focus the discussion successively on the two different causes of variability: radiation and dynamics.

The direct response of the atmosphere to UV irradiance variability has been observed to reach a maximum in the mesosphere around 65-70 km (see earlier discussion). This result is in agreement with results published earlier [Mohanakumar, 1985; Von Cossart and Taubenheim, 1987], even though their results obtained for the whole year have maximum amplitudes of 12°K and 6°K, respectively, compared with our yearly average value of 18°K. Such a discrepancy in amplitude may be lowered if the data were all treated by season; but the important fact is that the maxima are localized around the same altitude. It should be noted that the different results obtained in the two successive papers of Devahanarayan and Mohanakumar [1985a, b] can now be understood, as they refer to different altitude ranges, with the second one being close to the minimum of variability.

Neither the height distribution nor the amplitude of these results have been predicted by the models. In a recent paper, Brasseur et al. [1987], presenting the middle atmosphere response to solar activity, limit the model calculation to pressure below 0.1 mbar (~62 km), as the radiative scheme has not been developed to take into account the mesosphere. Anyhow, and from simplified calculations, they estimate that the positive correlation of the temperature with solar activity should peak around 70 km, with an amplitude of 0.25°K per 1% of solar variation at 205 nm. This would correspond to about 2.5°K at the most if using the extreme values of UV variability given by SBUV [Lean, 1986]. This amplitude is far below the observed ones and it may indicate some missing heating mechanism in the model. The same conclusion can be drawn for the Garcia et al. [1984] model: the sensitivity of the temperature to a change in the solar flux increases with altitude in the mesosphere, but the amplitude reached at 75 km is 1°-2°K for the whole solar cycle. It is worth mentioning that in this model a strong depletion of O_3 is predicted to occur around 70 km; this decrease in O_3 should be reflected by a increase in temperature at the same altitude, which is not present, probably because of the simplified cooling parametrization (Newtonian cooling) used in the model. This discrepancy between observation and models should be investigated further.

In the stratosphere the radiative effect is so small compared to the dynamical ones that the comparison should exclude all the data obtained during winter and even autumn. Then a large part of the discrepancies observed in the experimental results vanish (except for Zlotnik and Rozwoda [1976], who report of a 15°K amplitude in summer between 1964 and 1971 at 40 km). For the other authors the amplitudes observed in summer in the stratosphere are of a few degrees K and, when measurable, they indicate a positive correlation with the solar activity. However, most of the recent data (Angell and Korshover [1983]; Schwentek and Elling [1984]; and that reported in this paper) indicate that the effect is below the significant level. This result is not in disagreement with the models which predict, at the maximum, an amplitude of 2°K at the tropics and less than 1°K at middle latitudes [Garcia et al., 1984].

None of the previously mentioned models include a possible dynamical solar-induced mechanism, even though the influence of solar-induced dynamics has been proposed and discussed by several authors [Hines, 1974; Bates, 1977; Chandra, 1985, 1986]. In fact, the models used for prediction are two-dimensional models which cannot represent the planetary wave interactions; anyhow, modelists are still uncertain about what indirect mechanism has to be introduced in the models. The mechanism proposed by Hines [1974] assumes some change in the reflection or absorption of planetary waves under solar-disturbed conditions and is expected to be more relevant to middle and high latitudes in winter. Such a statement is in agreement with our results. Significant effects in the middle atmosphere temperature ozone and winds were predicted by the detailed calculations of Callis et al. [1985], but they have not been confirmed on long term variation. Observational evidence of solar variability effects on planetary wave activity have been, until now, limited to the time scale of the solar rotation period. In the lower stratosphere, Ebel et al. [1986] reported significant results indicating 27- and 13.5-day periods coherent with the 10.7-cm flux between the 50- and 10-mbar levels. The winter results reported in this paper are the first evidence of the long term effect of planetary wave activity in the upper stratosphere and mesosphere.

This interpretation could explain part of the confusion in the already published results. The disagreement mentioned earlier in the sign and amplitude of the results of solar-induced variations of stratospheric temperature may be understood if a large fraction of this variation is linked to the planetary wave activity. There is a priori no reason to have a positive response in the mesosphere and a negative one in the stratosphere, as in the case reported here, which could only be characteristic of a specific site (44°N, 6°E) at a given period. The reverse situation would be occurring elsewhere and/or during other periods. The stratospheric winter temperature at Berlin may have exhibited different causes of variation during successive decades, as reported by Schwentek [1971] (-20°K at 35 km) and later in Schwentek and Elling [1984] (<+2°K at 35 km). Recently, Mohanakumar et al. [1987] have pointed out a different behavior between eastern and western hemispheres, the trends at the tropics being exactly opposite. The amplitude (30°K) and phase of the effect observed by Kokin et al. [1981] in the winter polar region, can obviously only be understood in terms of dynamics.

We suggest that the large dispersion in the amplitudes and signs of the observations is real and can be interpreted as due to planetary wave variability. Such effects observed locally would very likely not be seen on a zonal mean; this may trigger a different way to look at satellite data.

However, the period of observation on which the results reported here are based is too short to insure the relationship of this dynamical change with solar activity, and the possibility of a trend of different origin has to be considered. Since other important geophysical phenomena have occurred in the same time range, one may assume that the temperature trend observed by lidar is due to a change of planetary wave activity triggered by other causes. This could be related to the statement made by Mahlman and Fels [1986], in an attempt to explain the Antarctic ozone depletion, that "sometime after 1979, there must have been a substantial reduction of the wintertime planetary scale disturbance activity." This statement, made for a local situation in the southern hemisphere, may be valid in the northern hemisphere, but it is clear that more inquiry need to be carried out to investigate this possibility.

Conclusion

The study of the temperature trend observed over France (44°N, 6°E) between 1979 and 1985 indicates an increase of temperature in the stratosphere and a large decrease in the mesosphere, mostly since early 1982. The amplitude of the observed effect is much larger than predicted from photochemical models. The seasonal variation of the trend and its height distribution suggest that the observed variation is due to a superposition of two effects: a direct response of the middle atmosphere to the change in UV irradiance as a function of solar cycle which affects the whole mesosphere, with a strong maximum in summer around 70 km, and an effect of dynamical nature occurring mainly in winter and having all the characteristics of the variability induced by planetary waves. We suggest that a change in the planetary wave activity is responsible for the long-term variation observed in winter. We cannot conclude if the coupling between those two effects could enhance the direct response to UV irradiance variation which is found to be much larger than predicted, but their superposition has an obvious consequence on the spatial and temporal diversity of the expected observations. Whether the dynamically induced variation is or is not induced by the solar variability is beyond the scope of this paper and the answer will require analysis of longer series of data.

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