Middle atmosphere response to the 27-day solar rotation as observed by lidar

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MIDDLE ATMOSPHERE RESPONSE TO THE 27-DAY SOLAR ROTATION AS OBSERVED BY LIDAR

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Abstract. The response of the middle atmosphere temperature to short term solar UV radiation related to the 27-day period of the sun has been studied by Rayleigh Lidar at mid-latitude in the height range 30-90 km. Among the 9 sequences, each of 3 to 4 months duration, which corresponds to clear solar signature, two types of behavior have been found : either the temperature response is positively correlated with the solar UV flux in the whole height range, or the response reverses abruptly from positive to negative within the height interval 40-60 km. It is important to notice that this second type of behavior is observed as well in summer or in winter, i.e. even in the absence of planetary wave activity, but has only been seen during the Westward phase of the QBO.

If such a change of the temperature is confirmed to be solar induced, this response to change in the UV flux is clearly different from the one we observed for the 11-year solar cycle. Therefore the 27-day signature of atmospheric structure should not be used as a proxy for the 11-year variation.

Introduction

The study of solar-atmosphere relationship is crucial to understand the mechanisms of radiative heating and ozone balance and therefore to study the potential impact of the middle atmosphere on tropospheric climate. It is also necessary to identify and hopefully understand the effects of solar perturbations in order to detect possible anthropogenic effects. The study reported in this paper is limited to temperature, as they are the only lidar data available at this day in large quantity; we will anyhow always keep in mind the complex relationship between ozone and temperature in order to interpret the results.

The studies on long term cycles such as the 11-year solar cycle, like the one recently published by Hauchecorne et al. [1991], suffer mostly from the lack of statistical results. The study of middle atmospheric response to solar UV variations occurring on shorter time scales, as the 27-day period related to solar rotation, is an obvious other promising approach.

Several studies have in the recent past shown convincing correlations between ozone and short term UV variability. Keating et al. [1987], Hood and Jirikowic [1991] have used simultaneous temperature and ozone data to relate their respective responses to solar UV changes. They all rely on satellite data and suffered from the limited length of the sequence available, and from the accuracy of the measurement which led to the use of zonal means. Most of the studies, except the latest ones, used mean equatorial data to avoid the effect of planetary waves perturbations.

The purpose of this paper is to present temperature changes obtained at middle altitude, over southern France in relationship with the 27-day UV change.

Data description

The temperature data used for this study were obtained at the Observatoire de Haute Provence (France; 44°N, 6°E) from 1981 to 1991, and at the Centre d'Essais des Landes (France; 44°N, 1°E) from 1986 to 1991, both using the Rayleigh lidar technique. The method and the characteristics of the instruments are described in details in several publications [Hauchecorne and Chanin, 1980]. The measurements are obtained at each site with a good time coverage (100 profiles per year) and a good accuracy (better than 1 K at 50 km). The altitude range covered by the measurements extends continuously from 30 km to 90 km. Each profile is integrated over several hours and the initial height resolution is degraded to 3 km to filter out the short period fluctuations due to gravity waves and improve the accuracy.

The radiative heating in the middle atmosphere is dominated by the absorption of UV wavelengths around 205 nm. Unhappily the measurements of the UV solar flux are not continuously available with an adequate accuracy. We rely on the fact that the solar UV flux variability is highly uniform as a function of wavelength [Donnelly, 1988], and then used the Solar Lyman-alpha flux data measured on board Solar Mesosphere Explorer for the period 1982-1986 [Mount and Rottman, 1985] as they provide the best accuracy. When they were no more available, we used the combined Nimbus7-NOAA-9 data which are considered as a good UV proxy.

External and internal forcing

The solar rotation of the active regions on the solar disk which have a lifetime of several solar rotations, induces variations in the UV irradiance received by the atmosphere. The periods could vary from 27 days to 34 days. The nature of quasi-random appearance and disappearance on the sun of these active regions in space and time leads to a very complex UV signal where the principal spectral component is around 28 days but is highly variable in amplitude, phase and frequency. A 13-day oscillation could also appear, when two active regions are situated on opposite sides of the sun.

The temperature in the middle atmosphere is always perturbed by internal forcing principally by upwards propagating planetary waves from the troposphere; the maximum activity occurs during winter periods when westerly winds prevail in the lower stratosphere. The temporal and vertical structure of these waves have been largely studied for several years and the lidar data obtained during the last winters have contributed to their description [Hauchecorne and Chanin, 1983]. The temporal characteristics of the temperature perturbation correspond to Rossby waves with periods varying from 10 to 20 days and a succession of stratospheric warmings with periods from 25 to 60 days.

Analysis of the data

The different sequences of data used in this analysis have been selected considering both the large 27-day variability of the UV flux and the quality of the time coverage of the temperature data. The periods selected in reference to the solar flux have been determined by using the method of the wavelet transform applied to the 205 nm solar flux as seen on Figure 1. This spectral analysis recently developed by Grossman and Kronland-Martinet [1988] leads to a spectral time scale decomposition. Instead of using a sinusoidal function to decompose the signal f(x), a Morlet wavelet is used. The wavelet function φ present only few oscillations in a gaussian envelop that are dilated (a) to obtain spectral informations and translated (b) to obtain space informations. Then the wavelet

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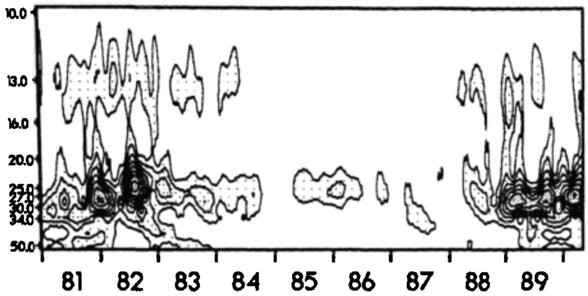

Fig. 1. Wavelet transform of the solar UV flux (Nimbus 7-NOAA 9) from 1981 to 1990. The horizontal axis represents the time (in years) vertical one the periods (in days).

transform gives a two-dimensional and complex function F(a,b) which provides the spectral module and phase as a function of time :

$$F(a,b) = a^{\frac{1}{2}} \int_{-\infty}^{+\infty} \varphi^*\left(\frac{x-b}{a}\right) f(x)\, dx$$

We have also used this method with the time-series of the temperature, as the correlation of spectral and temporal maxima could give a better insight of the solar induced atmospheric changes. This transform is particularly well adapted to the atmospheric solar and planetary waves forcing because the lifetime of these effects corresponds only to several oscillations. Systematic time-series correlation cannot clearly isolate the solar response of the atmosphere from the important wave activity having the same time scale. The Fourier method has to be adapted to take into account the quasi-random nature of the time series and has been applied here to obtain temperature change on the time scale of the sun's rotation with a relatively small temporal window of 3 to 4 months (each corresponding to about 30 to 40 data points), when the amplitude of the solar cycles are relatively important. During such periods the amplitude is expected not to change largely and the frequency resolution (0.008 to 0.011 day^{-1}) is sufficient to separate solar perturbations from the atmospheric perturbations associated to wave activity.

To conclude on the significance of the peaks found in the spectral decomposition, the cross spectrum analysis of the unfiltered time series is carried out applying the methods of time series analysis described by Jenkins and Watts [1969]. The statistical significance is given by the peak exceeding the 95% confidence level reflecting the response of the atmosphere to changes of solar UV radiation. The phase lag between both time series can be deduced from the phase of the cross spectrum analysis. The different steps of the analysis are illustrated in Figure 2.

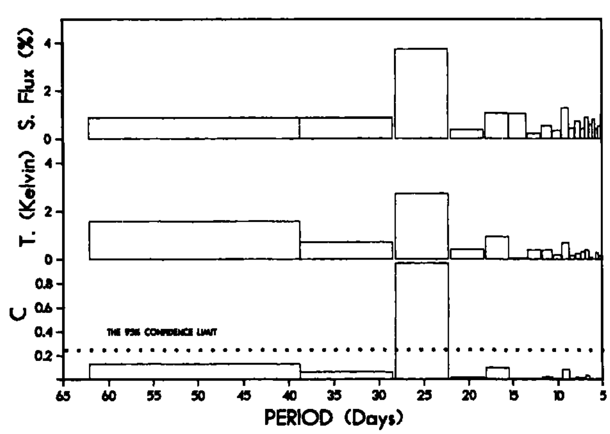

Fig. 2. Spectral analysis for the period between May to August 1985 : spectrum of the Lyman alpha solar flux (top), spectrum of the temperature at the altitude of 57 km (middle), and cross-spectrum between solar flux and temperature (bottom). Periods on the horizontal axis are expressed in days.

Before giving the results one should describe the way we have choosen to represent the outputs of the analysis : Abrupt changes of the phase lag by half a period have been observed as a function of altitude and simultaneously the module of the cross-spectrum tends to zero. This leads to the interpretation of changes with altitude in the sign of the correlation rather than abrupt change in the phase lag. Therefore on the figure 3, 4 and 6 presenting the results, the function called correlation is obtained from the module of the cross-spectrum (which is always positive) affected with a positive or negative sign depending upon the phase lag. As for the phase lag it is corrected by half a period when we assumed the correlation to be negative. The confidence level and the incertainty on the phase of the cross-spectrum are calculated following Jenkins and Watts [1969]. The noise which affects the temperature spectrum is determined assuming an ideal gaussian white noise with variance σ. In this case the probability $Q(w_o)$ of finding a certain power w_i within a frequency bin larger than a given value w_o is given by the following expression :

$$Q(w_o) = \int_{w_o}^{\infty} p(w_i)\, dw_i = \exp\left[\frac{w_o}{2\,\sigma^2}\right]$$

In the ideal white noise case, a plot $Q(w_o)$ versus wo will be a straight line where the slope is a measure of the variance σ of the original time series. Then the noise signal w_n could be deduced from σ for any given probability (here 95%).

Results

In all the 9 cases which we have studied, the upper mesosphere responds positively to increases of solar UV with a significative correlation factor within the 95% confidence level. In the height range 40-60 km, in 5 cases out of the 9 selected periods, the responses are negative and highly correlated with the solar flux with temperature variations almost as large as in the upper mesosphere. Due to a possible contribution of the planetary waves to the signature which we are trying to relate to a solar response, it seems reasonable to study separately the winter and the summer cases:

-Five periods were selected in winter ; the temperature response of the region 40-60 km could be classified into two types of behavior : either the whole region exhibits a positive response in all the height range; this happened only in one winter case in January-March 1982 (Figure 3). A maximum amplitude of 10 K is in this case observed at 60 km. In the four other cases the response is alternatively positive and negative with a null response at 40 and around 60 km (Figure 4). Obviously in wintertime such temperature change may be thought to be due to planetary waves having a period in phase

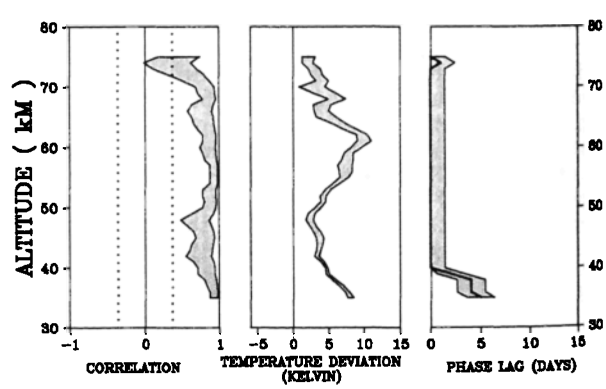

Fig. 3. Amplitude as a function of altitude of the 27-day spectral component for the period from January to March 1982. Correlation (left), temperature deviation (middle), and phase lag (right) between solar and temperature series are given. 95 % confidence level (dash line), phase lag uncertainties and white noise level (shaded area) are also plotted.

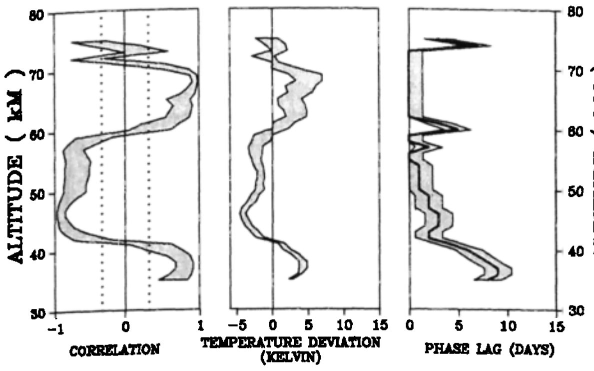

Fig. 4. As in fig 3 for the period between January to March 1983.

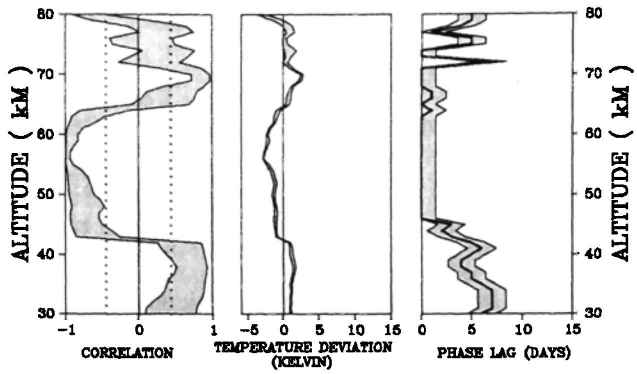

Fig. 6. As in fig 3 for the period between May to August 1985

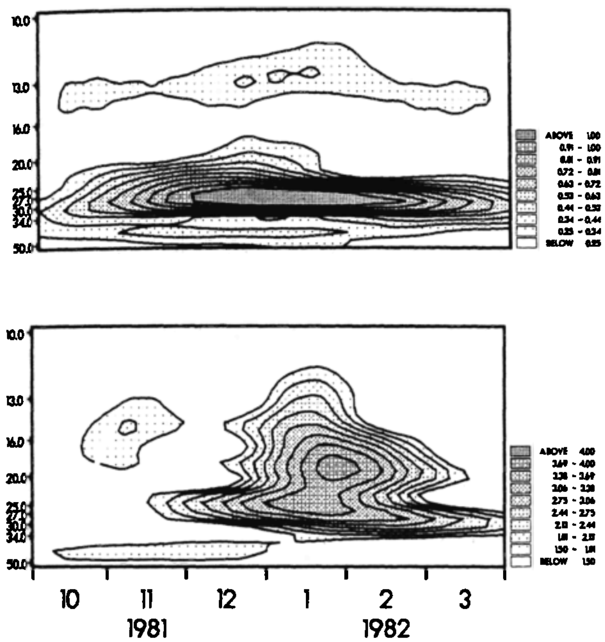

Fig. 5. Wavelet transform (as in fig 1) for the period from October 1981 to March 1982, of the solar flux (top) and the temperature at 55 km (bottom).

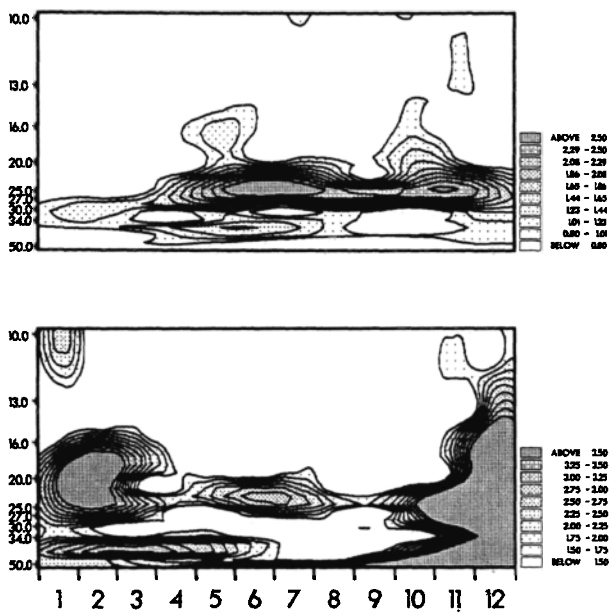

Fig. 7. As in fig 5 for the period from January to December 1985.

with the solar flux. Such a change of sign of the temperature perturbation is in fact familiar between the stratosphere and the mesosphere, but with very different characteristics : i.e. during stratospheric warmings, the minimum of variability is always observed at the stratopause, the opposite of what is observed here. The wavelet transform (Figure 5) applied on both the UV flux and the 55 km temperature was performed to help separating the possible solar response from internal forcing : in that case it is clear that a 18 day wave is present, as well as a long lasting 27-day wave of large amplitude which could be forced by the solar UV change; however it is difficult to relate unambiguously this 27-day wave to the solar signal of identical period. A weaker 13-day oscillation has also occurred in the solar flux during this period but the temperature response is less clear, even though, in two other cases, we had observed a similar response for the 13-day wave and the 27-day wave with an identical vertical signature.

-The amplitude of the temperature variations deduced from the four summer periods seems to be smaller than in winter, even though a positive response is always observed in the upper mesosphere. Below the altitude of 65 km the amplitudes of the temperature changes are under the 95 % confidence level except for the period of summer 1985. The analysis of that period, from May to August (Figure 6), shows a behavior very similar to the one seen in the 4 cases in winter. The major difference is that summer periods are not disturbed by wave activity and the correlation obtained with the UV flux could not in this case be attributed to planetary waves (Figure 7).

The phase lags between temperature data and solar forcing are not always easy to determined for low level of correlation which is the case when the sign of the correlation changes. This is the reason of the appearance of peaks around the zero correlation level which are obviously not significant. Except at those levels, phase lags are well defined and they vary from 0 to a around 5 days from the upper mesosphere down to the upper stratosphere.

Compared to earlier studies of the 27-day variability, the data set considered here is obviously limited to one region and the results may be different from global ones; on the other hand the number of data treated is rather large as, after selection of the high solar variability periods, a total of more than 30 months of data were used.

Comparison with recent investigations

The temperature responses to the 27-day solar forcing has never been studied with high vertical resolution at mid-latitude. But these results are not in contradiction with the ones obtained in previous equatorial studies based on SAMS data by Keating et al. [1987]. In the mesosphere, around 65-70 km, a positive maximum response is obtained in both data set, and the negative response obtained in the 40-60 km range with the lidar data was in fact seen with SAMS between 30 and 40 km, but the authors interpreted it as a positive effect with a long phase lag (>13 days). Due to the higher vertical resolution of the lidar, the abrupt change comes out more clearly, but a phase change of 10 days in about 5 km is also visible from SAMS data. Analysis of the SAMS and SBUV data at all latitudes up to 60°N, from October 1981 to April 1982, were performed by Hood and Jirikowic [1991]. They revealed that the temperature oscillations seen at higher latitudes are anticorrelated and have larger amplitudes (±3 K) than those obtained at lower latitudes. Such results were already suggested by Ebel et al. [1986] and Chandra [1986]. The lidar observations during the winter 1982, period used by Hood and Jirikowic [1991] are in agreement with the satellite results at 60°N : i.e. the temperature deviation is around 3 K at 45 km and in phase with the solar flux. Considering the shifted position of the polar vortex towards Europe, it is not surprising that our site, even though at 44°N, behaves in a similar manner than the mean 60°N latitude. The expected anticorrelation between different layers of the atmosphere mentionned in that paper is confirmed by our observations.

Discussion

The results presented here are not consistent with the expectations based on purely radiative and photochemical considerations [Brasseur et al., 1987] : the amplitudes are too large and the sign of the correlation is unexpected about half of the time; if we would consider that the response is constantly positive, the time lag would be larger than expected. The mechanism of temperature change induced by solar variations in the middle atmosphere is not yet understood both on the scale of the 27-day and the 11-year cycles. But the fact that dynamic causes take an important part in the atmospherical response becomes more and more convincing; these new results, as well as the ones recently published [Hauchecorne et al., 1991], even within their local limits, are conforting such hypothesis.

The sharp change of behavior around 40 and 60 km observed in more than half of our cases could be interpreted as due to the change of sign of the temperature-ozone relationship, which varies itself abruptly from a dynamically driven region to a chemically driven one ; such a rapid change as a function of altitude is also seen in the vertical ozone response to the QBO by SAGE II [Mc Cormick et al., 1989]. The fact that the sign of the QBO plays a role in the response of the atmosphere to a solar forcing is not a new issue [Labitzke and van Loon, 1988]. In the specific case of the 27-day cycle, its role can be understood if the solar response is, as suggested by several authors [Ebel et al, 1986; Hood and Jirikowic, 1991], amplified and modulated by dynamical processes and those will be influenced by the QBO. Contrary to earlier assumptions that the causes of such variations would be purely dynamical, the newly proposed interaction between stationary and travelling waves would amplify the weak solar signal which, according to present models would make it indetectable. Our purpose in writing this paper is to present some results for tests studies in simulation of models including such new coupling mechanisms.

Conclusion

Two remarks in form of conclusion :

- It should be noticed that most of the analysed satellite results correspond to a period of decreasing solar activity (1979-1982), and even for the lidar data which covers now a solar cycle, very few clear cases of monochromatic 27-day cycles could be found in the rising phase of the cycle 22 (1986-1990) : most of our cases (7 out of 9) were selected in the period 1982-1986. This implies that in the next few years, during the declining phase of the cycle 22, there should be very intense studies on this subject, both from the ground and obviously from space, with the contribution of UARS.

- Considering the intense activity going-on to separate the 11-year solar forcing from anthropogenic trends, it is worth mentionning that, from our data analysis, we feel that the signatures observed on the 11-year and 27-day scales are too different to extrapolate the atmospherical response on the 27-day cycle for the 11-year cycle response, even if in both cases dynamical processes are concerned.

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