SOLAR VARIABILITY AND MINOR CONSTITUENTS IN THE LOWER THERMOSPHERE AND IN THE MESOSPHERE*

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Abstract. The variation in the solar irradiance related for example to the 11-year cycle leads to changes in the photodissociation and photo-ionization of the upper and middle atmosphere. The strength of the particle precipitation is also modified. These phenomena are responsible for cyclic variations in the concentration of neutral constituents such as water vapor, nitric oxide, atomic oxygen and ozone, and of ionic compounds in the E- and D-region.

Such effects have been simulated by means of a zonally-averaged two-dimensional model taking into account the latitudinal and seasonal dependences. As an example, the increase of thermospheric nitric oxide with solar activity, the corresponding enhancement of the downward flux of NO reaching the stratosphere during the winter and the impact of this effect on the photoionization will be considered.

1. Introduction

Systematic observations of the radiation emitted by the Sun and reaching the Earth's atmosphere have shown that the irradiance in significant parts of the solar spectrum is subject to appreciable variations as a function of time. A 6.6% variability at all wavelengths with a 1-year period has to be attributed to the ellipticity of the Earth's trajectory around the Sun and affects the photochemical balance in the terrestrial atmosphere. The solar irradiance exhibits another variability with the 27 day rotational period of the Sun which should be attributed to the uneven distribution of the plages on the solar disk. According to the preliminary observations obtained from a spectrometer on board the SME satellite (Rottman, 1982), the corresponding variations could be of the order of 30% at Lα, 12% in the Schumann–Runge continuum, 10% in the Schumann–Runge bands, 5% between 190 and 208 nm, 3% between 208 and 240 nm, 2% between 240 and 260 nm and 1% between 260 and 304 nm.

The variability in the solar emission with a period of 11 years is systematically observed in the decametric range of the spectrum but is poorly known for the wavelength region corresponding to the photochemical processes.

The atmospheric response to periodic variations in the solar output has been investigated by means of numerical models which simulate the most important aeronomic processes. Frederick (1977) and Rycroft and Theobald (1978) have determined the possible changes in the trace species concentration in relation with the solar rotation period. Callis and Neally (1978, a, b), Penner and Chang (1978), Callis *et al.* (1979), Brasseur and Simon (1981), and De Baets *et al.* (1981) have discussed the possible composition changes in the stratosphere induced by the 11 year solar cycle. In this paper, we intend to infer from 2-D model calculations the response of the mesospheric composition to an 11 year modulation of the solar output. The variation

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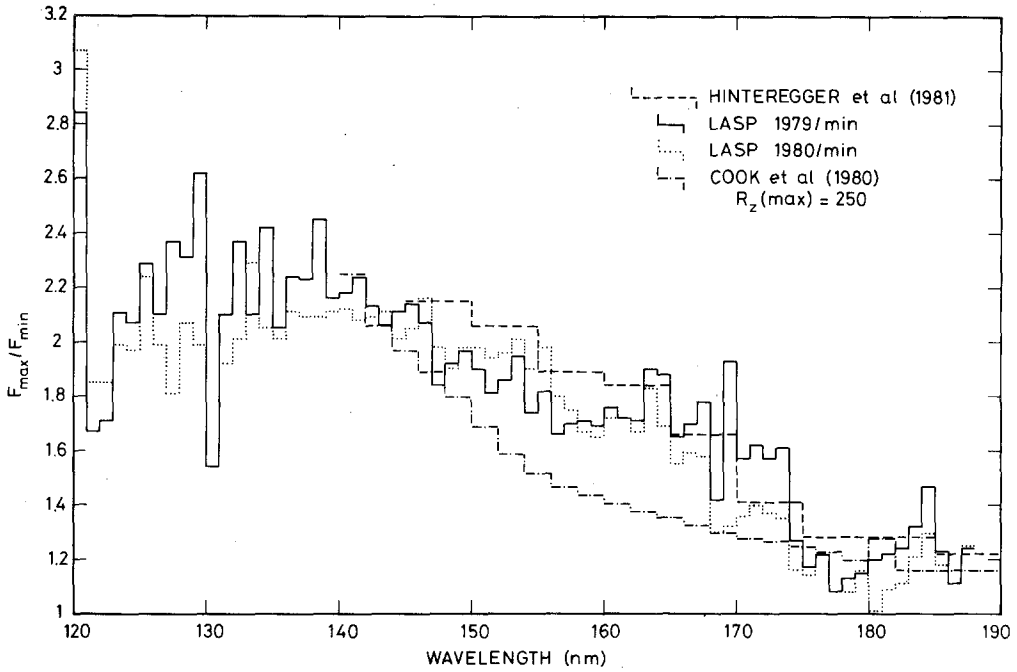

Fig. 1. Solar irradiance variability related to the rising phase of solar cycle 21 from 120 to 190 nm. The values suggested by Hinteregger *et al.* (1980) are adopted in the model calculation.

TABLE I

Solar irradiance in the EUV and X rays spectral region. Values adopted in the model for minimum and maximum solar activity

λ (nm)	Solar irradiance (cm^{-2} s^{-1})		Ratio maximum/minimum
	Minimum activity	Maximum activity	
102.6 (Lβ)	3.5×10^9	1.2×10^{10}	3.4
97.7 (C III)	4.4×10^9	1.0×10^{10}	2.3
91.0–79.6	7.5×10^9	1.5×10^{10}	2.0
79.6–73.2	1.0×10^9	2.0×10^9	2.0
73.2–66.5	5.0×10^8	1.0×10^9	2.0
66.5–37.5	4.0×10^9	1.2×10^{10}	3.0
37.5–27.5	7.5×10^9	2.0×10^{10}	2.7
27.5–15.0	7.5×10^9	2.0×10^{10}	2.7
15.0–8.0	5.0×10^8	2.0×10^9	4.0
8.0–6.0	2.5×10^7	1.0×10^8	4.0
6.0–4.1	2.5×10^7	1.0×10^8	4.0
4.1–3.1	7.5×10^6	3.0×10^7	4.0
0.8–0.5	2.9×10^2	2.9×10^4	100
0.5–0.33	2.0×10^1	2.0×10^3	100
0.33–0.15	1.0×10^0	1.0×10^2	100

in the solar irradiance which is introduced as a model input is taken from Hinteregger *et al.* (1981) above 120 nm (Figure 1) and is based on the data published by Banks and Kockarts (1973) and Nicolet and Bossy (1981) below 120 nm (Table I). A factor of 2 variability is assumed for the Lα line at 121.6 nm according to the analysis by Bossy and Nicolet (1981).

2. Modelling of the Atmospheric Response to Solar Variability

The model which is used in the present study derives the zonally averaged meridional distribution of neutral and ionic species between the altitudes of 40 and 100 km and from pole to pole. In the neutral atmosphere, one considers the most relevent reactions between species belonging to the oxygen, hydrogen and nitrogen families. In the ionized atmosphere, the reaction scheme suggested by Ferguson (1979) is adopted with the rate constants adopted by Reid (1977) in his model of the D region.

The meridional and vertical transport is assumed to be driven by the general circulation (mean motions) and by large scale eddy diffusion induced in this altitude range mainly by gravity waves. The wind components are based on the data suggested by Murgatroyd and Singleton (1961) while the components of the eddy tensor are taken from Ebel (1980).

The continuity/transport equations are solved with proper boundary conditions by an alternating direction method (Peaceman and Rachford, 1955). A more detailed description of this model as well as the chemical scheme is given by Brasseur *et al.* (1983).

The variation in the solar activity is simulated by a modification in the solar irradiance (see Figure 1 and Table I) corresponding to a 20% variability in the region of the Schumann–Runge bands of molecular oxygen. Above the aluminium ledge of 208 nm, the irradiance is assumed to remain unchanged.

A variation in the ionization rate by particle precipitation is also introduced according to Heaps (1978). Since this rate is largely determined by the state of the magnetosphere, its value decreases when the solar activity increases. Finally, it should be emphasized that the nitric oxide injection in the mesosphere is determined by the net integrated NO production rate in the thermosphere which is directly controlled by solar activity. According to several observations, the concentration of NO at 100 km is clearly correlated with the 10.7 cm flux emitted by the Sun. In order to deal with this effect, the downward flux of NO at the upper boundary of the model (100 km) has been enhanced at all latitudes by a somewhat arbitrary factor of 2 between minimum and maximum activity.

3. Selected Model Results

In order to estimate the respective effect of each perturbation considered above, different calculations have been performed. In the first model run, the injection of nitric oxide from the thermosphere has been uniformly multiplied by 2 while the other parameters

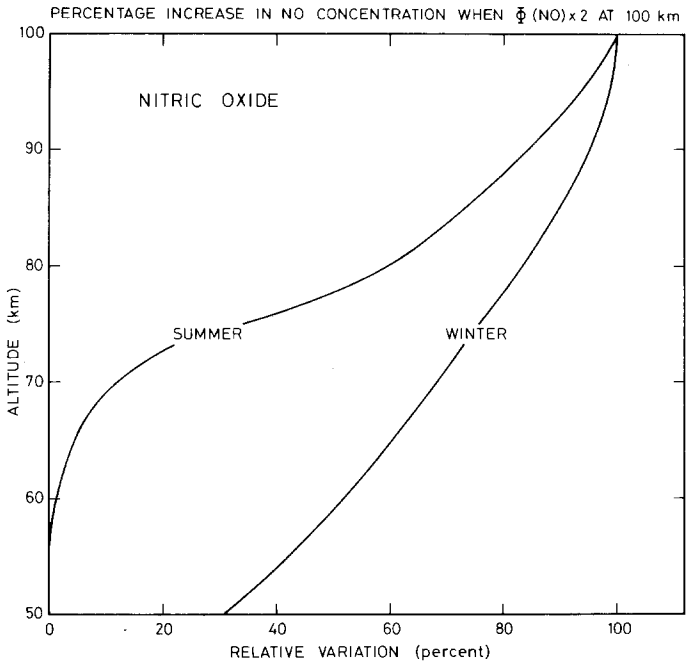

Fig. 2. Relative variation as a function of the altitude of the nitric oxide concentration when the downward flux of NO at 100 km is multiplied by 2. Mid-latitude winter and summer distribution.

(solar irradiance, particle precipitation, ...) have been kept constant. The resulting variation in the NO concentration is shown in Figure 2. The two curves are representative respectively of a summer and a winter mid-latitude condition. In the summer case, the thermospheric perturbation penetrates down to about 65 km only since the destruction of NO by photodissociation and recombination is quite intense. During the winter however, nitric oxide is only weakly destroyed and reaches easily the stratopause level. This hemispheric asymmetry is enlarged by the general circulation cell and by the seasonal difference of the large scale eddy diffusion which is more intense in winter. In summary, the modulation of the thermospheric production of NO could slightly modify the amount of nitrogen oxides and consequently of ozone in the upper stratosphere during the winter season. In the summer however, from the NO point of view, the thermosphere and stratosphere are completely decoupled.

The variability in the mesospheric NO concentration leads to a modification in the ionization rate of the D region since the most important formation mechanism of ion production in this altitude range is due to the action of the Lα radiation on nitric oxide (Nicolet, 1945). Figure 3 shows how the total ionization rate is enlarged when the NO downward flux at 100 km is multiplied by 2. In the E region, the main ion source is due to the action of the EUV radiation on O_2 and N_2 molecules and the sensitivity of the ionization rate to a change in the NO concentration becomes small.

In a second model run, the NO downward flux from the thermosphere, the solar irradiance and the particle precipitation have been simultaneously changed in order to

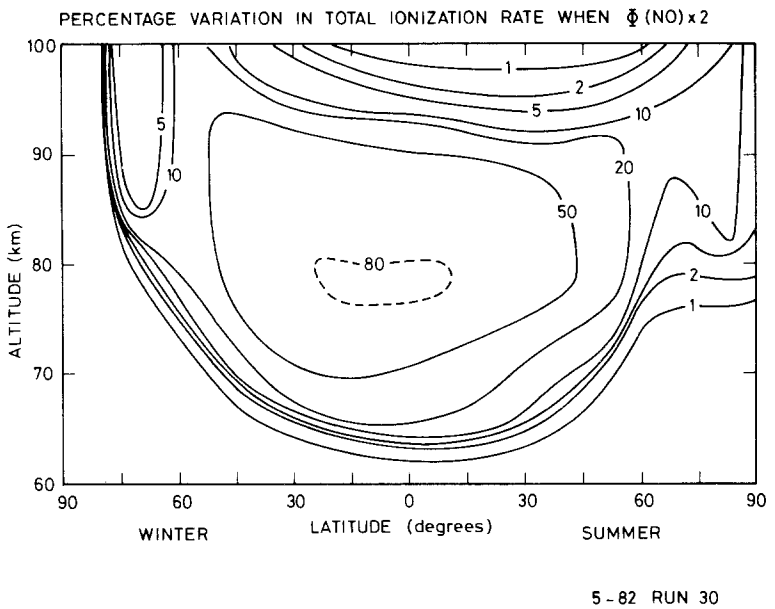

Fig. 3. Relative variation of the total ionization rate resulting from a factor of 2 increase in the NO flux at 100 km.

reproduce a rather realistic variation of the mesospheric input during an entire solar cycle. The corresponding change in the nitric oxide distribution is shown in Figure 4. The winter hemisphere is mainly controlled by the thermospheric variability while, in the summer, the NO concentration is reduced by at most 20 percent due to the enhancement in the photodissociation coefficient of this molecule. The slight positive variation which is observed in the vicinity of the summer hemisphere should be attributed to a rather strong horizontal transport but is also due to the fact that the N_2O concentration is prescribed (and therefore kept constant) in the model.

The change in the rate of ionization is reproduced in Figure 5. As expected, the variation is now considerably larger and its shape quite different. In the E region, the most important effect is due to the O_2^+ formation while in the D region, one has now to consider simultaneously the modulation of the Lα line intensity of the Sun and the variability in the NO distribution. Below 60 to 70 km, the ionization is due to energetic particle precipitation and its rate therefore decreases when solar activity increases. The shape of the isolines around 60 degrees latitude has to be attributed to the modulation of the REP particles which are assumed to vary proportionally to the cosmic rays intensity.

The resulting variation in the electronic concentration from solar minimum to solar maximum is shown in Figure 6. Again, the presence of two separate regions controlled respectively by solar radiation and particle precipitation can clearly be distinguished. The model calculation shows that, with the adopted assumptions, the concentration of the electrons can be increased by almost a factor of 2 near 80 km with a maximum in the equatorial region.

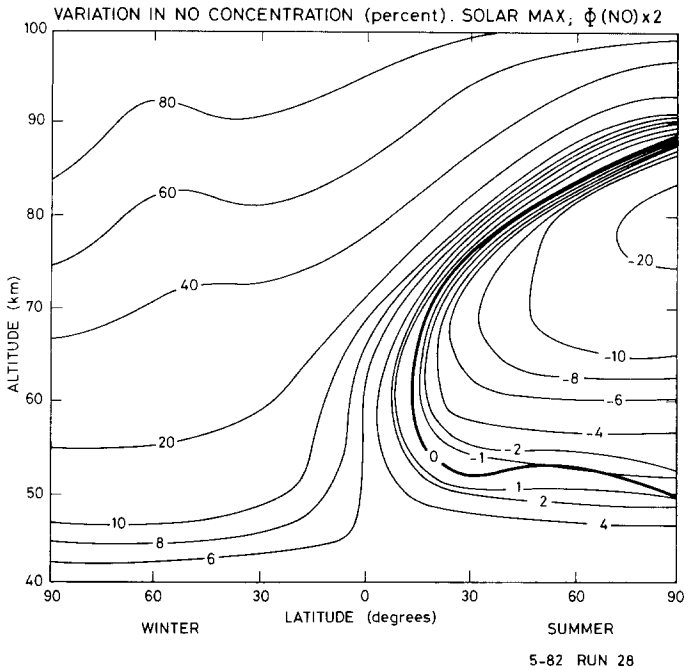

Fig. 4. Meridional distribution of the calculated variation in the nitric oxide concentration between minimum and maximum solar activity.

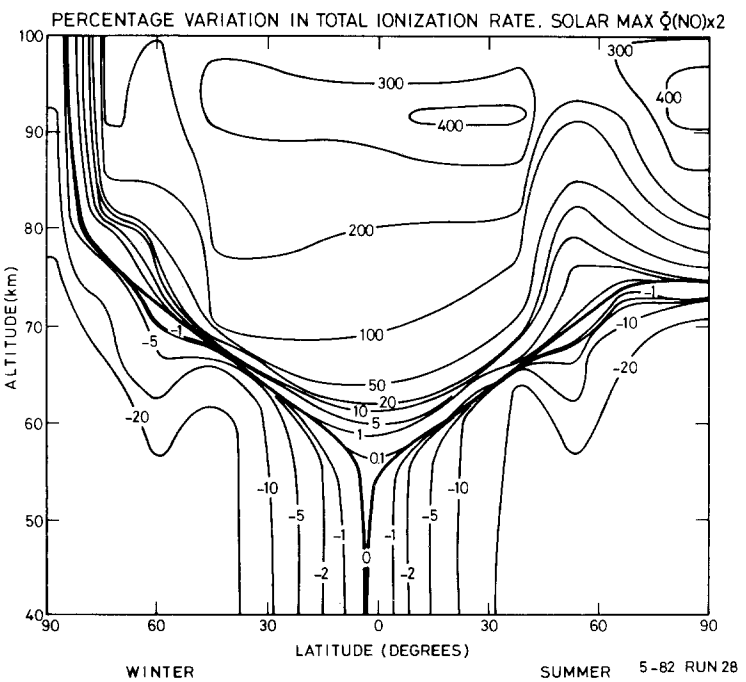

Fig. 5. Relative variation in the total ionization rate between minimum and maximum solar activity.

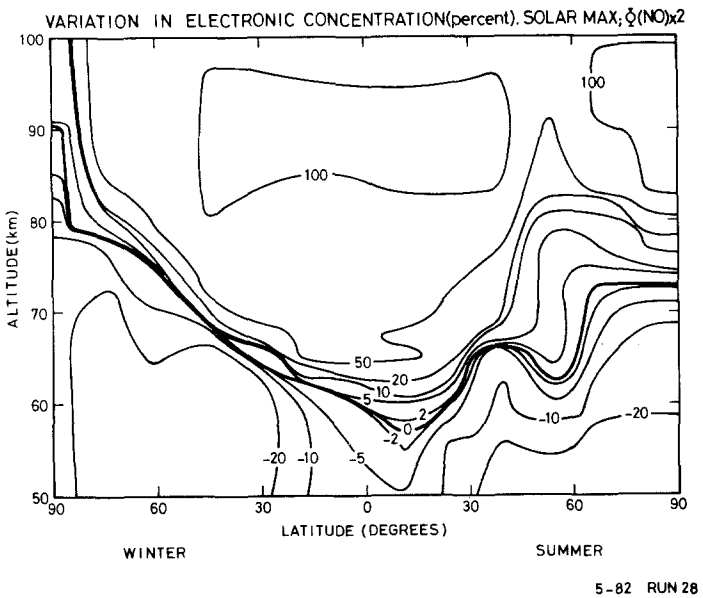

Fig. 6. Meridional distribution of the calculated variation in the average electronic concentration between minimum and maximum solar activity.

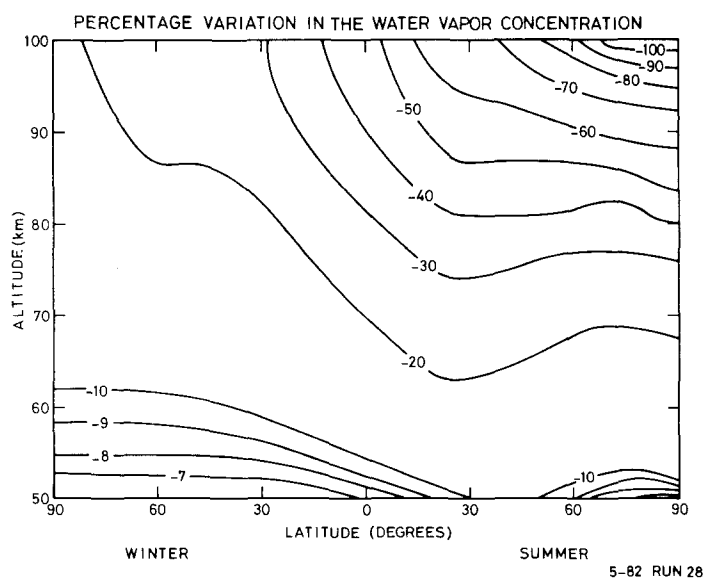

Fig. 7. Meridional distribution of the calculated variation in the water vapor concentration between minimum and maximum solar activity.

The water vapor plays a key role in controlling the neutral as well as the ionized atmosphere. Its sensitivity to the 11 year solar cycle is shown in Figure 7. Since the H_2O molecule is destroyed mainly by direct photodissociation by Lα, its variability is the most intensive in the summer hemisphere where its lifetime is the shortest. During the winter, the water vapor distribution is essentially dynamically controlled. At the mesopause, for example, the variability in the H_2O mixing ratio, according to the model calculation, is of the order of 50% in the summer hemisphere and 20% only in the winter hemisphere. The corresponding variation in the HO_x concentration between solar minimum and maximum is a decrease of 3 to 7% in summer and an increase of 10% in winter.

The response of odd oxygen in the mesosphere to such variations is consequently dependent on the seasonal conditions. Figure 8 shows that the ozone and atomic oxygen concentrations are expected to increase in the summer hemisphere directly with the solar activity. This variation is explained by the enhancement of the photodissociation rate of molecular oxygen and by the reduction of the HO_x amount. In the winter hemisphere, where the attenuation of the solar irradiance is larger and where the concentration of odd hydrogen is generally enhanced, the model shows a reduction in the O_x concentration when solar activity increases. It should be noted however that the numbers corresponding to these relative variations are rather small and that the detection of changes is not always straightforward. Satellites such as SME should improve our knowledge of the correlation between atmospheric composition and solar variability on different time scales.

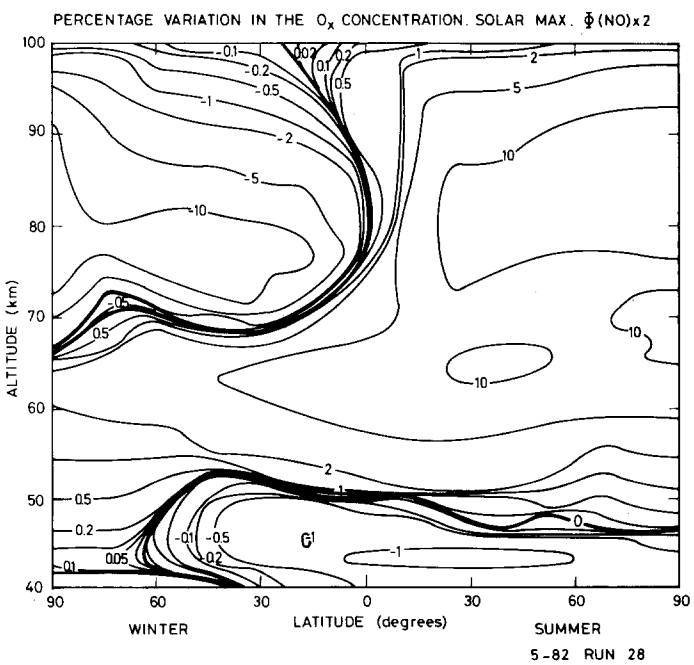

Fig. 8. Meridional distribution of the calculated variation in the odd oxygen concentration between minimum and maximum solar activity.

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