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B - 1180 BRUXELLES

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the lower thermosphere and in the mesosphere

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G. BRASSEUR, P. DE BAETS and A. DE RUDDER

B E L G I S C H I N S T I T U U T V O O R R U I M T E - A E R O N O M I E

3 - Ringlaan
B - 1180 BRUSSEL

FOREWORD

This paper has been presented at the SCOSTEP meeting held in Ottawa, Canada in May 1982.

AVANT-PROPOS

Ce texte constitue le résumé d'une communication présentée à la réunion du SCOSTEP qui s'est tenue en mai 1982 à Ottawa, Canada.

VOORWOORD

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VORWORT

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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 photoionization 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, 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 the 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.

Résumé

La variation de l'éclairement solaire en fonction du cycle d'activité undécennal produit des modifications du taux de photodissociation et de photoionisation dans l'atmosphère supérieure et moyenne. L'existence du cycle solaire module également l'intensité de la précipitation des particules énergétiques (rayonnement cosmique,...). Ces phénomènes entraînent des variations cycliques de la concentration des constituants neutres (vapeur d'eau, oxydes d'azote, oxygène atomique, ozone,...) et des ions.

De tels effets sont simulés à l'aide d'un modèle bidimensionnel qui prend en compte les variations selon l'altitude, la latitude et la saison. A titre d'exemple, l'accroissement avec l'activité solaire de la quantité d'oxyde d'azote dans la thermosphère, l'augmentation correspondante de l'injection de NO jusque dans la stratosphère, au cours de la saison d'hiver, avec un impact sur l'ionisation de la région D, sont envisagés dans cette étude.

Samenvatting

De variatie van de zonnestraling in functie van de 11-jarige cyclus leidt tot veranderingen in de fotodissociatie en de fotoïonisatie van de hoge en de midden atmosfeer. De intensiteit van de precipitatie van energetische deeltjes wordt eveneens gemoduleerd. Deze verschijnselen zijn verantwoordelijk voor de cyclische veranderingen in de concentratie van neutrale bestanddelen (waterdamp, stikstofoxyde, atomaire zuurstof, ozon) en van de ionen in het E- en D-gebied.

Dergelijke effecten worden gesimuleerd met behulp van een tweedimensionaal model dat rekening houdt met hoogte-, breedte- en seizoensveranderingen. Ten titel van voorbeeld worden de verhoging van de thermosferische stikstofoxyde, de overeenkomstige stijging van de injectie van NO tot aan de stratosfeer tijdens de winter en de neerslag van dit effect op de ionisatie in het D-gebied en dit werk bestudeerd.

Zusammenfassung

Die elfjährigen Variationen der Sonnenausstrahlung ergeben Änderungen in der Photodissoziation und in der Photoionisation der höheren und mittleren Atmosphäre. Die Intensität der Partikelniederschlag is auch verändert. Diese Phänomenen induzieren zyklische Variationen in der Dichte der ungeladenen Teilchen sowie Wasserdampf, Stickstoffoxyde, Sauerstoff, Ozon und in der geladenen Teilchen der E- und D-Schichte.

Solche Effekten sind simuliert mit Hilfe eines zweidimensionalen Modells das Variationen mit Breite und mit Jahreszeiten einbegriff. Zum Beispiel, werden der Anstieg des thermosphärischen Stickstoffoxyde mit Sonnenaktivität und der Anstieg des stratosphärischen Winter NO Strömung und das Effekt auf der Ionisation betrachtet.

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 percent variability at all wavelength 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 disc. 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 50 percent at Lyman α , 15 percent in the Schumann-Runge continuum, 10 percent in the Schumann-Runge bands, 5 percent between 190 and 208 nm, 3 percent between 208 and 240 nm, 2 percent between 240 and 260 nm and 1 percent 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 (1971) 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 calcu-

lations the response of the mesospheric composition to an 11 year modulation of the solar output. The variation in the solar irradiance which is introduced as a model input is taken from Hinteregger et al. (1981) above 120 nm (fig. 1) and is based on the data published by Banks (1973) and Nicolet and Bossy (1981) and Kockarts below 120 nm (table 1). A factor of 2 variability is assumed for the Lyman α 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 altitude of 40 and 100 km and from pole to pole. In the neutral atmosphere, one considers the most relevant 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 component 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).

TABLE 1.- Solar irradiance in the EUV and X rays spectral region. Values adopted in the model for minimum and maximum solar activity.

$\lambda(\text{nm})$	Solar irradiance ($\text{cm}^{-2}\text{s}^{-1}$)		Ratio maximum/minimum
	Minimum activity	Maximum activity	
102.6(Ly β)	3.5×10^9	1.2×10^{10}	3.4
97.7(CIII)	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

The variation in the solar activity is simulated by a modification in the solar irradiance (see fig. 1 and table 1) corresponding to a 20 percent 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 (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

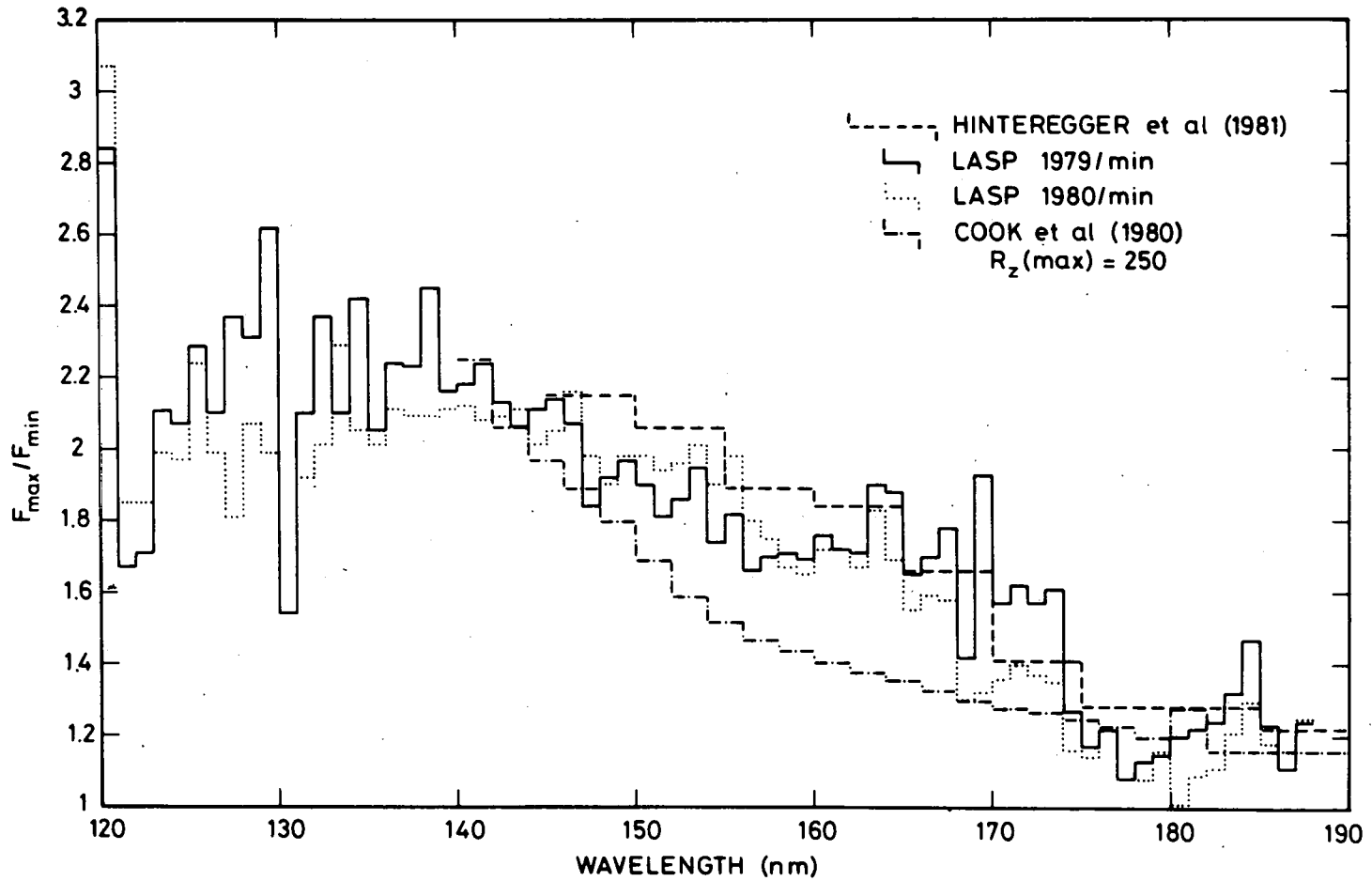


Fig. 1.- Solar irradiance variability related to the rising phase of solar cycle 21 from 120 to 190 nm. The values suggested by Hinteregger et al. (1980) are adopted in the model calculation.

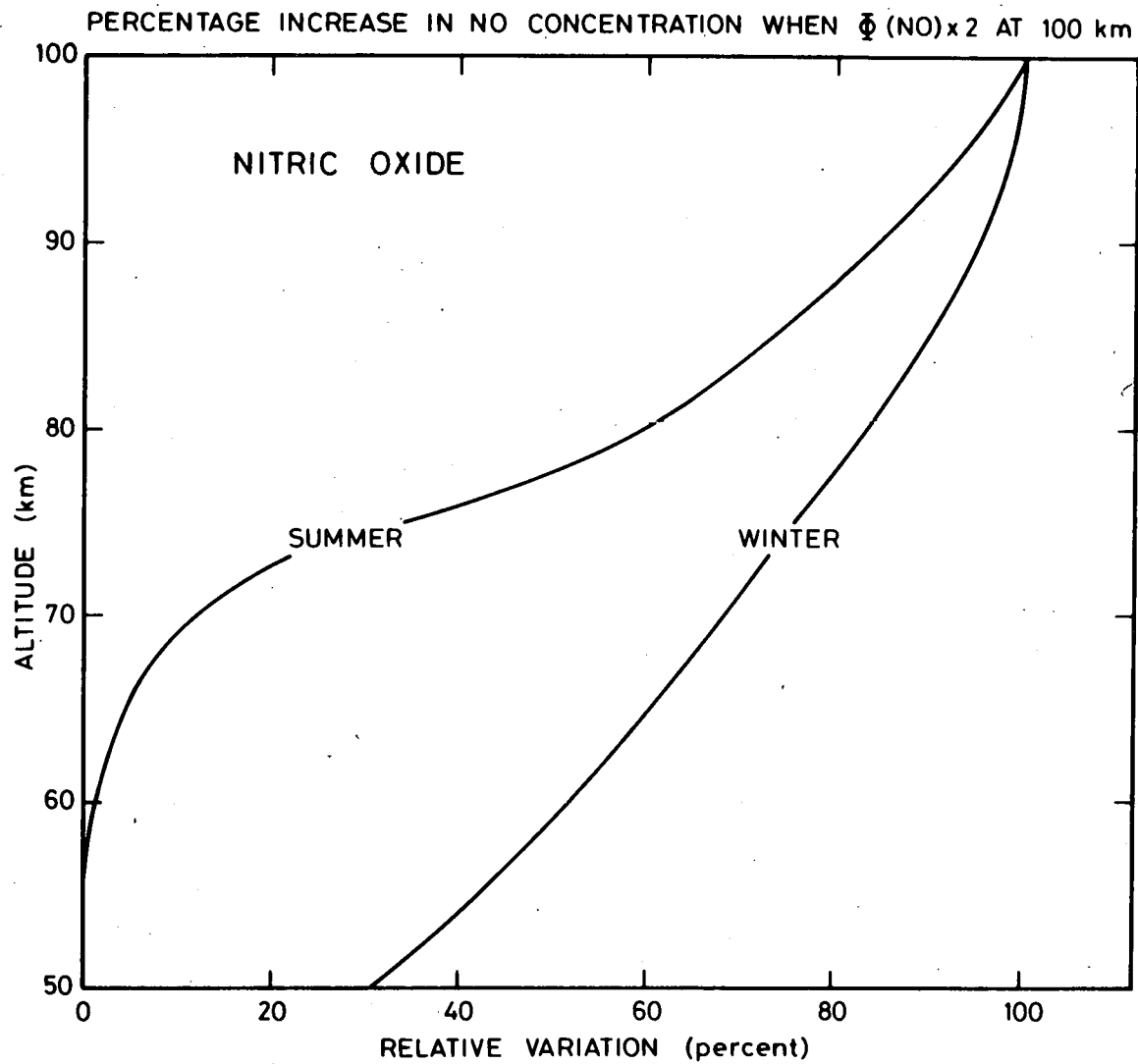


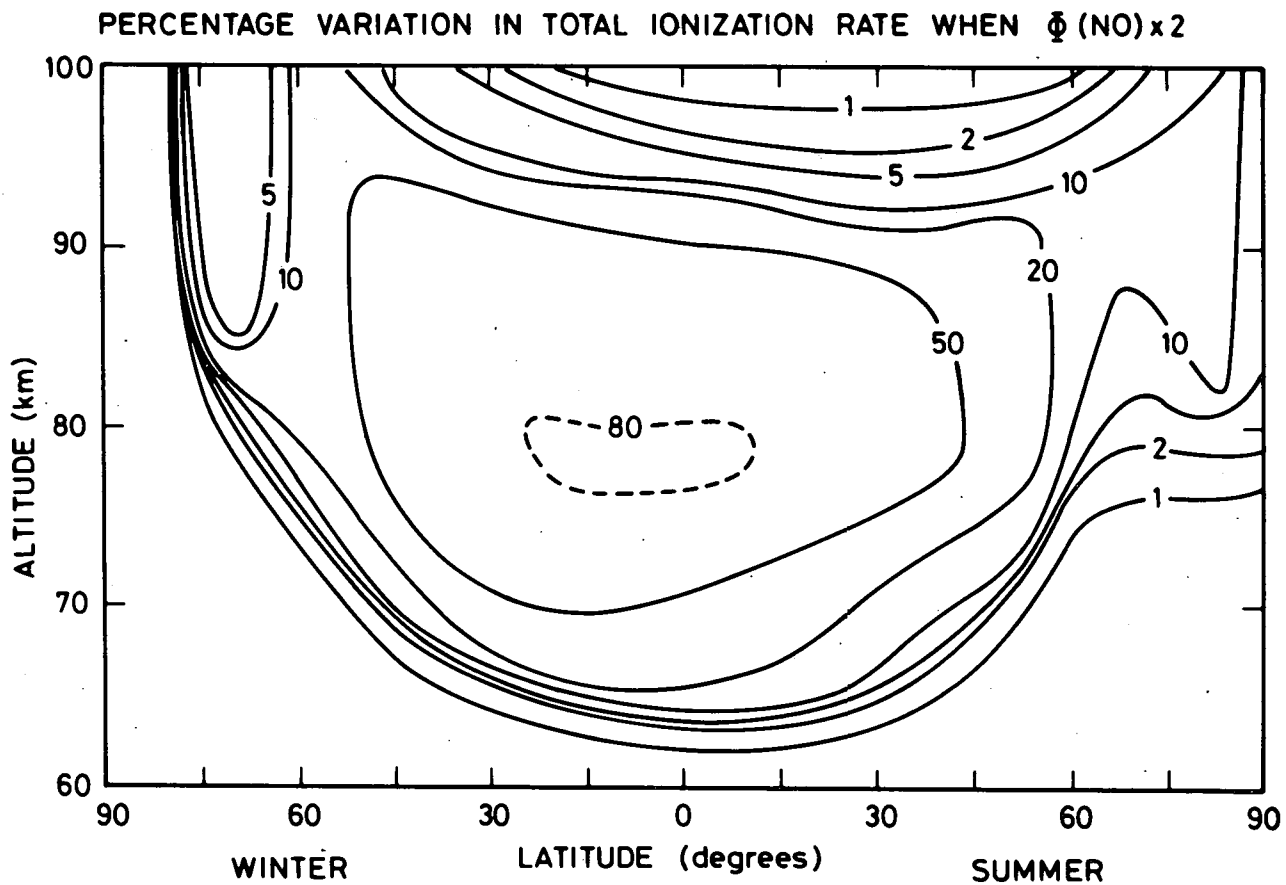
Fig. 2.- Relative variation as a function of the altitude of the nitric oxide concentration when the downward flux of NO at 100 km is multiplied by 2. Mid-latitude winter and summer distribution.

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 Lyman α 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 O₂ and N₂ 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 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 N₂O 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



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

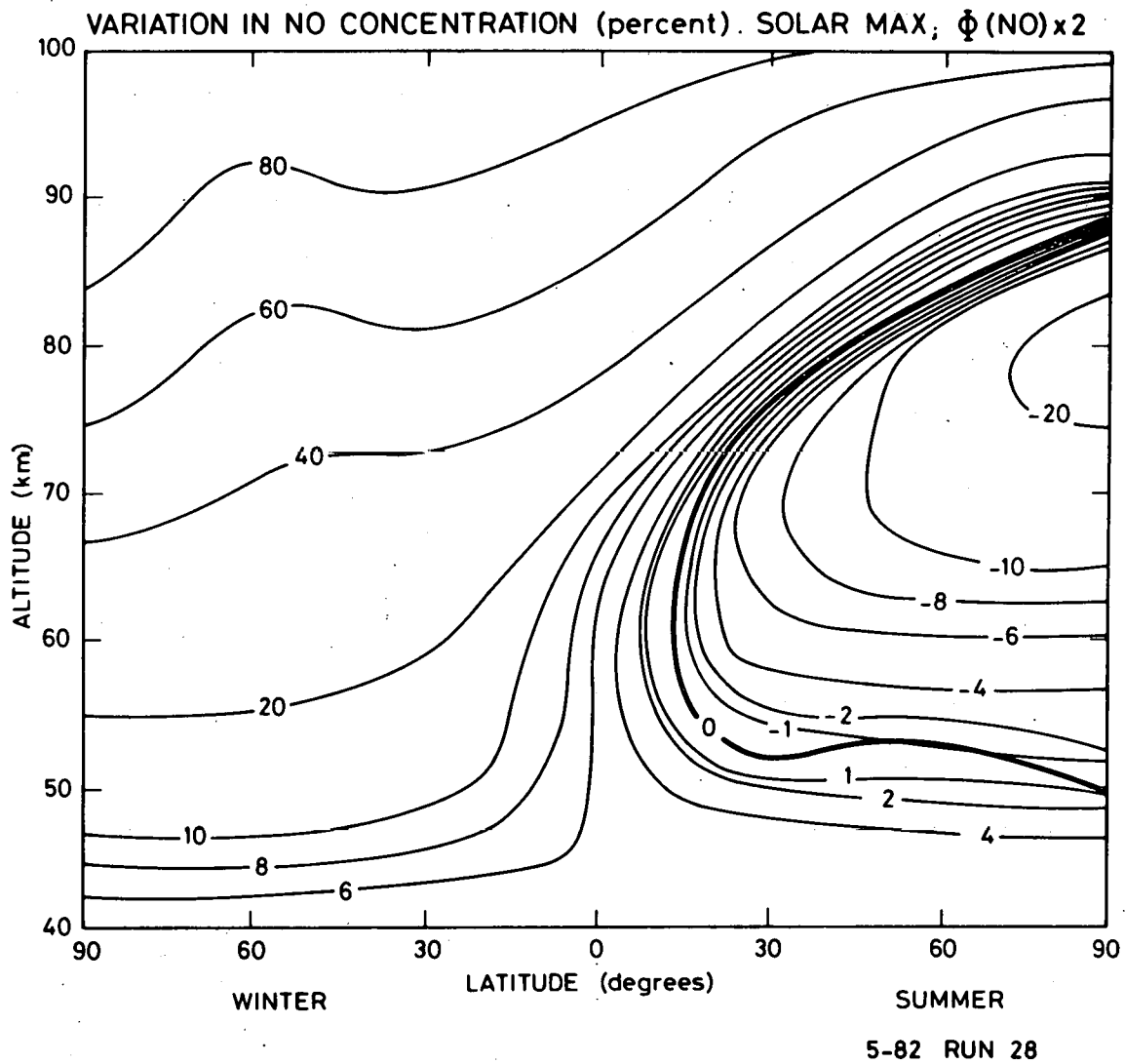


Fig. 4.- Meridional distribution of the calculated variation in the nitric oxide concentration between minimum and maximum solar activity.

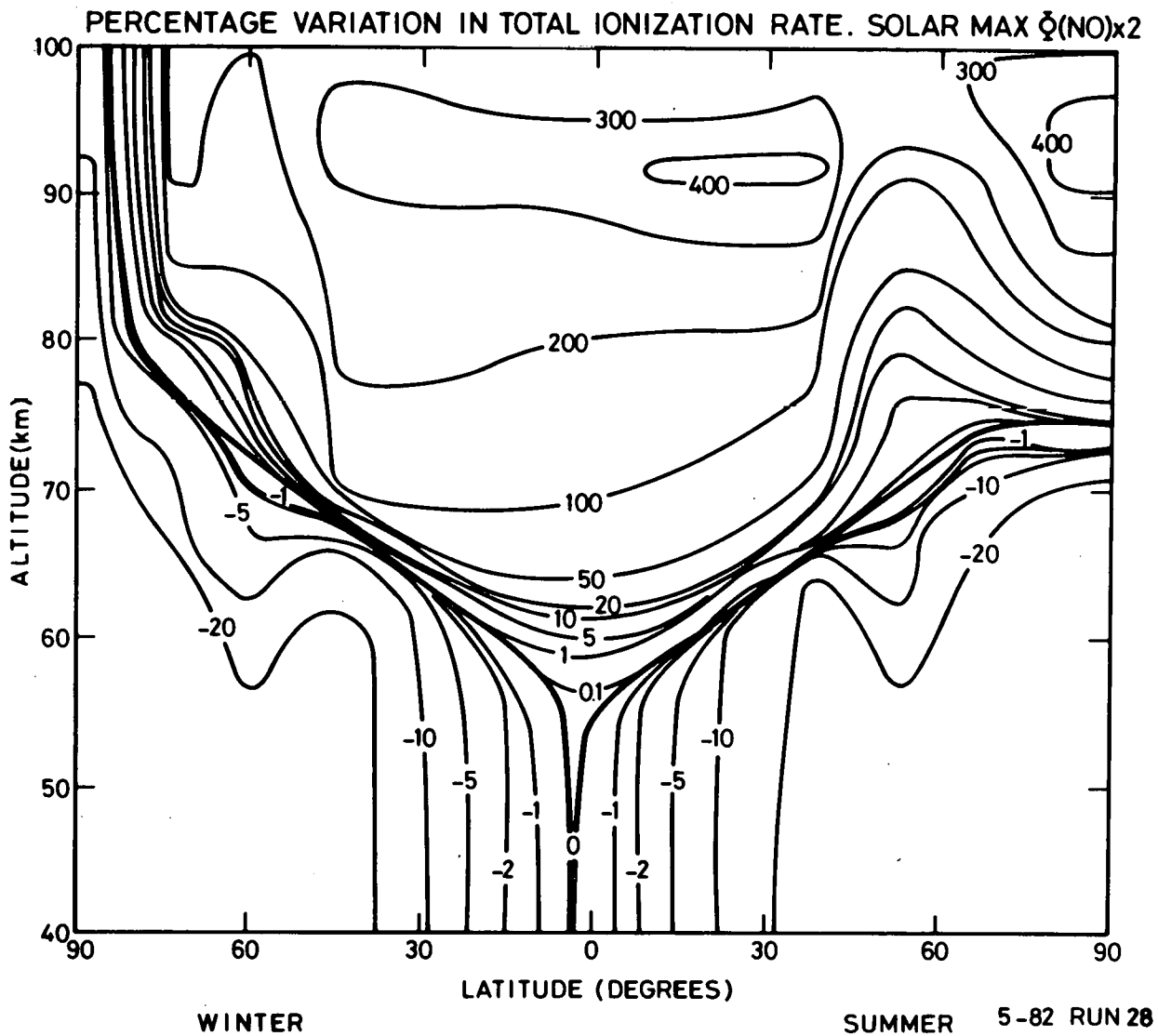


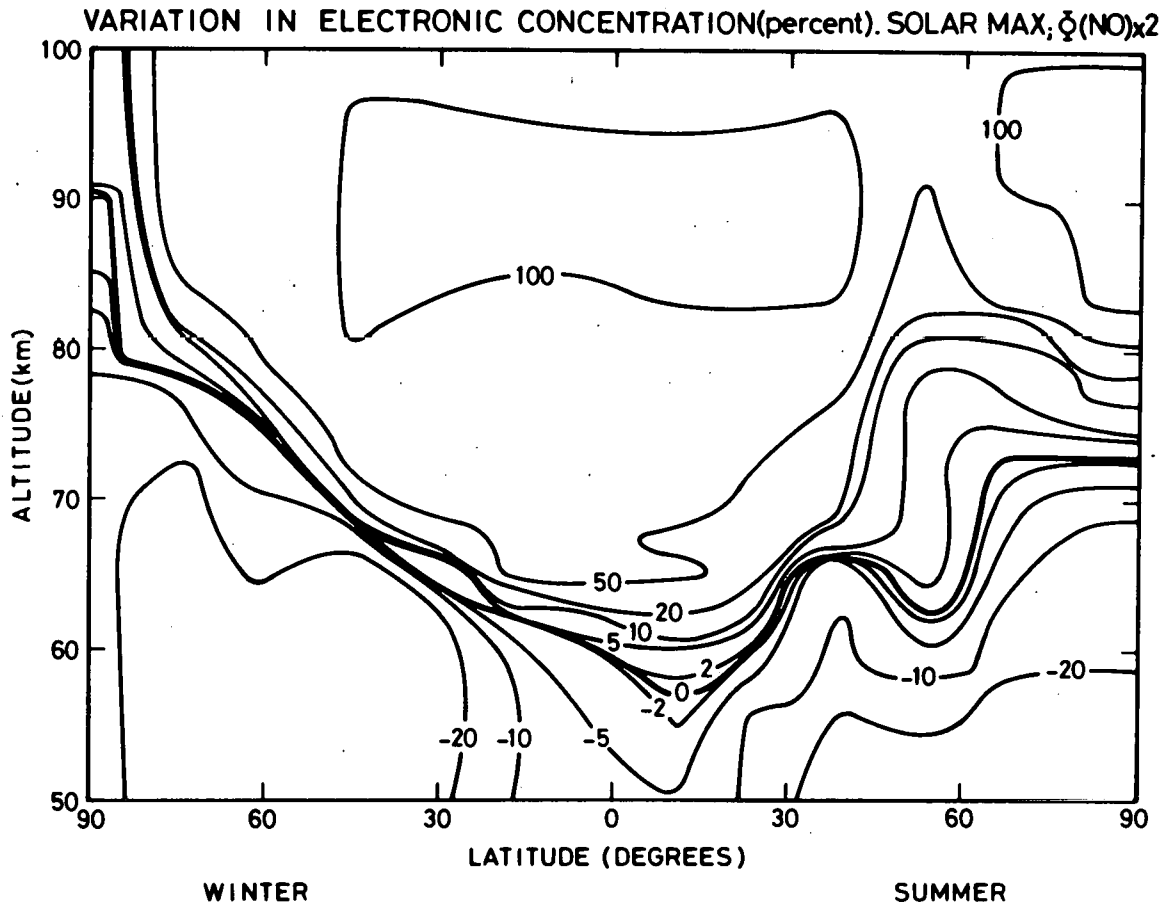
Fig. 5.- Relative variation in the total ionization rate between minimum and maximum solar activity.

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 Lyman α 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.

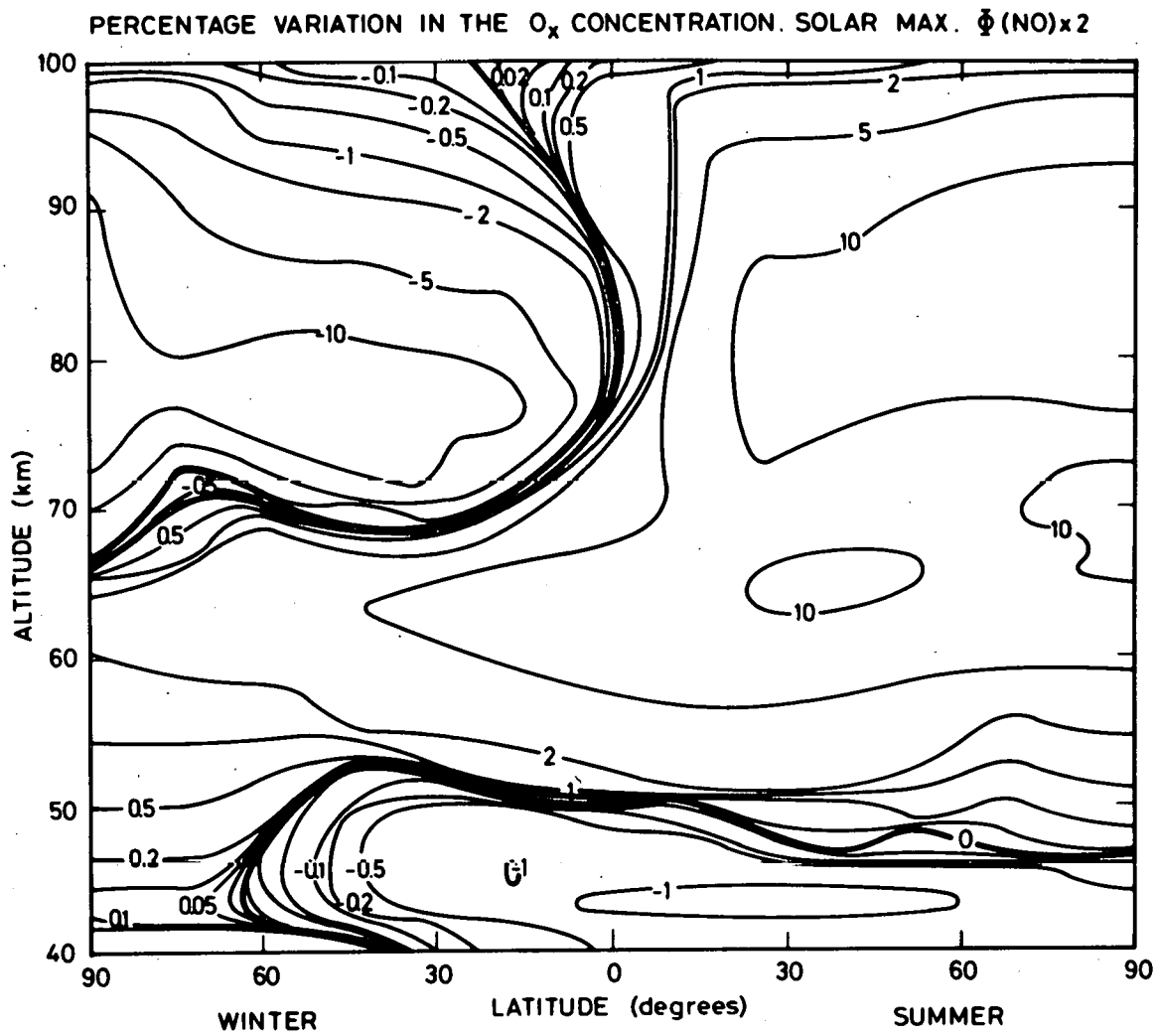
The water vapor plays a key role in controlling the neutral as well as the ionized atmosphere. Its sensitivity to the 11 year solar cycle is shown in figure 7. Since the H_2O molecule is destroyed mainly by direct photodissociation by Lyman α , its variability is the most intensive in the summer hemisphere 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 percent in the summer hemisphere and 20 percent 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 percent in summer and an increase of 10 percent 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



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



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

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.

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