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COUPLING BETWEEN THE THERMOSPHERE AND THE STRATOSPHERE:
THE ROLE OF NITRIC OXIDE

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ABSTRACT

Two-dimensional model calculations reveal that the chemical conditions at the stratopause are related to the state of the thermosphere. This coupling mechanism can be partly explained by the downward transport of nitric oxide during the winter season and consequently depends on the dynamical conditions in the mesosphere and in the lower thermosphere (mean circulation and waves). In summer, the photodissociation of nitric oxide plays an important role and the thermospheric NO abundance modulates the radiation field reaching the upper stratosphere. Perturbations in the nitric oxide concentration above the mesopause could therefore have an impact in the vicinity of the stratopause.

As indicated for example by DANILOV and TAUBENHEIM (1983), the behavior of the D-region is significantly different in summer and in winter. During the first of these seasons, the electron density seems fairly dependent on the solar zenith angle while, during the winter, considerable day to day variations completely mask any control of the ionosphere by solar or geophysical parameters. Furthermore, as reported already by APPLETON in 1937, anomalous increases in absorption of high frequency radio waves occur during certain groups of winter days. Even outside these irregular winter anomaly events, the absorption and consequently the electron concentration appears to be considerably higher in winter than in summer. Since the quiet time ionization in the D-region is due primarily to the action of the solar Lyman- α radiation on nitric oxide molecules, the understanding of the lower ionosphere and its probable control by dynamical processes requires a detailed understanding of the NO distribution in the mesosphere.

In order to achieve such a study, a two-dimensional model with coupled chemical and dynamical processes has been constructed. This model ranges from 40 to 100 km altitude and from the North to the South pole. Dynamical parameters such as the meridional circulation and the eddy diffusion tensor are prescribed. In particular, the two-dimensional eddy components are taken from EBEL (1980) but, as indicated hereafter, some changes have been introduced in several model runs in order to estimate the sensitivity of the dynamical activity in the lower thermosphere on the calculated concentration values. This model which is in many aspects similar to the model developed by SOLOMON et al. (1982) and which is described in detail by BRASSEUR and DE BAETS (1983), considers the most important chemical and photochemical processes related to the odd oxygen, odd nitrogen and odd hydrogen species as well as the positive and negative ions and the electrons. This paper will deal essentially with the behavior of nitric oxide below 100 km.

Nitric oxide is produced in the stratosphere by the oxidation of nitrous oxide (N_2O) in the presence of the electronically excited atomic oxygen $O(^1D)$. An additional source, essentially at high latitude, is due to the action of the cosmic rays. In the thermosphere, ions which are produced by solar EUV and X rays as well as by particle precipitation, especially in the auroral belts (relativistic electron precipitation, solar proton events, etc.) lead to the formation of NO molecules. Direct dissociation or dissociative ionization of N_2 is another source of NO. Calculations made by RUSCH et al. (1981) indicate that each ion pair formation produces 1.3 nitric oxide mole-

cules. Consequently the thermospheric NO production rate will be controlled by the solar and geomagnetic activity. In the present paper, only quiet conditions will be considered. Downward transport of nitric oxide from the thermosphere will depend on the strength of the vertical exchanges and of the chemical stability of NO in the mesosphere. As indicated by Figure 1, the nitric oxide flux is directed downwards in the whole mesosphere during the winter when the lifetime of NO is long and the K_{zz} values are large, indicating that thermospheric nitric oxide could reach the stratosphere and interact with the ozone layer. Comparisons of calculated and observed O_3 density for different solar activity levels (SOLOMON and GARCIA, 1983) give indirect evidence for such a NO_x transport above $60^\circ N$ during the winter.

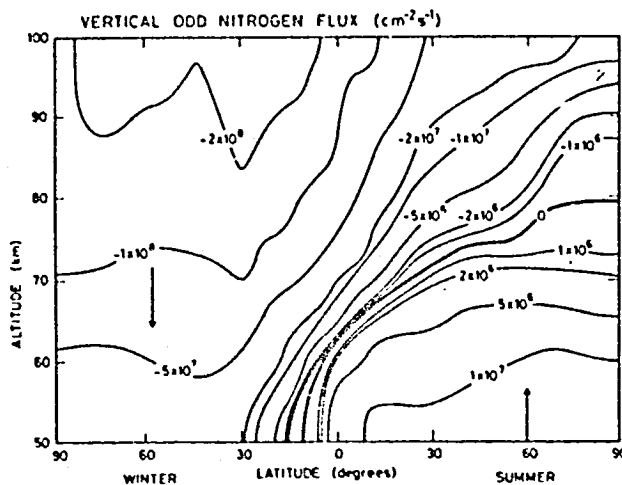


Figure 1. Meridional distribution of the vertical flux component of nitric oxide calculated with the exchange coefficients suggested by Ebel (1980).

During the summer season, the downward transport by eddy diffusion is weak and is even slowed down by the upward meridional circulation. The loss of NO by photodissociation and recombination is intense and is even enhanced by the fact that the lower temperature in the vicinity of the summer mesopause reduces the rate of the $N(^4S) + O_2$ reaction (reformation of NO after its photodissociation) and thus favors the $N(^4S) + NO$ reaction (destruction of odd nitrogen). Therefore no dynamical coupling between the thermosphere and stratosphere appears in summer and the nitric oxide flux is directed upwards during this period of the year. However, as pointed out by FREDERICK et al. (1983), the absorption of the UV radiation by variable thermospheric NO could modulate the radiation field reaching the lower mesosphere and the upper stratosphere and consequently modify the dissociation rate of nitric oxide in the δ bands at these levels. The magnitude of this effect appears however to be probably smaller than the 11 year variability of the solar irradiance. Figure 2 shows the calculated distribution of the nitric oxide concentration for winter and summer conditions. It can be seen that nitric oxide is present in winter and that the concentration minimum at the mesopause level is very weak during this season.

In order to estimate the sensitivity of the NO distribution on the strength

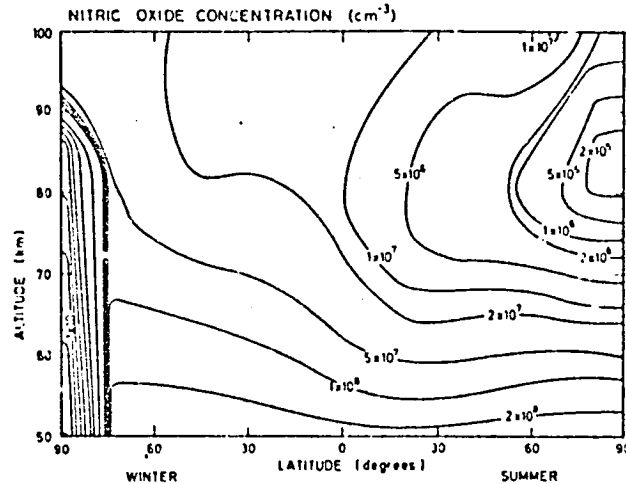


Figure 2. Meridional distribution of the nitric oxide concentration calculated with the exchange coefficients suggested by Ebel (1980).

of the vertical transport, the K_{zz} values have been decreased in the thermosphere by a factor which is uniform with latitude. Three cases have been considered: case 1 refers to the Ebel's values, case 2 to a very slow diffusion coefficient K_{min} and case 3 to an intermediate value. Figure 3 shows the 3 corresponding profiles for summer and winter mid-latitude. The K_{zz} profile suggested by ALLEN et al. (1981) to explain observed atomic oxygen distributions by their 1-D model is also indicated.

The nitric oxide mixing ratio and flux at the stratopause for the two extreme cases (1 and 2) are shown in Figure 4a and b. These figures indicate again that a coupling between the thermosphere and the stratosphere is possible essentially during the winter. The strength of the coupling as well as the

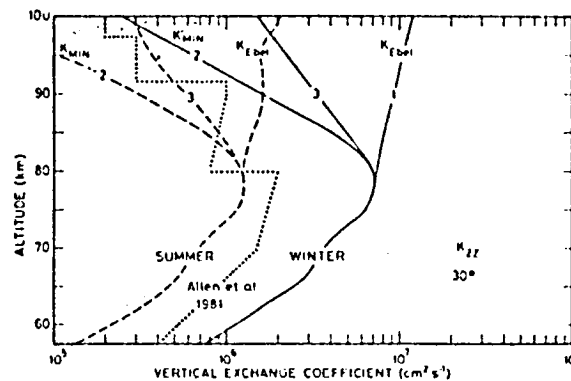


Figure 3. Different vertical exchange coefficients K_{zz} adopted in the model calculations. Vertical distributions represented at 30° latitude for winter and summer conditions. The profile used by ALLEN et al. (1981) is also indicated.

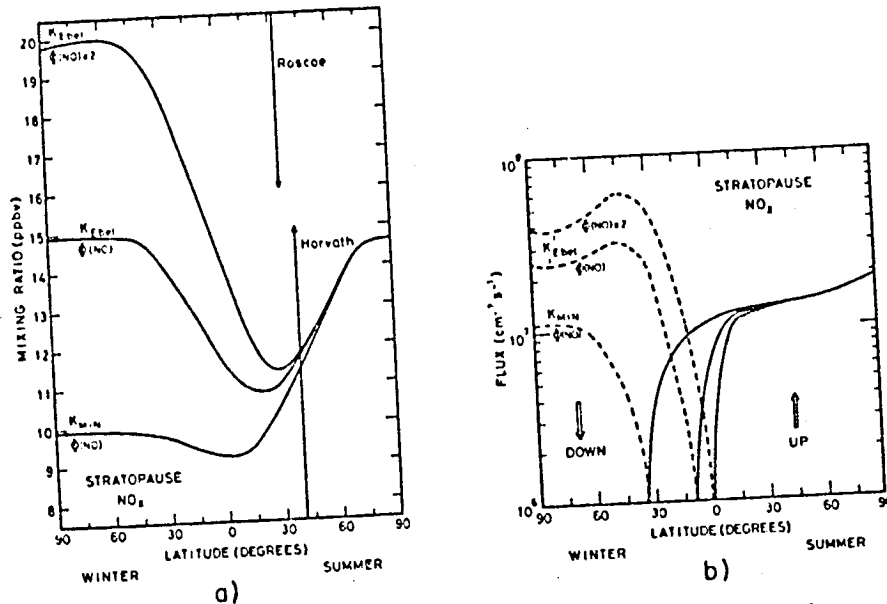


Figure 4a. Latitudinal and seasonal distribution of the nitric oxide mixing ratio calculated at the stratopause (50 km altitude) assuming different conditions: K_{Ebel} refers to the exchange coefficients suggested by Ebel, K_{min} to the smallest vertical eddy diffusion depicted in fig. 3; (NO) refers to an upper boundary flux conditions corresponding to quiet solar conditions (Solomon, private communication, 1981) and (NO) $\times 2$ to the imposed flux which has been multiplied by 2.

Figure 4b. Same as in fig. 4a but for the nitric oxide vertical flux.

latitude of the border between the downward and the upward NO exchange regions varies with the adopted K_{zz} profile and with the downward flux imposed at the upper boundary (which reflects the integrated NO production above this level and consequently the solar and geomagnetic activity). In order to estimate this last effect, the nitric oxide flux at 100 km has been uniformly doubled. The corresponding impact on the stratopause NO is also indicated in Figures 4a and b.

Comparisons between observed and calculated nitric oxide profiles are not straightforward since the measured concentrations exhibit large variations. This variability might partly be attributed to instrumental errors but it also reflects the large changes occurring in the real world. It seems however that most observations show a concentration minimum near 85 km altitude (10^6 to 10^7 cm^{-3}) but that this minimum is considerably weaker during the winter (5×10^6 to $5 \times 10^7 \text{ cm}^{-3}$). Observations made during winter anomaly events (BERAN and BANGERT, 1979) show large NO densities and a vertical profile indicating almost perfect mixing conditions (and consequently strong vertical exchanges between 50 and 80 km).

The comparison between available data and the calculated profiles obtained

with the 3 different transport coefficients suggests that case 3 (intermediate K_{zz}) is somewhat more representative of most nitric oxide observations than the other eddy diffusion profiles. The corresponding meridional distribution of NO is shown in Figure 5 and should be compared with the results depicted in Figure 2. It should be remembered that these model results refer to average seasonal and diurnal conditions. The magnitude of the diurnal variation of NO at selected altitude and at 30 degrees latitude can be estimated from Figure 6.

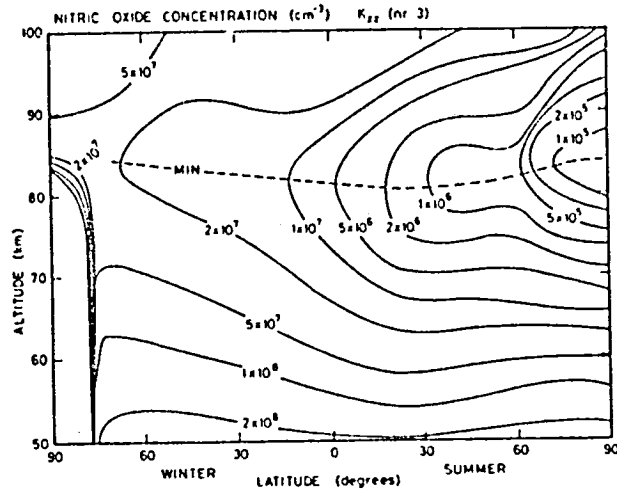


Figure 5. Meridional distribution of the nitric oxide concentration calculated with the intermediate values of K_{zz} (case 3) and Ebel's values for K_{yy} and K_{yz} .

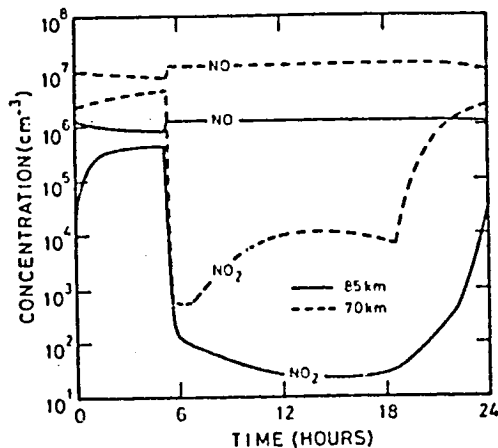


Figure 6. Diurnal variation of nitric oxide and nitrogen dioxide calculated at 70 and 85 km altitude for spring conditions and 30 degrees latitude. The total NO_x concentration is assumed to be 1.2×10^7 and $1.2 \times 10^6 \text{ cm}^{-3}$ at 70 and 85 km, respectively.

Finally, the electronic concentration which is derived from the NO distribution shown in Figure 5 and which is obtained from a detailed ionic model is represented in Figure 7. It can be seen that the concentration of electrons is considerably higher in winter owing to the fact that the nitric oxide density is larger during this season and that the temperature and consequently the effective electron loss are higher in the winter hemisphere. The model explains thus satisfactorily the observed higher radio wave absorption during wintertime (which is sometimes called the regular component of the winter anomaly) but cannot explain the causes of the irregular components of such anomalous events since the calculations are performed with seasonal averages of temperature, diffusion coefficients and wind components. Satellite data might provide indications on the relative role played by nitric oxide and by the temperature in the appearance of sudden anomalous absorption events.

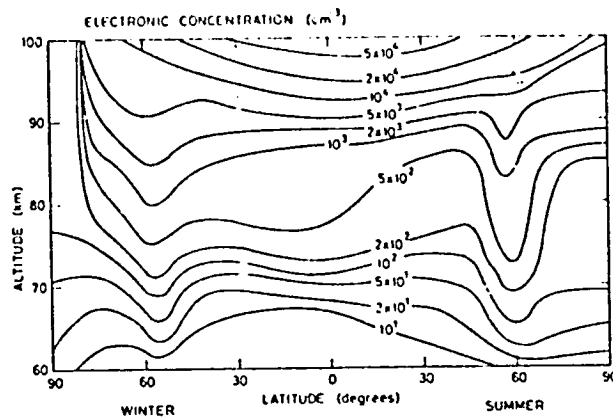


Figure 7. Meridional distribution of the 24 hours averaged concentration of electrons calculated with the NO distribution shown in figure 5. These values correspond to solar quiet conditions.

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