

INSTITUT D'AERONOMIE SPATIALE DE BELGIQUE

3 - Avenue Circulaire

B - 1180 BRUXELLES

## **AERONOMICA ACTA**

A - N° 270 - 1983

**Coupling between the thermosphere and  
the stratosphere : the role of nitric oxide**

by

**G. BRASSEUR**

BELGISCH INSTITUUT VOOR RUIMTE-AERONOMIE

3 - Ringlaan

B - 1180 BRUSSEL

## FOREWORD

This paper has been presented at the International Symposium on Ground-based Studies of the Middle Atmosphere held in Schwerin (GDR) from May 9 to May 13, 1983. It will be published in the Middle Atmosphere Program Handbook.

## AVANT-PROPOS

Cet article résume la communication présentée au symposium international intitulé "Ground-based Studies of the Middle Atmosphere" qui s'est tenu à Schwerin (RDA) du 9 au 13 mai 1983. Il sera publié dans le "Middle Atmosphere Program Handbook".

## VOORWOORD

Dit artikel werd voorgesteld tijdens het internationaal symposium over "Ground-based Studies of the Middle Atmosphere", gehouden te Schwerin (DDR) van 9 tot 13 mei, 1983. Het zal verschijnen in het "Middle Atmosphere Program Handbook".

## VORWORT

Dieser Text wurde vorgestellt während der internationale Tagung über "Ground-based Studies of the Middle Atmosphere", in Schwerin (DDR) von 9 zum 13. Mai, 1983. Der Text wird in dem "Middle Atmosphere Program Handbook" herausgegeben werden.

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

by

G. BRASSEUR

## 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.

## Résumé

Des calculs effectués à l'aide d'un modèle bi-dimensionnel montrent que les conditions chimiques à la stratopause sont liées à l'état de la thermosphere. Ce mécanisme de couplage peut être expliqué en hiver par le transport de l'oxyde d'azote vers le bas et dépend donc directement des conditions dynamiques dans la mésosphère et la thermosphère inférieure (circulation générale moyenne et ondes). En été, la photodissociation de l'oxyde d'azote joue un rôle important et le NO thermosphérique absorbe la radiation qui produit cette photodissociation dans la mésosphère et la stratosphère supérieure. Les perturbations dans la concentration de l'oxyde d'azote au-dessus de la mésopause peuvent donc produire des effets jusqu'à proximité de la stratopause.

## Samenvatting

Berekeningen die gedaan werden met behulp van een tweedimensionaal model tonen aan dat de chemische toestanden aan de stratopauze nauw verbonden zijn met de staat van de thermosfeer. Dit koppingsmechanisme kan gedeeltelijk verklaard worden door het benedenwaarts transport van stikstofoxyde tijdens de winter en is bijgevolg afhankelijk van de dynamische toestanden in de mesosfeer en de lagere thermosfeer (gemiddelde algemene circulatie en golven). Tijdens de zomer, speelt de fotodissociatie van de stikstofoxyde een belangrijke rol en de thermosferische NO absorbeert de straling die deze fotodissociatie veroorzaakt in de mesosfeer en de hogere stratosfeer. De storingen in de concentratie van de stikstofoxyde boven de mesopauze kunnen dus hun invloed doen gelden in de nabijheid van de stratopauze.

## Zusammenfassung

Berechnungen gemacht mit der Hilfe von einem zweidimensionalen Modell zeigen dass die Zustände an der Stratopause eng verbunden sind mit dem Zustand der Thermosphäre. Dieser Kupplungsmechanismus kann teilweise erklärt werden durch das hinuntertransportieren vom Stickstoffoxyd im Winter und ist folglich abhängig von den dynamischen Zuständen in der Mesosphäre und der niedriger Thermosphäre (mittlere allgemeine Zirkulation und Wellen). Im Sommer, ist die Photodissoziation vom Stickstoffoxyd sehr wichtig und das thermosphärische NO absorbiert die Strahlung die die Photodissoziation verursacht in der Mesosphäre und der höhern Stratosphäre. Die Störungen in der Konzentration vom Stickstoffoxyd über der Mesopause können also Effekt haben in der Nähe der 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  $\alpha$  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 ( $\text{N}_2\text{O}$ ) in the presence of the electronically excited atomic oxygen  $\text{O}(^1\text{D})$ . 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, ...) lead to the formation of NO molecules. Direct dissociation or dissociative ionization of  $\text{N}_2$  is another source of NO. Calculations made by Rusch et al. (1981) indicate that each ion pair formation produces 1.3 nitric oxide molecules. 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  $\text{O}_3$  density for different solar activity levels (Solomon and Garcia, 1983) give indirect evidence for such a  $\text{NO}_x$  transport above  $60^\circ \text{N}$  during the winter.

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  $\text{N}(^4\text{S}) + \text{O}_2$  reaction (reformation of NO after its photodissociation) and thus favors the  $\text{N}(^4\text{S}) + \text{NO}$  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.

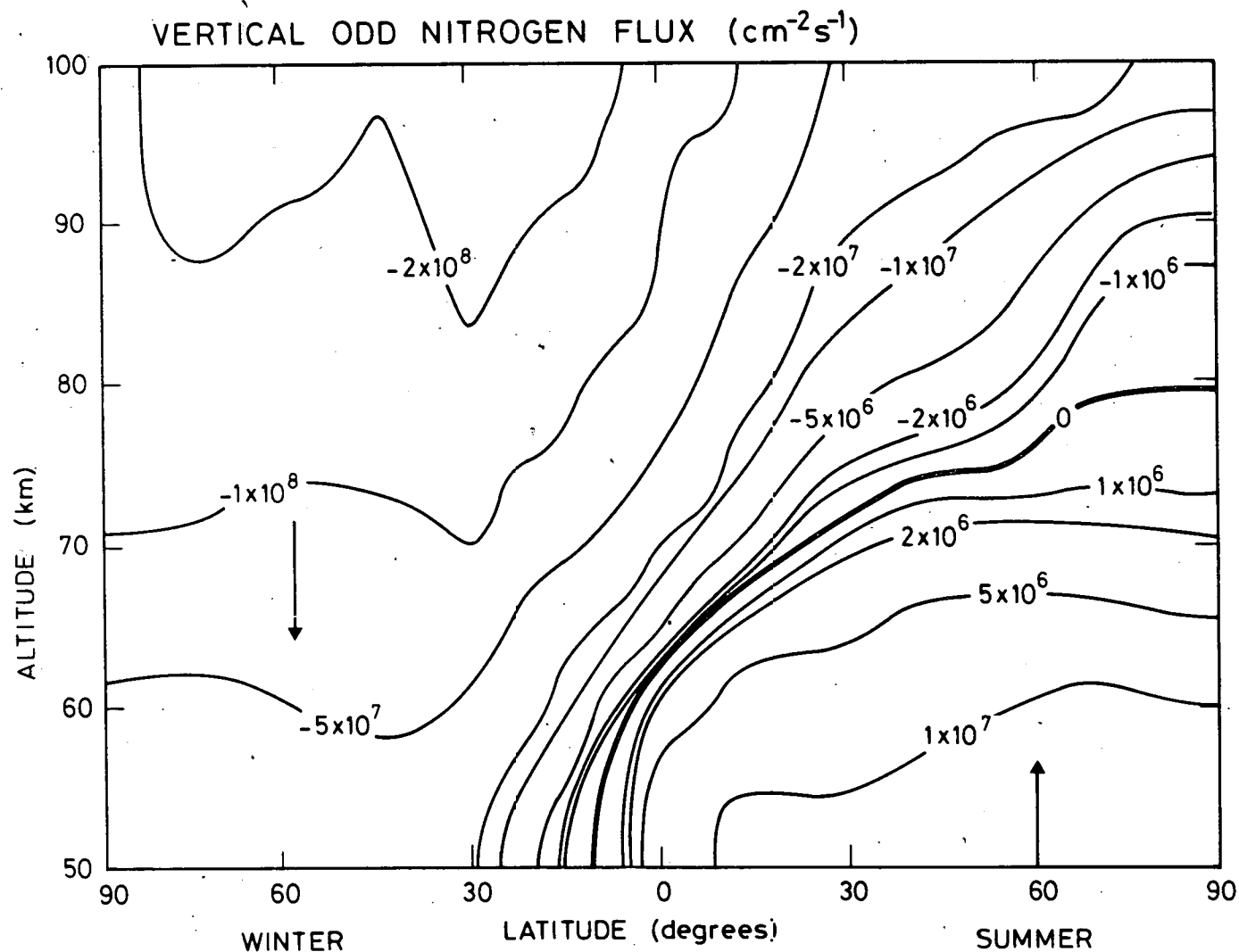


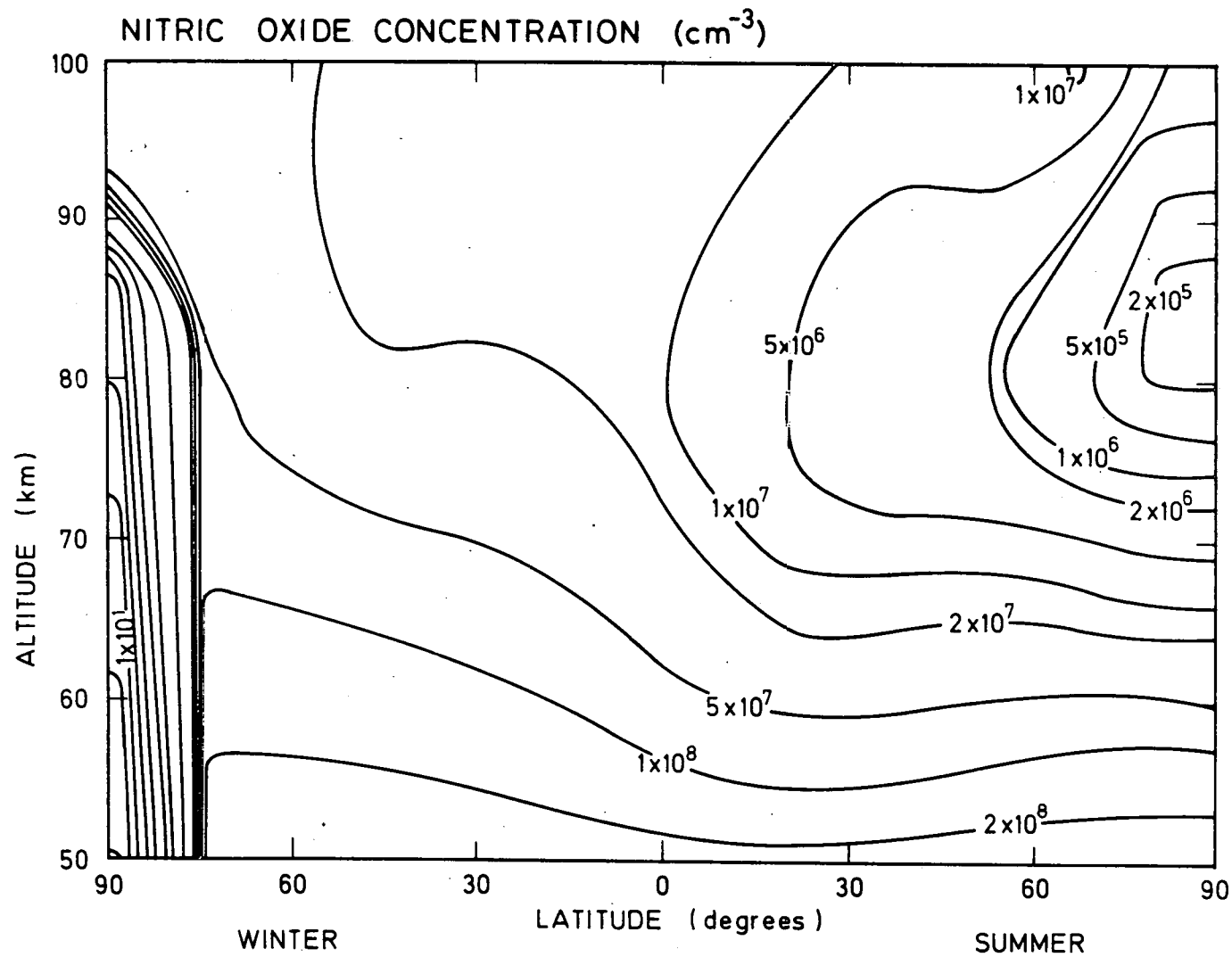
Fig. 1. Meridional distribution of the vertical flux component of nitric oxide calculated with the exchange coefficients suggested by Ebel (1980).

(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  $\delta$  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 more 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 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  $K_z$  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 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.





5-82 RUN 26

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

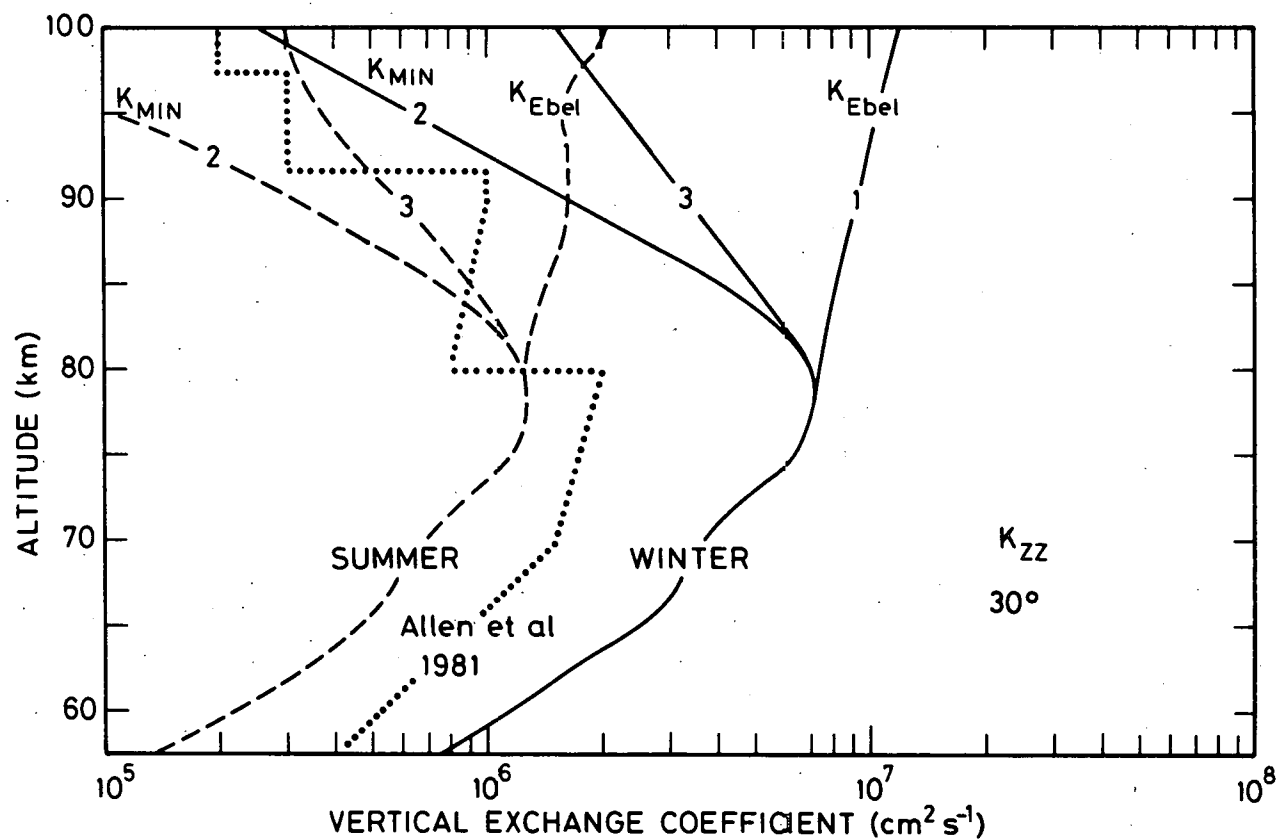


Fig. 3. Different vertical exchange coefficients  $K_{zz}$  adopted in the model calculations. Vertical distributions represented at  $30^\circ$  latitude for winter and summer conditions. The profile used by Allen et al. (1981) is also indicated.

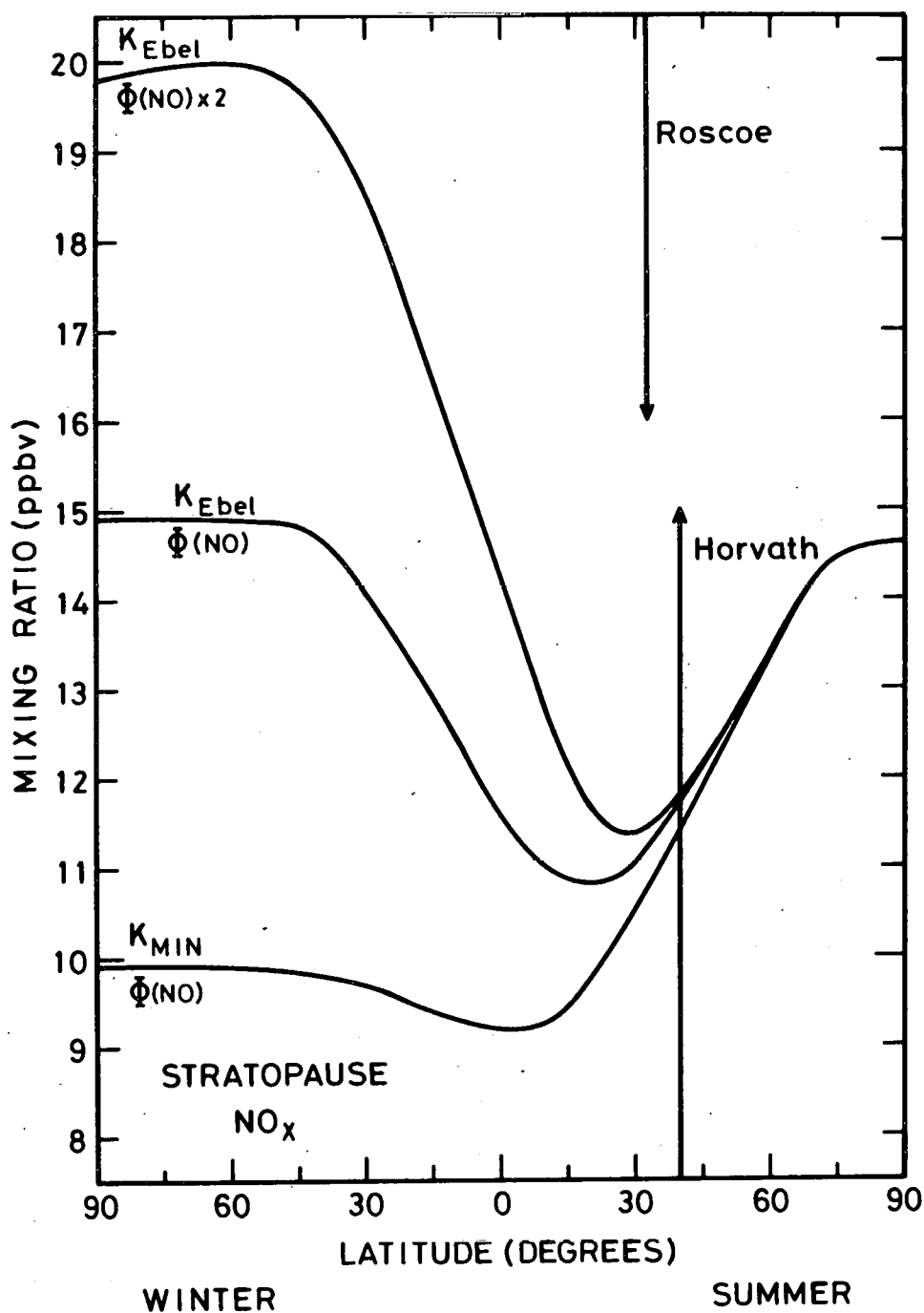


Fig. 4a. Latitudinal and seasonal distribution of the nitric oxide mixing ratio calculated at the stratopause (50 km altitude) assuming different conditions :  $K_{\text{Ebel}}$  refers to the exchange coefficients suggested by Ebel,  $K_{\text{Min}}$  to the smallest vertical eddy diffusion depicted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

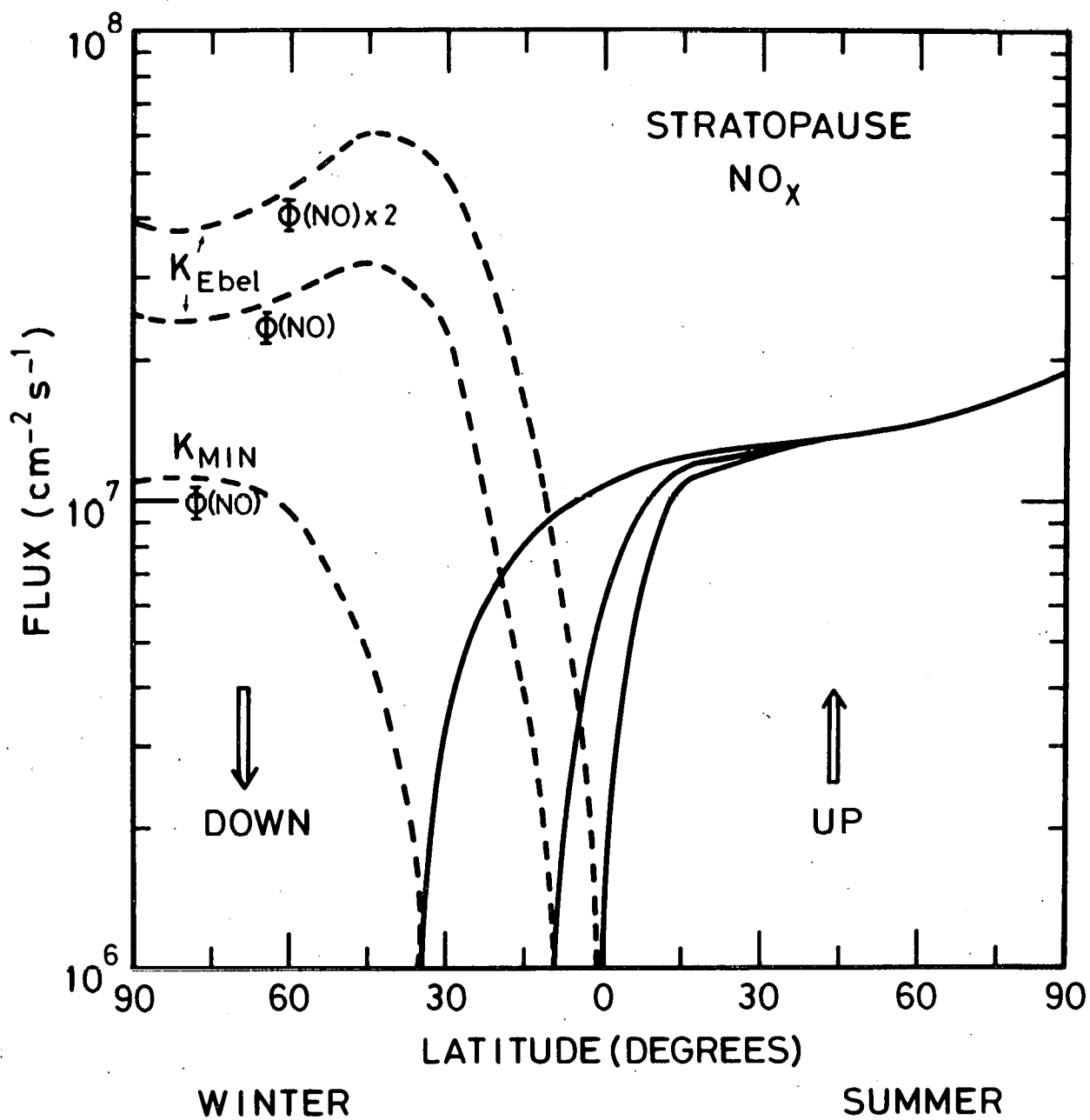
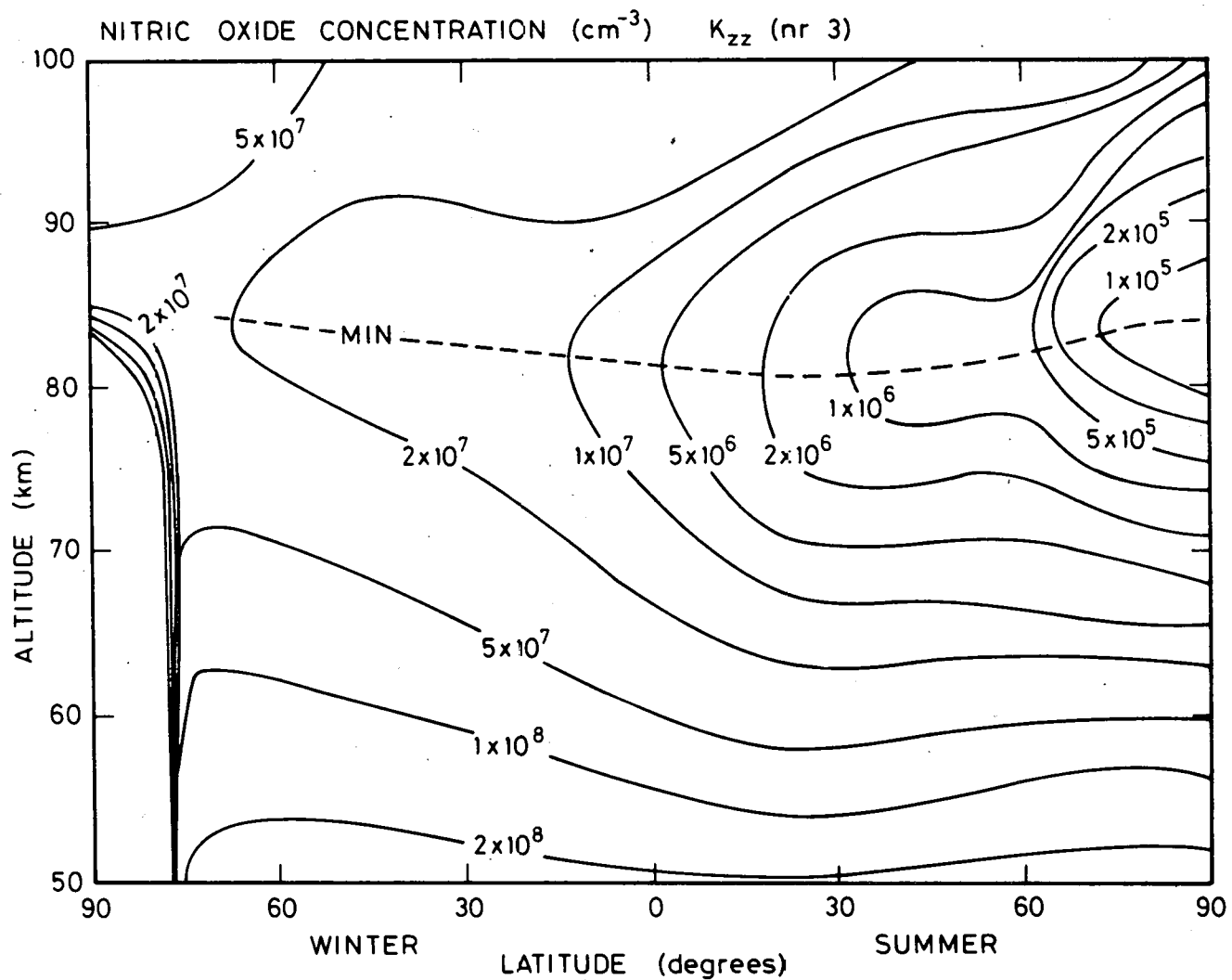


Fig. 4b. Same as in fig. 4a but for the nitric oxide vertical flux.

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  $10^7$   $\text{cm}^{-3}$ ) but that this minimum is considerably weaker during the winter ( $5 \times 10^6$  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.

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



RUN 38

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

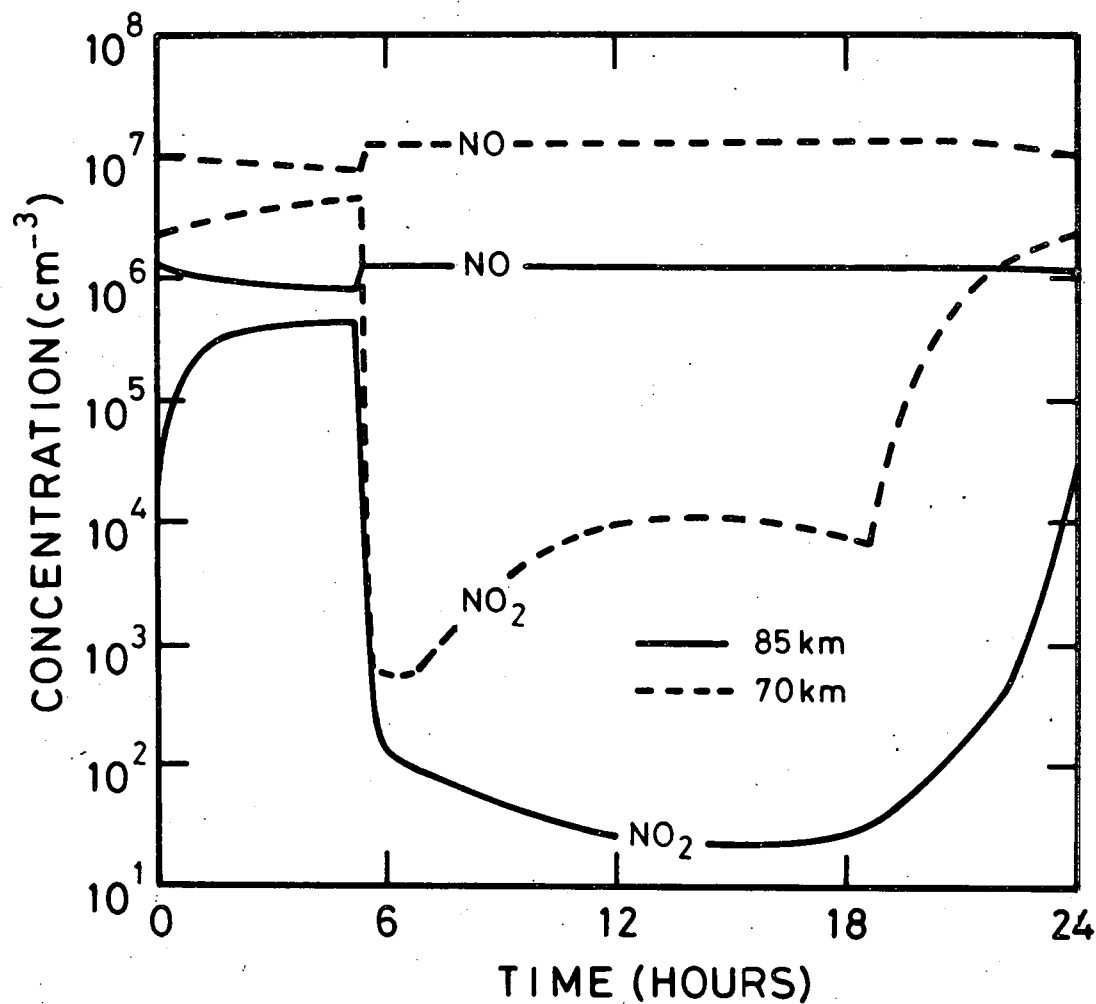
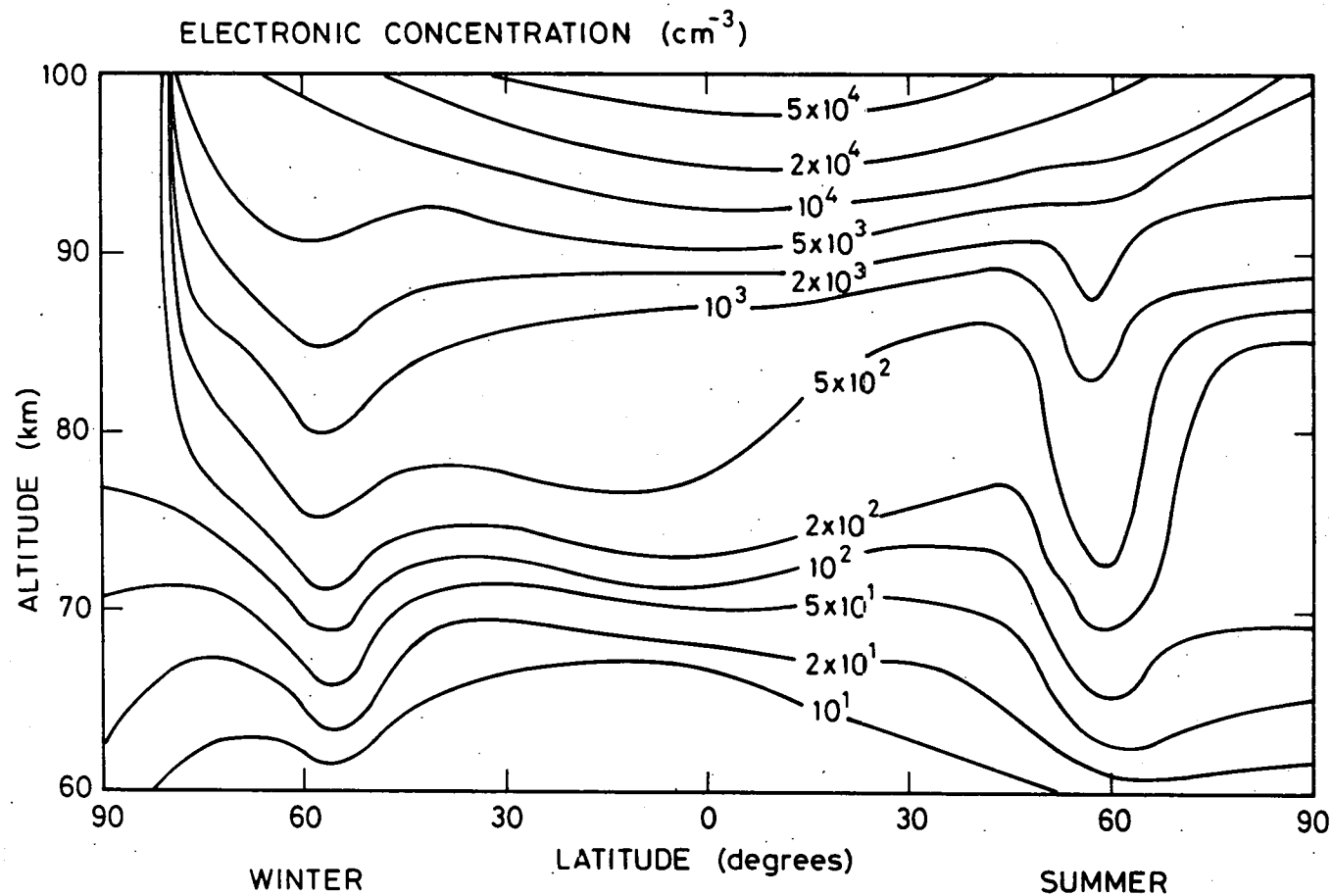


Fig. 6. Diurnal variation of nitric oxide and nitrogen dioxide calculated at 70 and 85 km altitude for spring conditions and 30 degrees latitude. The total NO<sub>x</sub> concentration is assumed to be  $1.2 \times 10^7$  and  $1.2 \times 10^6$  cm<sup>-3</sup> at 70 and 85 km respectively.



RUN 53

Fig. 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 quite conditions.



might provide indications on the relative role played by nitric oxide and by the temperature in the appearance of sudden anomalous absorption events.

## REFERENCES

- ALLEN, M., Y.L. YUNG and J.W. WATERS, Vertical transport and photochemistry in the terrestrial mesosphere and lower thermosphere (50-120 km), J. Geophys. Res., **86**, 3617, 1981.
- APPLETON, E., Regularities and irregularities in the ionosphere - I, Proc. Roy. Soc., A **162**, 451, 1937.
- BERAN, D. and W. BANGERT, Trace constituents in the mesosphere and lower thermosphere during winter anomaly events, J. Atm. Terr. Phys., **41**, 1091, 1979.
- BRASSEUR, G. and P. DE BAETS, Minor constituents in the mesosphere and lower thermosphere, in preparation (1983).
- DANILOV, A.D. and J. TAUBENHEIM, NO and temperature control of the D-region, Space Sci. Rev., **34**, 413, 1983.
- EBEL, A., Eddy diffusion models for the mesosphere and lower thermosphere, J. Atm. Terr. Phys., **42**, 617, 1980.
- FREDERICK, J.E., R.B. ABRAMS and P.J. CRUTZEN, The delta-band dissociation of nitric oxide : A potential mechanism for coupling thermospheric variations to the mesosphere and stratosphere, submitted to J. Geophys. Res., 1983.
- RUSH, D.W., J.C. GERARD, S. SOLOMON, P.J. CRUTZEN, and G.C. REID, The effect of particle precipitation events on the neutral and ion chemistry of the middle atmosphere, I Odd nitrogen, Planet. Space Sci., **29**, 767, 1981.
- SOLOMON, S., P.J. CRUTZEN and R.G. ROBLE, Photochemical coupling between the thermosphere and the lower atmosphere, I Odd nitrogen from 50 to 120 km, J. Geophys. Res., **87**, 7206, 1982.
- SOLOMON, S. and R.R. GARCIA, Transport of thermospheric NO to the upper stratosphere?, preprint, 1983.