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Final Report

Title: Understanding the latitude structure of nitric oxide in the mesosphere and lower thermosphere

Agency: **NASA** PI: **T.J. Fuller-Rowell** Award: **NAG5-2753**

The goal of the proposed work was to understand the latitude structure of nitric oxide in the mesosphere and lower thermosphere. The problem was portrayed by a clear difference between predictions of the nitric oxide distribution from chemical/dynamical models and data from observations made by the Solar Mesosphere Explorer (SME) in the early to mid eighties. The data exhibits a flat latitude structure of NO, the models tend to produce at equatorial maximum.

The first task was to use the UARS-HALOE data to confirm the SME observations. Data from the UARS-HALOE instrument was successfully extracted from the database for the years 1992 -1995 inclusive. These data were converted from mixing ratios to absolute number densities, and sorted for periods surrounding the equinoxes (one month either side) for both sunrise and sunset periods. Maps of NO density as a function of latitude and height, from 70 to 130 km were created for each equinox for both sunrise and sunset.

The purpose of this first phase was to verify the UARS NO structure is consistent with the SME data. One of the fundamental differences between the UARS and SME observations is the sampling. SME, in polar orbit, recorded the latitude structure in the afternoon sector each overpass. UARS, however, in its inclined orbit only builds the latitude picture at sunrise and sunset over a period of about a month. The structure is therefore modulated by any change that has occurred over that period in the production sources, such as EUV flux. The data must therefore be sorted as a function of solar activity, and, if the data is over a short period, it must also be sorted by geomagnetic activity. Sufficient data now exists that the equinox structure can be obtained by sorting only by solar activity.

Another difference in the UARS-HALOE data is that all longitudes are sampled. A picture of the latitude /longitude distribution can be obtained at sunrise and sunset. This presentation of the data clearly shows the response to geomagnetic or auroral activity. In the longitude sector of the magnetic pole, in both north and south hemispheres, the signature of auroral production penetrates well into mid latitudes in the geographic frame. It is therefore important when averaging in longitude to use the geomagnetic coordinate system. This was done for the figures presented in this report.

A useful consequence of the sampling in latitude and longitude is that it is possible to search for a signature of the South Atlantic Anomaly (SAA). This region has been known for decades to contain significantly higher fluxes of energetic proton and electron precipitation. What has not been quantified is the response to this source. The UARS NO data was analyzed at various altitudes in the mesosphere and lower thermosphere to determine if any signature of the SAA was present; none could be found.

The important conclusion from this first phase of the data analysis was that the HALOE sunset data showed close agreement with the 3.00 pm SME data This is illustrated in Figure 1, which shows both the latitude structure and the absolute magnitudes are in excellent agreement. Small differences were also seen in the sunrise and sunset structure.

The next task was to determine the cause of the discrepancy between modeled and observed nitric oxide latitude structure. Progress in modeling has involved, firstly, the implementation of a revised solar flux model for soft X-ray flux. This new EUV model incorporated data recorded by the SOLRAD satellite. The data was completely recalibrated and revealed soft X-ray fluxes significantly larger than previous empirical solar flux models. It has been shown by many authors that the soft X-rays are responsible for a large part of the NO production at mid and low latitudes.

This new solar flux model was incorporated into the 2D zonally-averaged upper mesosphere and thermosphere model to investigate the impact on the simulated latitude structure of NO. The results showed a slightly weaker latitude structure than was apparent using the original Hinteregger spectrum, improving the agreement between the model and SME and UARS data somewhat, but the model still showed a significant equatorial maximum.

To perform more comprehensive model sensitivity studies a one-dimensional photo-chemical diurnal model was used. The 1D model was run for a series of latitudes to build a picture of the latitude structure. The model was used to investigate the impact of three changes in the odd nitrogen chemistry. These include: use of the new JPL rates for the reaction $N(^4S)+O_2 \rightarrow NO+O$; the effect of increased photolysis of NO by S-R bands; and the effect of using faster collisional deactivation rate for reaction $N(^4S)+O_2 \rightarrow NO+O$. Figure 2 illustrates the effect of each of these processes . The combination has clearly lead to a flattening of the latitude variation of the NO density at the height of the peak near 110 km. The lower panel shows the equivalent height latitude assembled from the series of 1D simulations at a series of latitudes. This work was presented at the AGU fall meeting 1995 (Fuller-Rowell et al. 1995). Note that the 1D model does not include auroral precipitation so that the high latitude increase is not produced or expected.

At first sight it appears the problem can be resolved by adjusting odd nitrogen reaction rates. When this knowledge was incorporated into a three-dimensional, chemical/ dynamical model the results could not be duplicated. The three dimensional model clearly differs from the 1D model in a number of ways. The neutral atmosphere and temperatures are calculated self-consistently rather than relying on MSIS empirical model; horizontal advection is included to transport the long-lived chemical species; the 3D model uses a very simple treatment for estimating the photo-electron ionization rates; and the 3D model includes auroral production with the appropriate offset between the geomagnetic and geographic coordinate systems. The final phase of the project was to determine which of these differences was the cause of the difference between the 3D model and the data/1D model. The theory for the dependence of PE ionization on NO structure was presented at the Birmingham COSPAR (Fuller-Rowell et al., 1996).

The results from the final phase indicated that the latitude structure in the photo-electron (PE) production rate was the most important. In the early versions of the 3D code the assumption was made that the ratio between solar photon ionization and secondary PE ionization was simply a function of optical depth; this translates to a pressure level dependence only. The 1D dimensional code was not so restricted by computer resources so used a more sophisticated PE production algorithm. Examination of the latitude structure of the ratio of photon/PE ionization rates in the 1D model revealed a latitude, or zenith angle, dependence in addition to the pressure level variation. The theory is clear: photon ionization rates, near the NO peak height around 110 km, arise from photons with wavelengths from soft X-rays to 102. nm. Soft X-rays, producing the PE spectrum, tend to have smaller optical depths compared to the longer wavelength photon source. This leads to a flatter latitude structure in the PE ionization source and introduces a latitude dependence in the ratio of photon/PE ionization rates. This latitude dependence in the PE ionization rates was parameterized from the 1D photo-electron transport code as a function of solar zenith angle, solar cycle, and intensity of X-ray flux, and was incorporated into the 3D model. Using this parameterized photo-electron ionization rate model the 3D simulations were able to produce a much flatter latitude structure for nitric oxide, in much better agreement with the SME and UARS-HALOE data.

Although it now appears that chemistry and the latitude structure of the primary ionization sources can resolve much of the NO problem, the other primary influence on the latitude structure is transport by the wind field. This aspect was pursued by identifying empirical zonally-averaged wind models to incorporate into the model. Three wind models were identified. The first, and most obvious is the CIRA wind model assembled from an amalgamation of thermospheric and middle atmosphere observation. The second is a model assembled from many years of ground-based wind observations from meteor traces and partial reflection techniques, by Portnyagin and Soloveva. The model covers altitudes from 70-110 km so must be merged either with the CIRA model at higher altitudes of with the modeled structure. The third wind model identified as a potential source for this study is that constructed from the UARS WINDII data by Charles McLandress. This model has its attractions since it is consistent, in time, with the observing periods used to construct the NO distribution. The altitude range covered by the model is limited to the 70-110 km by the lack of suitable emission features in the WINDII observations. Although altering the wind field did introduce additional structure in the latitude distribution of NO, it did not significantly improve the agreement between model and data at equinox.

The UARS-HALOE NO data was also sorted as a function of season and solar activity. A subset of the data is shown in Figure 3. The sunrise and sunset data has been sorted in three levels of solar activity and three seasons (Nothern summer, Northern winter, and equinox). The data shows a clear pattern, with a steady increase in mid and low latitude NO with the rise of the solar cycle. There is also a distinct difference between the height/structure in the illuminated summer high latitude compared with winter. Simulations with the 3D model shows reasonable agreement with the overall structure as a function of season, latitude, and solar cycle (Figure 4).

A review of modeling the distribution of nitric oxide including the results of this study will be presented at the Nagoya COSPAR meeting, and will be submitted for publication.

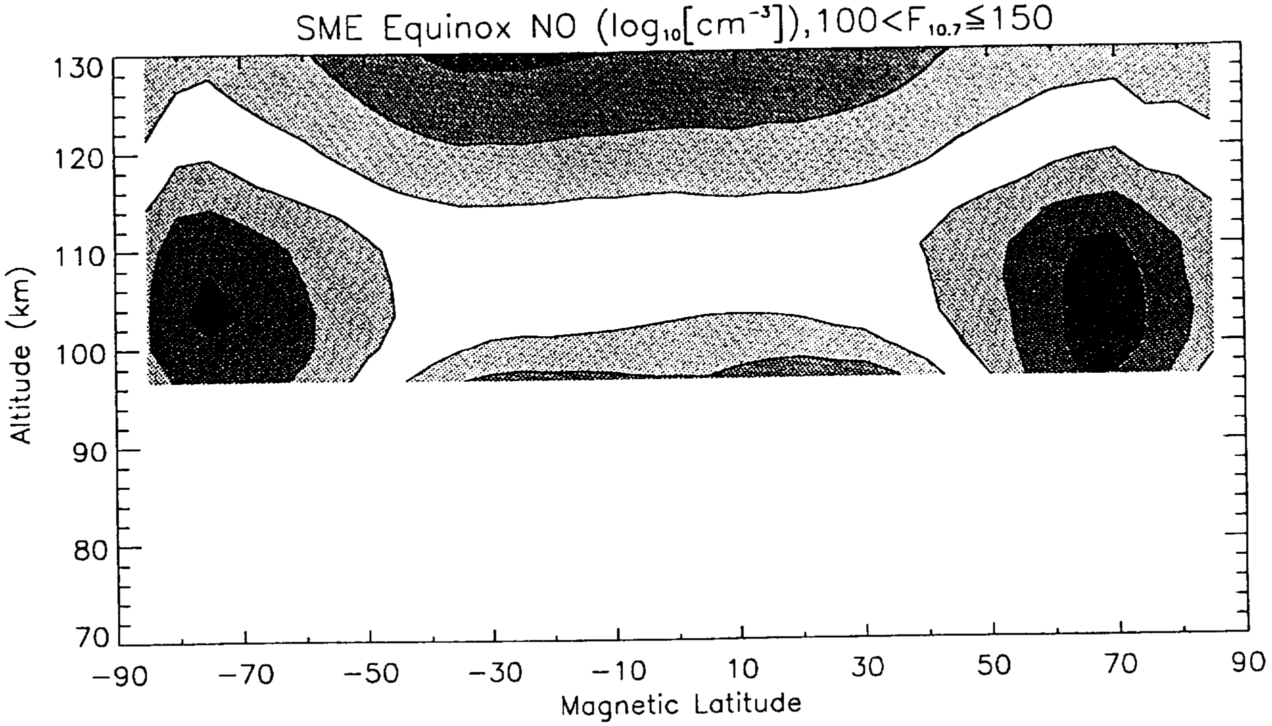
Figure Captions

Figure 1. Comparison of the latitude structure from SME at the 3pm local time sector (upper panel) with HALOE observations at sunset (lower panel). Both are from data one month either side of equinox at moderate solar activity.

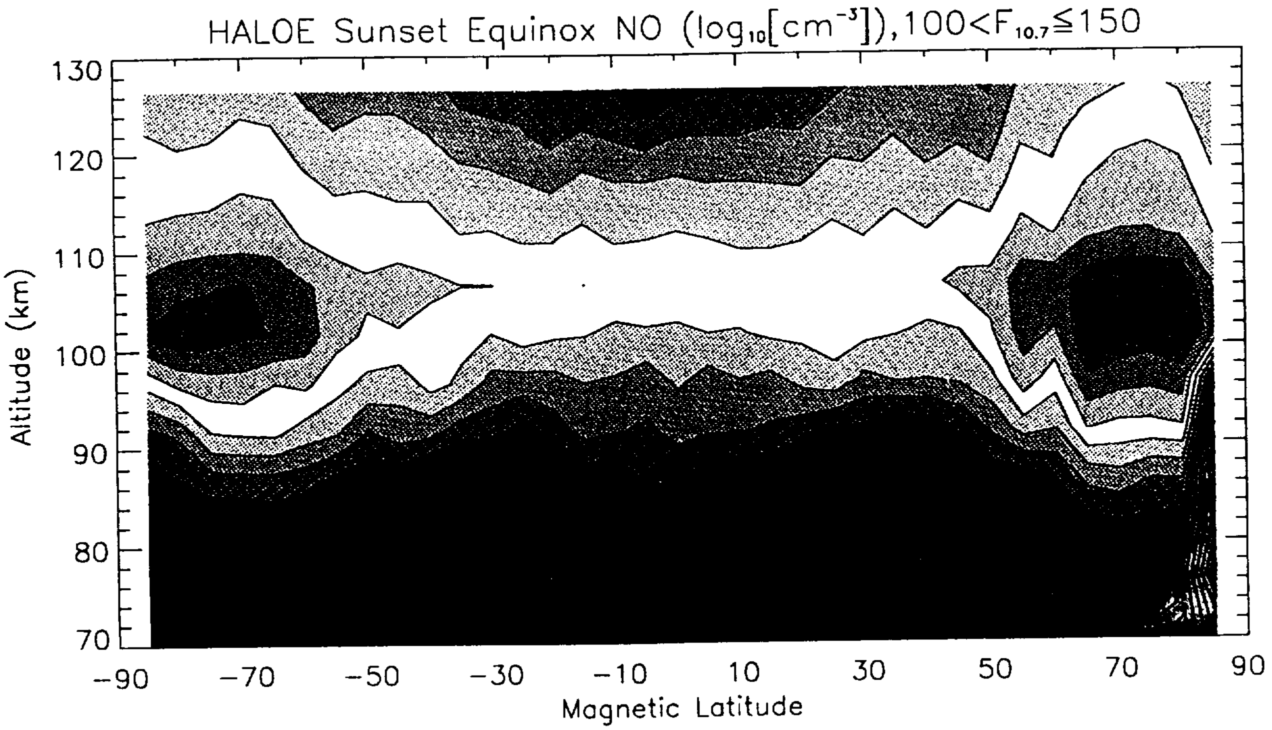
Figure 2. Top panel shows the effect on the latitude structure of NO at 106 km of changing chemical reaction rates (see text). The lower panel shows the height/latitude structure with all three reactions taken into consideration.

Figure 3. Summary of seasonal, latitude, and solar cycle dependence of NO density from HALOE sunset observations.

Figure 4. Model simuations of seasonal, latitude, and solar cycle dependence of NO density at sunset for comparison with Fig. 3.



SME Equinox NO ($\log_{10}[\mathrm{cm}^{-3}]$), $100<F_{10.7}\leq 150$



HALOE Sunset Equinox NO ($\log_{10}[\mathrm{cm}^{-3}]$), $100<F_{10.7}\leq 150$

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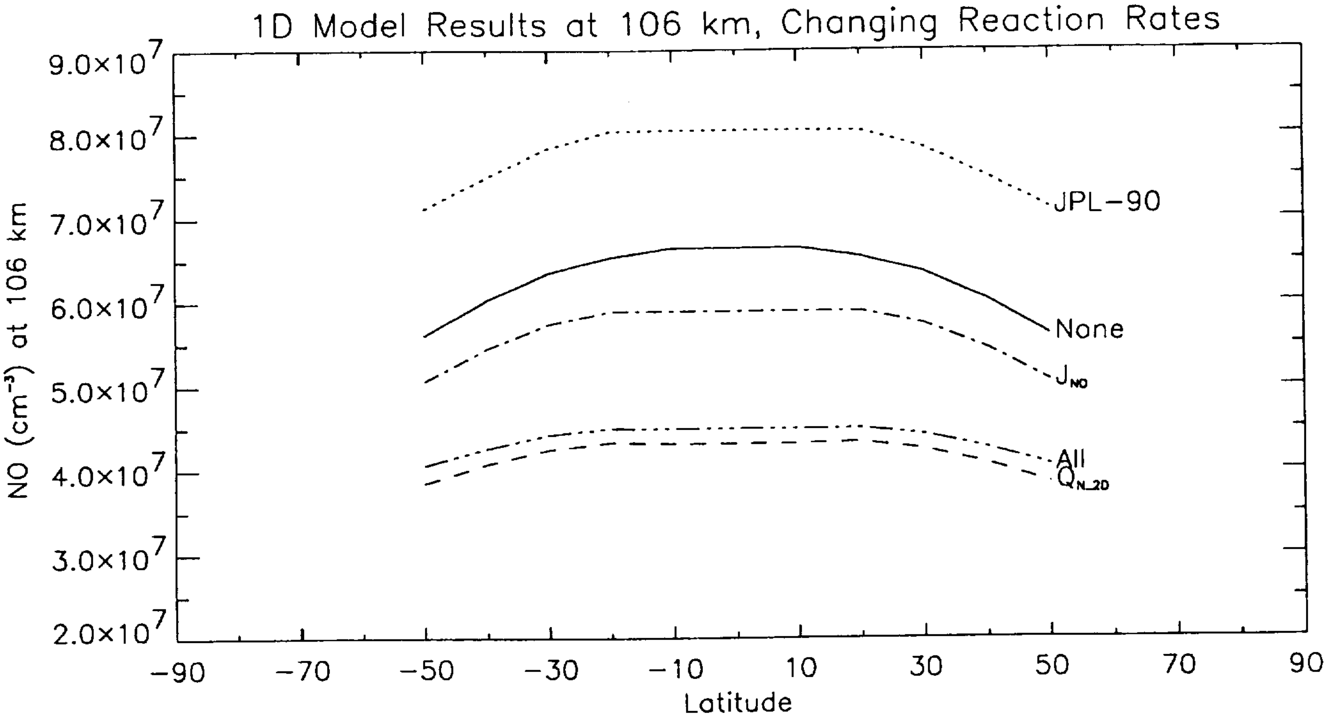
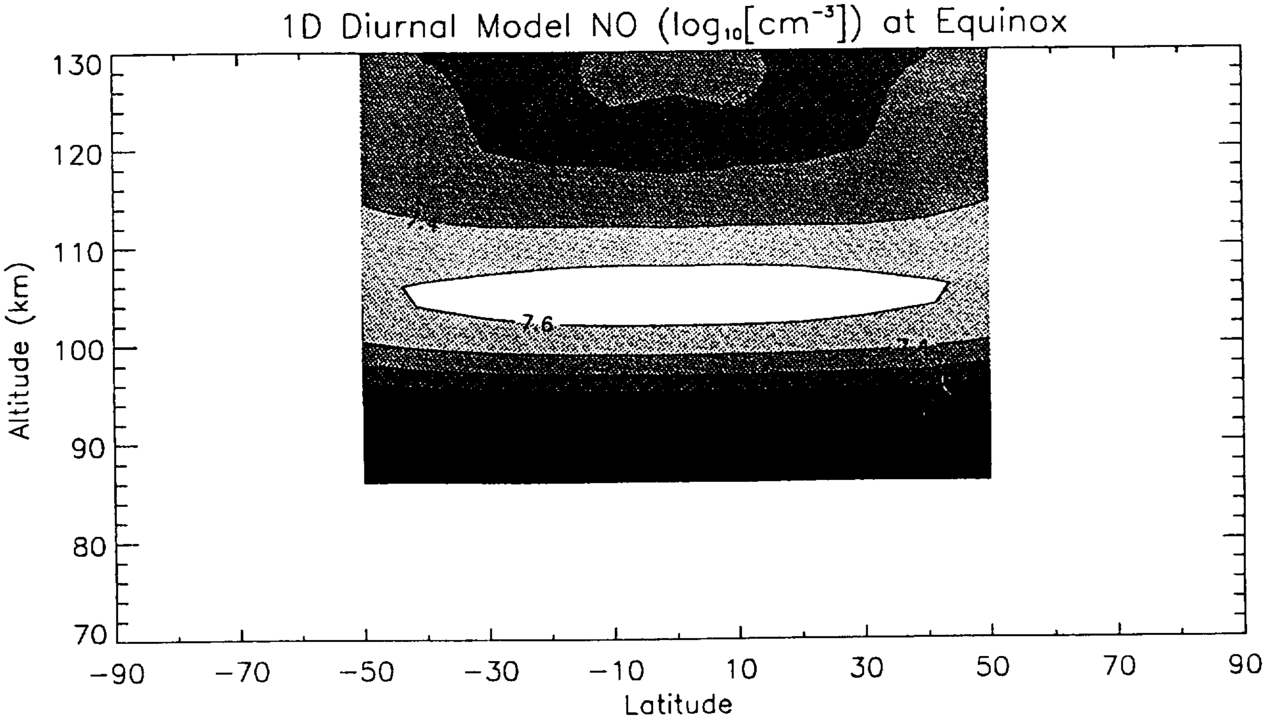
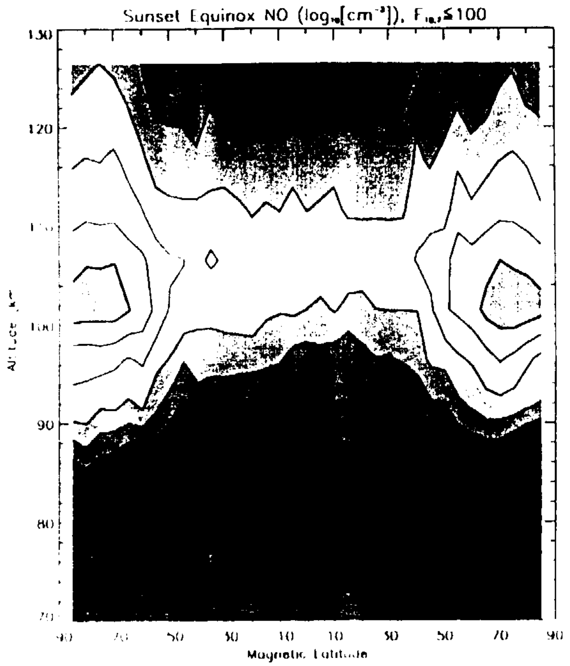
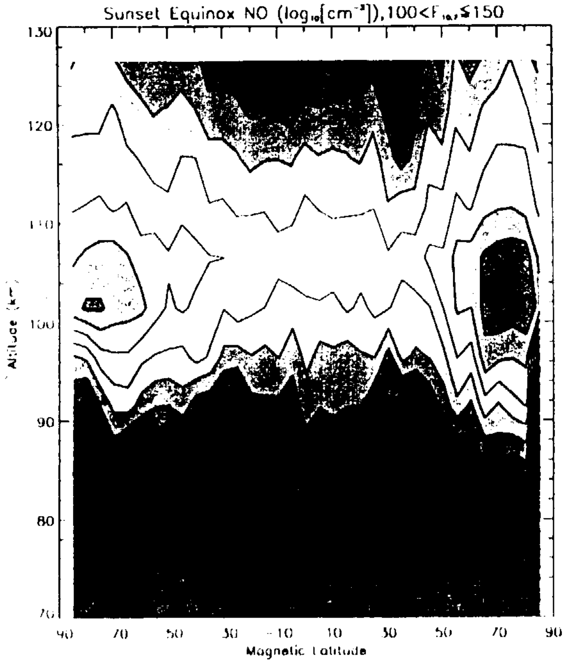


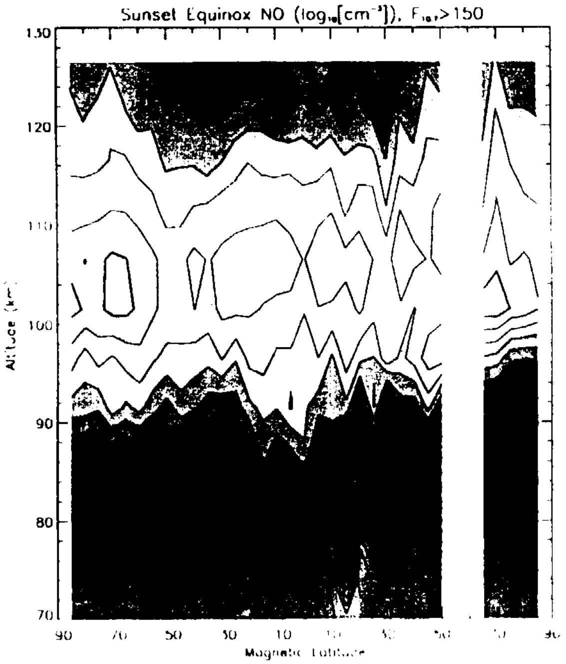
1D Model Results at 106 km, Changing Reaction Rates



1D Diurnal Model NO ($\log_{10}[cm^{-3}]$) at Equinox


Sunset Equinox NO ($\log_{10}[\mathrm{cm}^{-3}]$), $F_{10.7}\leq 100$


Sunset Equinox NO ($\log_{10}[\mathrm{cm}^{-3}]$), $100<F_{10.7}\leq 150$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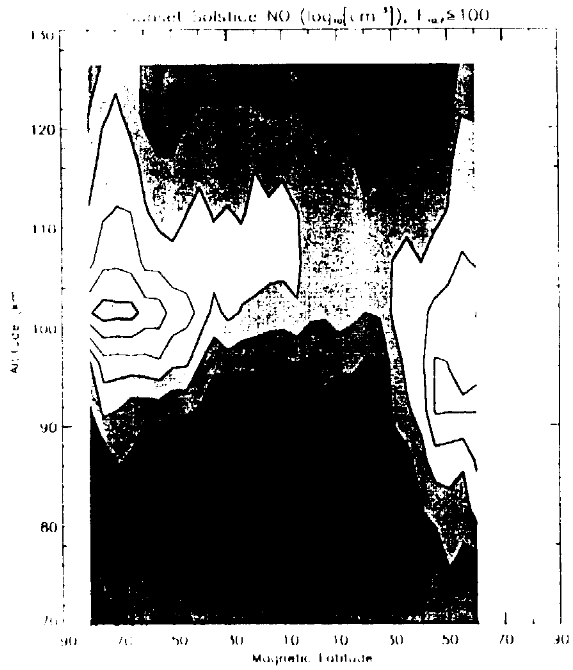
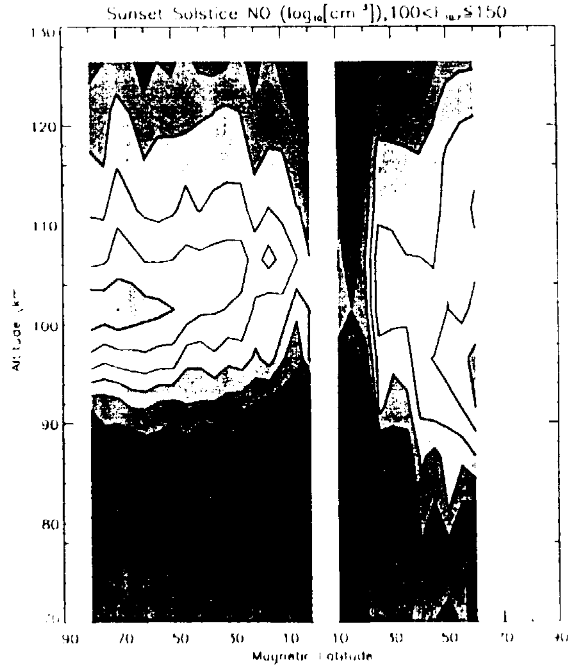
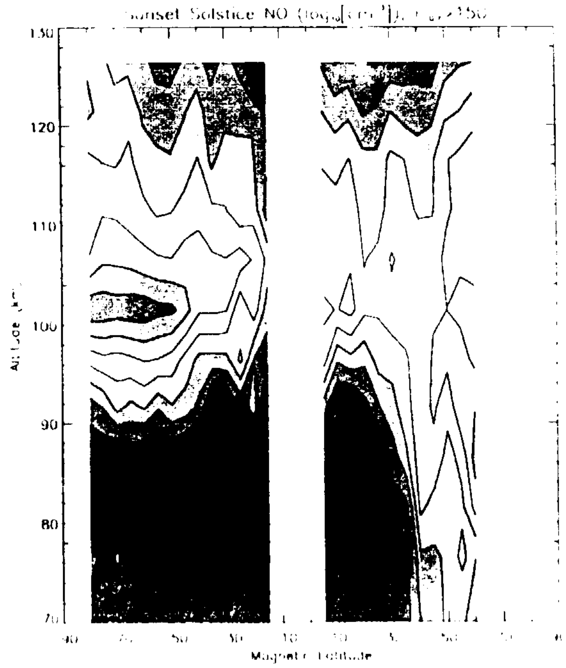

Sunset Solstice NO ($\log_{10}[\mathrm{cm}^{-3}]$), $F_{10.7}\leq 100$


Sunset Solstice NO ($\log_{10}[\mathrm{cm}^{-3}]$), $100<F_{10.7}\leq 150$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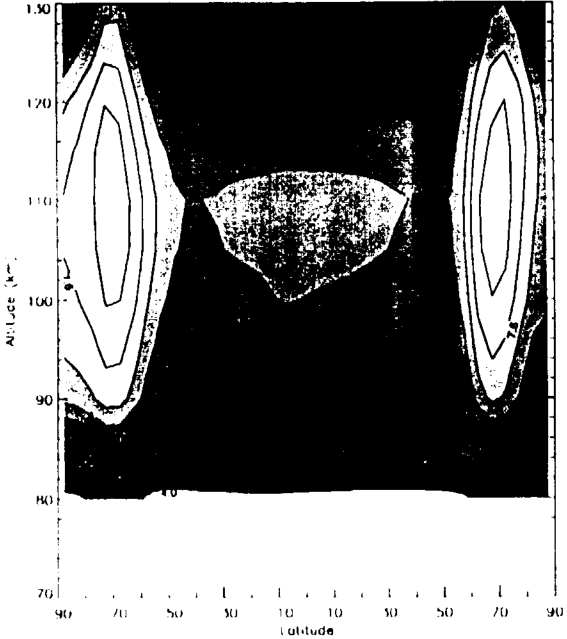
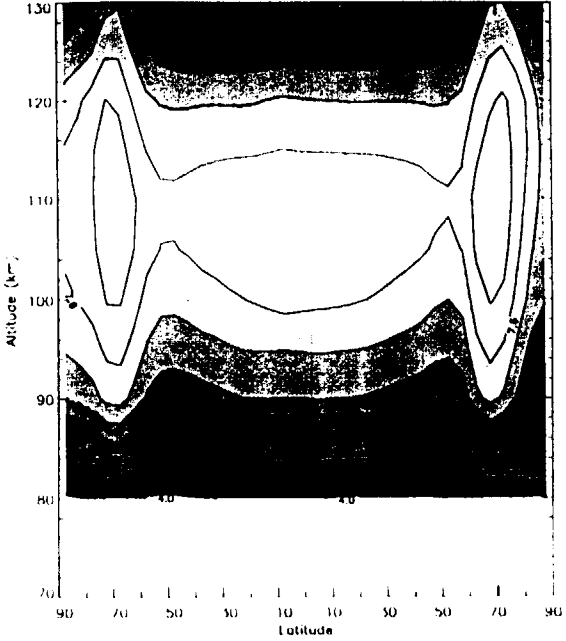
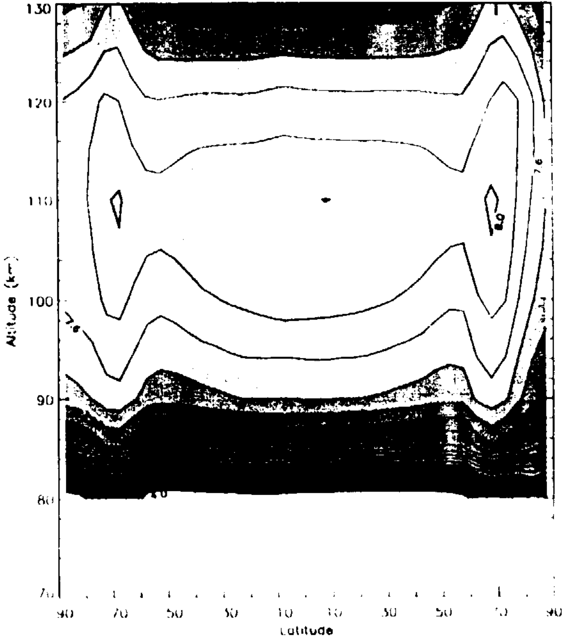
3-D Model Sunset Equinox NO ($\log_{10}$[cm^{-3}]), $F_{10.7}$=80



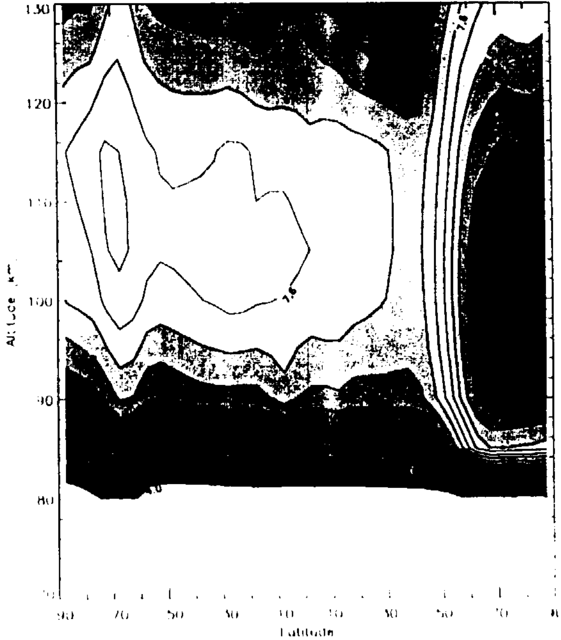
3-D Model Sunset Equinox NO ($\log_{10}$[cm^{-3}]), $F_{10.7}$=125



3-D Model Sunset Equinox NO ($\log_{10}$[cm^{-3}]), $F_{10.7}$=180



3-D Model Sunset Solstice NO ($\log_{10}$[cm^{-3}]), $F_{10.7}$=125



3-D Model Sunset Solstice NO ($\log_{10}$[cm^{-3}]), $F_{10.7}$=180