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IMPACT OF SPACE SHUTTLE ORBITER REENTRY ON MESOSPHERIC NO_x*

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Abstract

Shuttle orbiter reentry will produce large amounts of nitric oxide (NO) through shock heating at mesospheric altitudes. The effects of this reentry are modeled by considering an impulsive source of NO in time-dependent equations including photochemistry and transport. The model uses an odd-nitrogen approach similar to Strobel's. Parameterized flux boundary conditions are imposed at the mesopause and stratopause and concentrations of the odd nitrogen species (NO, NO_2, NO^+, $N(^4S)$ and $N(^2D)$) are found numerically by a finite difference scheme. A localized disturbance can last many hours, depending on the effectiveness of eddy transport. Although the model is one-dimensional, effects of horizontal transport are also included approximately.

I. Introduction

Theoretical modeling of the behavior of minor constituents in the mesosphere is difficult enough even in an assumed steady state but nevertheless we have performed some time-dependent calculations of odd nitrogen species. The reason we did this was to quantitatively study a situation which has been discussed qualitatively in many circles in the past year or two, namely what will happen when the proposed space shuttle orbiter reenters the earth's atmosphere. The orbiter itself is to be an aircraft 36 m long and 23 m wingspan, weighing 90,000 kg, close to the dimensions of a commerical airliner. Its reentry is to be characterized by the orbiter's losing most of its orbital kinetic energy along an almost constant altitude leg of its trajectory at about 70 km, extending roughly a quarter of the way around the earth.

In the shock-heated wake the ambient atmosphere is disturbed; much of the molecular oxygen and nitrogen is converted to nitric oxide, atomic nitrogen and atomic oxygen. Detailed aerodynamical estimates of the extent of this conversion have been made by Park.[1] Such estimates depend on details of the trajectory, the aircraft materials and many other aerodynamic considerations. Park has outlined these and shown that for example one can expect the orbiter to produce an amount of NO of the order of 10% of the orbiter mass on each reentry. This means about 9000 kg of nitric oxide will be distributed along the reentry trajectory along a path, say 10^4 km long. Each 1000 kg of NO is about 9×10^{28} molecules so the strength of such a line source is about 10^{21}/cm.

We think it is not too difficult to dismiss the likelihood of global effects of this large local disturbance. One argument proceeds simply by noting that even 100 missions per year adds only 10^6 kg or 1000 tons of NO per year to the mesosphere while natural sources are thought to provide about 100 times more than this. For example, the averaged downward flux of NO from the thermosphere into the mesosphere is of the order of 10^8 kg or 10^5 tons per year if one assumes fluxes like those of Strobel.[2,3]

The more localized disturbance cannot be so easily dismissed. One can note the physical and chemical mechanisms which should act to destroy or dilute the disturbance, namely transport and mixing processes and photochemical reactions. One can also use best guesses of typical wind speeds, molecular and eddy diffusion coefficients, chemical reaction rates and gaseous concentrations and estimate which processes will produce what effects and how fast, and of course, we have done this to get a rough feeling for the duration and extent of the disturbance. But the picture is a complicated one and we wanted to be as quantitative as possible without becoming entangled in the numerical analysis problems so common in modeling. We have thus used a fairly simple model which includes the important photochemistry and transport processes for the mesosphere.

II. Model

Table 1 shows the photochemical reaction scheme.

Table 1 (Adapted from Strobel[2,3])

REACTIONS INVOLVING N, NO, AND NO^+
below 90 km but above 50 km

(1)	$h\nu + N_2 \rightarrow N(^4S) + N(^4S)$	J_1
(2)	$N(^4S) + NO \rightarrow N_2 + O$	2.2×10^{-11}
(3)	$N(^4S) + O_2 \rightarrow NO + O$	$2.4 \times 10^{-11} \exp(-3975/T)$
(4)	$N(^4S) + O_2(^1\Delta) \rightarrow NO + O$	3.0×10^{-14}
(5)	$N(^4S) + O_3 \rightarrow NO + O_2$	$3.0 \times 10^{-11} \exp(-1200/T)$
(6)	$N(^4S) + O + M \rightarrow NO + M$	$1.0 \times 10^{-32}\, n(M)$
(7)	$h\nu + NO \rightarrow N(^4S) + O$	J_7
(8)	$h\nu + NO \rightarrow NO^+ + e$	I_8
(9)	$NO^+ + e \rightarrow N(^4S) + O$	$2.5 \times 10^{-7}\, (T/1000)^{-1.5}$
(10)	$NO^+ + e \rightarrow N(^2D) + O$	$7.5 \times 10^{-7}\, (T/1000)^{-1.5}$
(11)	$N(^2D) + O_2 \rightarrow NO + O$	6.0×10^{-12}
(12)	$N(^2D) + NO \rightarrow N_2 + O$	2.2×10^{-11}
(13)	$O_3 + NO \rightarrow NO_2 + O_2$	$9.5 \times 10^{-13} \exp(-1240/T)$
(14)	$O + NO + M \rightarrow NO_2 + M$	$6.8 \times 10^{-32}\, n(M)$
(15)	$O + NO \rightarrow NO_2 + h\nu$	6.4×10^{-17}
(16)	$N(^2D) + O \rightarrow N(^4S) + O$	2.0×10^{-13}
(17)	$N(^4S) + OH \rightarrow NO + H$	6.8×10^{-11}
(18)	$NO_2 + O \rightarrow NO + O_2$	$3.2 \times 10^{-11} \exp(-300/T)$
(19)	$NO_2 + h\nu \rightarrow NO + O$	8.0×10^{-3}
(20)	$NO_2 + N(^4S) \rightarrow N_2O + O$	1.2×10^{-11}
(21)	$NO_2 + N(^4S) \rightarrow N_2 + O + O$	
(22)	$NO_2 + N(^4S) \rightarrow N_2 + O_2$	
(23)	$NO_2 + N(^4S) \rightarrow NO + NO$	0.6×10^{-11}

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This set of reactions and reaction rates is the same as Strobel's except that we have added several reactions, e.g., $N(^2D) + NO \rightarrow N_2 + O$. By placing our upper boundary at 90 km we can eliminate the need to treat most of the ion-molecule reactions, leaving only (8), (9) and (10) for production and loss of NO^+. The regions above 90 km merely become sources of odd nitrogen for the mesosphere through a downward flux boundary condition; the strength of this source is varied by treating the downward flux as a parameter in the model.

We have used these chemical reactions in a time-dependent continuity equation written for ON ≡ odd nitrogen following Strobel's method. The idea is to lump all the nitrogen constituents except N_2 into one fictitious component called ON then solve the continuity equation for ON, then to use algebra on the resultant profile to solve for all the separate constituent concentrations, like $N(^4S)$, $N(^2D)$, NO, NO_2, and NO^+. This procedure is justified by the fact that chemical lifetimes for these constituents are less than transport times in the mesosphere as Strobel has shown. Thus, the algebraic equations we solve for the separate constituent concentrations are relationships based on photochemical equilibrium. The ON continuity equation itself includes the important transport terms and is written for the range 50 to 90 km.

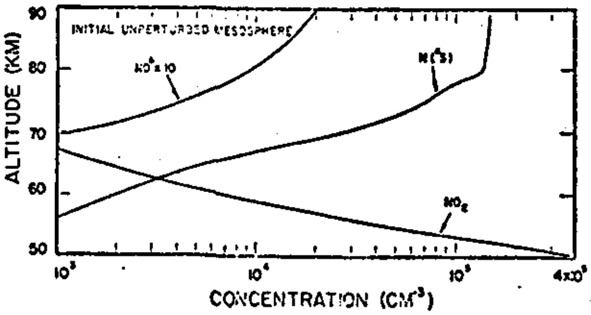

Figure 1. Undisturbed Mesospheric N, NO_2, NO^+ Profiles

Figure 1 shows the calculated steady state mesospheric odd nitrogen densities for the flux boundary conditions; $\phi_{90} = -10^8$, $\phi_{50} = 10^6$ cm^{-2} sec^{-1}. The NO density is off scale and will be seen in a later figure. $N(^2D)$ vanishes on this scale and is not shown. These results indicate one possible natural mesosphere which we have used as the undisturbed mesosphere which is to be perturbed by the shuttle orbiter reentry.

These profiles are from numerical solutions of a finite difference form of the one-dimensional continuity equation which includes the chemistry shown in Table 1 and all important transport processes in the vertical. Eddy diffusion is dominant transport term with $K_e = 5 \times 10^4$ at 50 km (as shown by Strobel), 5×10^6 at 90 km, varying exponentially with altitude.

One further feature of the model should be discussed before adding the shuttle orbiter perturbation. Although our model solves a one-dimensional continuity equation in the vertical we also allow for horizontal depletion of the disturbance. This is done by appending to the numerical solution an analytic solution of a diffusion equation in the horizontal. The horizontal eddy or molecular diffusion coefficient appears as a parameter in this diffusion equation. This allows us to watch the material leak out the sides of a box perpendicular to the trajectory of the orbiter. The disturbance has been initially spread into a box 1 km wide in both the horizontal and vertical. That point in time is labelled t = o and the solution is begun from there considering vertical diffusion plus horizontal depletion from the 1 km box. Thus the perturbed concentrations are averaged over a box $(1\ km)^2$ perpendicular to the trajectory.

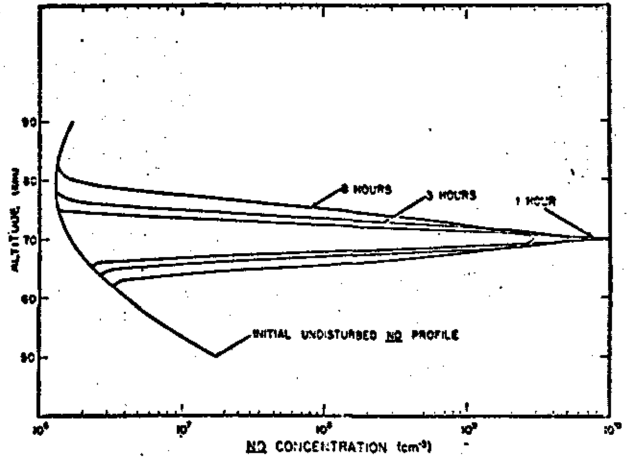

Figure 2. Undisturbed NO Profile with Shuttle Perturbation for Low Horizontal Diffusion Coefficient

Figure 2 shows the undisturbed background profile of NO with several perturbed profiles shown also. The times shown are 1, 3 and 8 hours after the time when the perturbation had spread to $\approx (1\ km)^2$ area around the initial wake line source. The horizontal diffusion coefficient was taken to be 10^3 at 50 km up to 10^5 at 90 km varying exponentially. Relaxation to ambient took place after approximately 110 hours. Figure 3 shows NO^+ versus time for the same case. The disturbance is again long lasting and, while easily detectable, is not large in absolute value.

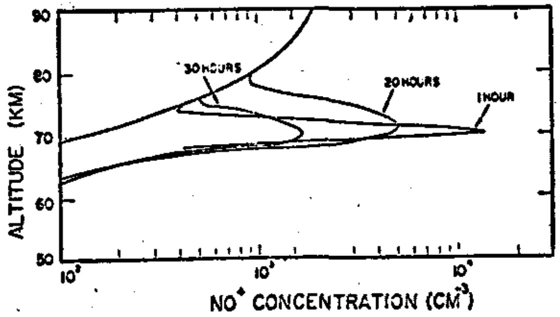

Figure 3. NO^+ Perturbation for Low Horizontal Diffusion Coefficient

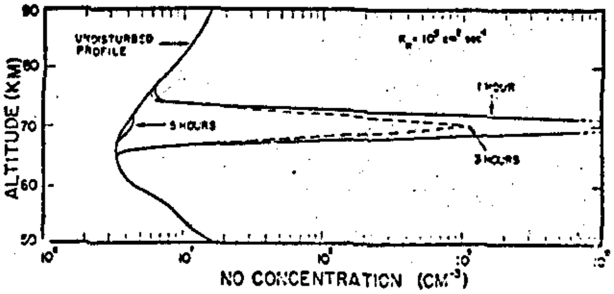

Figure 4. NO Perturbation for Horizontal Diffusion Coefficient = 10^5 cm^2 sec^{-1}

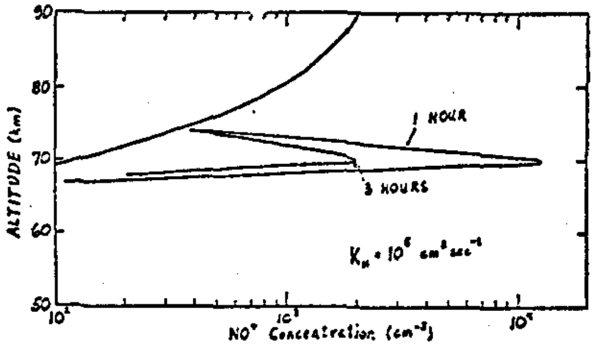

Figure 5. NO$^+$ Perturbation for Horizontal Diffusion Coefficient = 10^5 cm^2 sec^{-1}

Figures 4 and 5 show similar calculations in which the horizontal diffusion coefficients were taken to be 10^5 cm^2 sec^{-1} independent of altitude. In this case relaxation to ambient took place in ~5 hours. If the horizontal diffusion coefficient is larger yet, there will be a corresponding decrease in the lifetime of the disturbance.

III. Conclusions and Summary

We have modelled the localized effect of a single shuttle orbiter reentry on mesospheric odd nitrogen. The perturbations of the odd nitrogen species last for a time of the order of hours depending critically upon the value used for the horizontal diffusion coefficient. The processes included in the calculation are the perturbation of NO, photochemical reactions, and horizontal and vertical eddy diffusion. Effects which have not been modelled but may be important are perturbations in N and O, wind shear, diurnal variations and the influence of heat shield ablation products or water vapor. We have not considered specifically the problem of buildup from repeated orbiter reentries at the same place. However, the results indicate that even in the worst case the disturbance lifetime is less than 5 days. This combined with the fact that winds will move the disturbance fairly rapidly indicate that there is no possibility of buildup for any reasonable predicted launch frequencies.

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