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HOW WILL CHANGES IN CARBON DIOXIDE AND METHANE MODIFY THE MEAN STRUCTURE OF THE MESOSPHERE AND THERMOSPHERE ?

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Abstract. A global average model of the coupled mesosphere, thermosphere and ionosphere is used to examine the effect of trace gas variations on the overall structure of these regions. In particular, the variations caused by CO_2 and CH_4 doublings and halvings from present day mixing ratios are presented. The results indicate that the mesosphere and thermosphere temperatures will cool by about 10K and 50K respectively as the CO_2 and CH_4 mixing ratios are doubled. These regions are heated by similar amounts when the trace gas mixing ratios are halved. Compositional redistributions also occur in association with changes in the temperature profile. The results show that global change will occur in the upper atmosphere and ionosphere as well as in the lower atmosphere during the 21st century.

Introduction

Releases of trace gases from human activity have a potential for causing a major change in the climate of the Earth. Most discussions of the projected change have dealt with the troposphere [e.g., Manabe and Wetherald, 1975; Dickinson, 1986; Washington and Meehl, 1984; Dickinson and Cicerone, 1986; Ramanathan, 1988; and Hansen et al., 1988] and stratosphere [Fels et al., 1980; Solomon et al., 1985; Haigh and Pyle, 1982; Eckman et al., 1987; Brasseur and Hitchman, 1988; and Brasseur et al., 1988]. The troposphere is expected to warm and the stratosphere to cool as trace gas concentrations increase into the 21st century. The consequences of these processes on the atmosphere above 60 km have not yet been considered.

Brasseur and Hitchman [1988] used a two-dimensional numerical model of the stratosphere to show that the combined effects of projected trace gas increases to the end of the 21st century will result in major changes to both the ozone and temperature distributions. They find projected increases in chlorofluorocarbons (CFC's) to produce significant stratospheric ozone depletions with the largest losses occurring near the stratopause. Increasing CO_2 concentrations partially offset the decreases in ozone caused by the CFC's, but still an overall ozone decrease of 10 to 30% between low and high latitudes near the stratopause is expected. The net effect of the combined trace gas increases results in a peak stratopause cooling of 16 to 22K with somewhat smaller cooling throughout the entire stratosphere and lower mesosphere between 20 and 60 km.

Here, we use the projections of Brasseur and Hitchman [1988] and a global mean model of the mesosphere, thermosphere and ionosphere between 60 and 500 km, to investigate the overall sensitivity of these regions to perturbations caused by trace gas variations. Concentrations of CO_2 and CH_4 at 60 km are doubled and halved from 1950's global mean values of 330 ppm and 0.1 ppm, respectively. The doubling roughly mimics some tropospheric projections of 21st century concentrations [Bolin et al., 1986], whereas the halving mimics the low tropospheric values during the last ice age (200 ppm of CO_2 and 0.4 ppm of CH_4, respectively, Lorius et al., 1988). For the case of trace gas doublings, a significant cooling occurs throughout the mesosphere and thermosphere. The mesopause temperature decreases by about 10K and there is also a significant alteration in the compositional distributions of major and minor species throughout the mesosphere and thermosphere. When the trace gas levels are halved, there is a similar increase in temperature throughout the mesosphere and thermosphere with generally an opposite compositional redistribution from the case where the trace gases were doubled. The overall results indicate that global change resulting from trace gas variations is not confined only to the lower atmosphere but extends well into the mesosphere and thermosphere. This environmental change would affect satellite orbits and other aspects of man's activities in space.

Model

A self-consistent model of the global mean structure of the mesosphere, thermosphere and ionosphere has been developed and described by Roble et al. [1987] and Dickinson et al. [1987]. The model solves for the compositional profiles of O, O_2 and N_2 coupled through major constituent diffusion equations. It also includes as minor species with transport and appropriate photochemistry: $N(^4S)$, NO, H_2O, H, H_2, CH_4, CO, CO_2 and in photochemical equilibrium with the above: O_3, $O(^1D)$, $N(^2D)$, NO_2, OH, H_2O_2 and HO_2 and as passive tracers the distributions of He and Ar. It, furthermore, calculates ions in the E- and F-ionospheric regions: O^+, including diffusion, and O_2^+, N_2^+, NO^+ and N^+ in photochemical equilibrium. A D-region ion chemistry code is used to solve for various positive and negative ion cluster species. The model has separate thermodynamic equations for electron, ion and neutral temperatures with appropriate energy exchange processes. The neutral gas receives energy from solar photoelectrons, O_2 absorption in the Schumann-Runge continuum and bands, O_3

Table 1. Specified Lower Boundary Conditions (62 km)

Species		Mixing Ratio
N_2	-	0.78
O_2	-	0.21
H_2O	-	6.0×10^{-6}
H_2	-	0.5×10^{-6}
CH_4	-	0.1×10^{-6}
CO_2	-	330×10^{-6}
CO	-	0.2×10^{-6}
NO	-	10×10^{-9}
He	-	5.24×10^{-6}
Ar	-	9.34×10^{-3}

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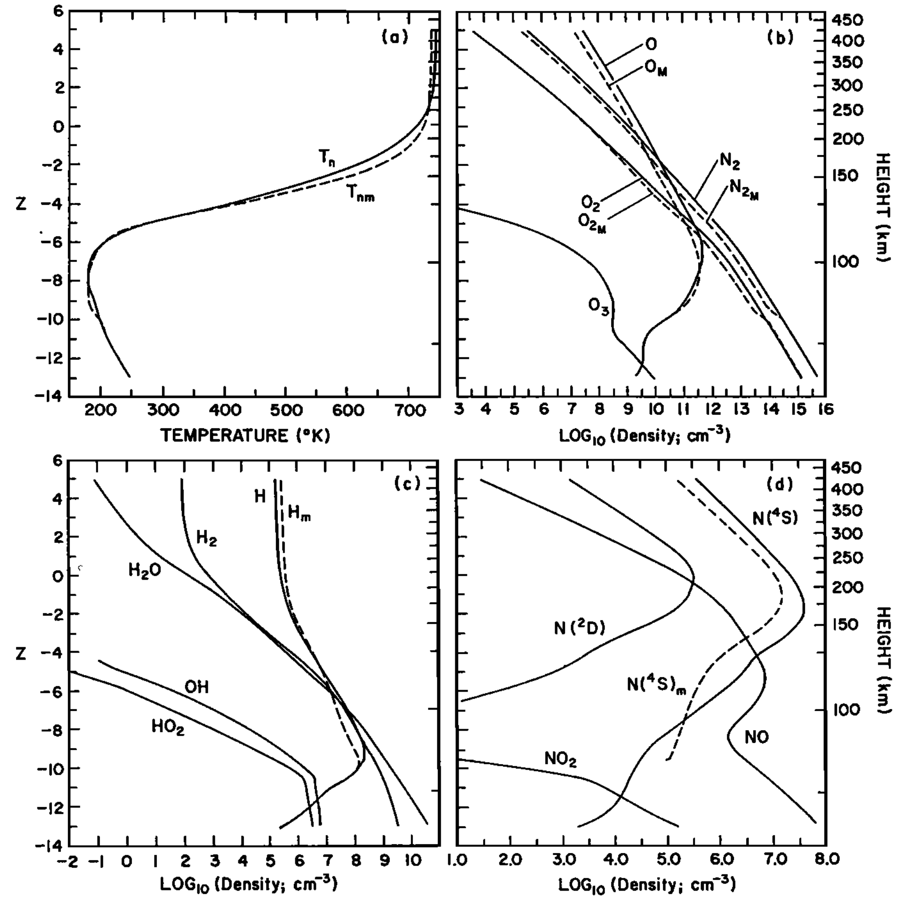

Fig. 1. (a) Calculated global mean neutral gas temperature profile, T_n, and the global mean neutral gas temperature profile from MSIS-86, T_{nm}, (b) calculated $\log_{10}$ O, O_2, O_3 and N_2 number density profiles (cm^{-3}) and similar profiles for major constituents from MSIS-86, $\log_{10}$ O_m, O_{2m} and N_{2m} (cm^{-3}), (c) same as (b) except for H, H_2, H_2O, OH, HO_2 and H_m, (d) same as (b) except for $N(^2D)$, $N(^4S)$, NO, NO_2 and $N(^4S)_m$, all for solar minimum, geomagnetic quiet conditions.

absorption in the Hartley and Huggins bands, excess energy from exothermic ion-neutral and neutral-neutral chemical reactions and also from prescribed auroral electron precipitation and Joule dissipation of ionospheric current heat sources. Neutral gas cooling includes CO_2-15μm, NO-5.3μm and O-63μm infra-red emissions and molecular and eddy thermal conduction. The global mean model is similar to that described by Strobel et al. [1985] for the mesosphere and Roble et al. [1987] for the thermosphere.

The model uses the complete CO_2 radiation code of Dickinson [1984] which includes both LTE and non-LTE CO_2 radiational processes and considers hot bands, isotopic bands, Voigt line shapes and radiative transfer as significant for mesospheric cooling. In the lower thermosphere CO_2 cooling rates are proportional to the product of atomic oxygen concentrations and the poorly known rate of energy exchange between O and CO_2. For our calculations we assume a quenching rate of 10^{-12} cm^3 s^{-1}. The Atmosphere Explorer-E solar EUV flux measurements of Hinteregger [1981] for solar minimum conditions, as modified by Torr and Torr [1985], are used in the model calculations. We use the Schumann-Runge continuum solar UV flux measurements of Rottman [1981]. The model also uses heating rates for the absorption of solar radiation in the Schumann-Runge bands of O_2 and in the Hartley, Huggins and Chappius bands of O_3 as specified in the WMO-16 report [1985].

The global mean model, rather than using an empirical model to represent atmospheric variables, calculates the temperature and composition profiles self-consistently from specified lower boundary conditions of long-lived species, as given in Table 1, and from the specification of external sources such as solar radiation, auroral particle precipitation and global Joule heating rates. The model, however, still requires a parameterized eddy diffusion profile to specify the vertical turbulent diffusion of heat and composition. This profile is obtained by adjusting it to obtain good agreement between the model calculated temperature and composition profiles and global average profiles from the U.S. Standard Atmosphere 1976 for the mesosphere and the mass spectrometer incoherent scatter model (MSIS-86) of Hedin [1987] for the thermosphere. Starting with arbitrary initial conditions, the model is integrated forward in time until a steady state is achieved for all temperature and composition profiles. Other features of the overall model are described in detail in Roble et al. [1987] and Dickinson et al. [1987].

Base Case

The global mean structure of the mesosphere and thermosphere for solar minimum, present-day conditions is shown in Figure 1. The model results are in reasonable agreement with the global mean structure obtained from the MSIS-86 empirical model above 85 km and with the U.S. Standard Atmosphere 1976 below that altitude. We perform sensitivity studies considering trace gas variations relative to this basic structure.

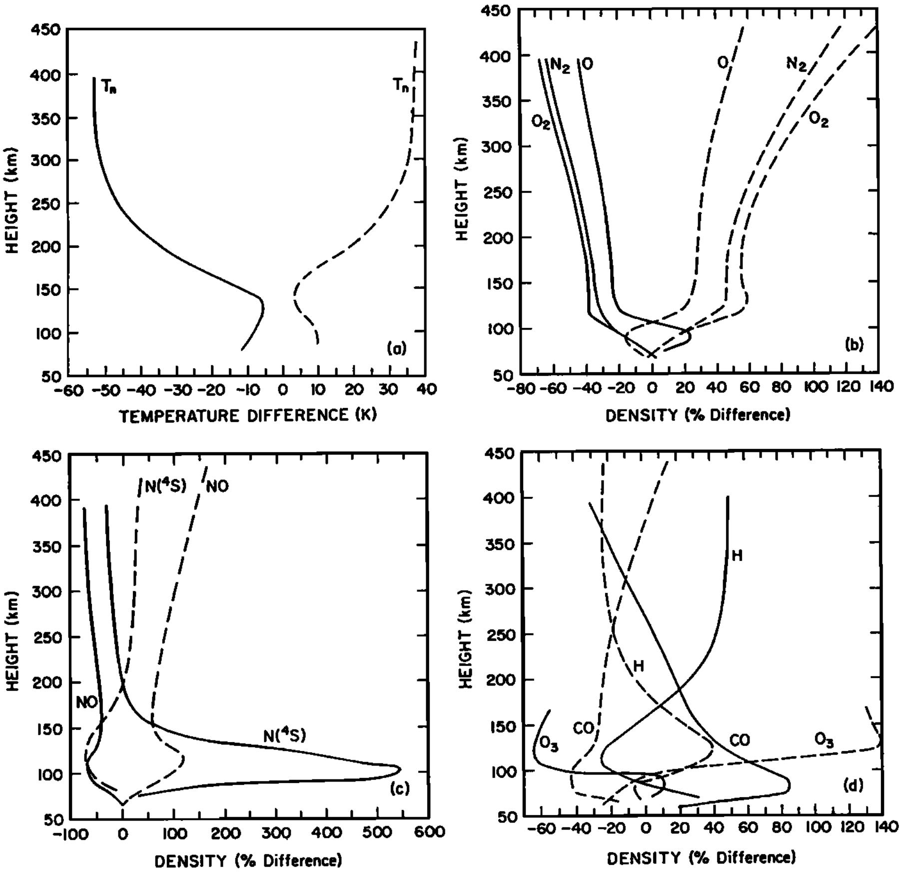

Fig. 2. Calculated (a) neutral gas temperature difference profile from the base case for the case where trace gases are doubled (solid lines) and halved (dashed lines), (b) density difference profiles (%) for O, O_2 and N_2 for the case where trace gases are doubled (solid lines) and halved (dashed lines), and (c) same as (b) except for NO and $N(^4S)$ and (c) same as (b) except for O_3, H and CO.

Sensitivity to Trace Gas Variations

The global mean model is used to perform calculations similar to the base case but with (1) CO_2 and CH_4 concentrations double, and (2) half of assumed values of 330 ppm and 0.1 ppm at 60 km respectively. These changes were applied only at the lower boundary of the model and are propagated upward by the model as it approaches steady state. The calculated temperature difference from the base state given in Figure 1a, is shown in Figure 2a for the two cases. When CO_2 and CH_4 are doubled, the temperature in the mesosphere cools by 10K and the thermosphere cools by 50K whereas comparable warming occurs when they are halved. The global mean stratospheric temperature up to the stratopause is determined from the calculations of Brasseur and Hitchman [1988] for the case of enhanced CO_2 and CH_4 concentrations giving a stratopause temperature 17K cooler than present day conditions. For the case of reduced CO_2 and CH_4 concentrations we assume a stratopause temperature 10K warmer than present. Radiative transfer from the underlying stratosphere determines in part the mesospheric temperature structure.

In addition to the thermal restructuring to trace gas variations, there are also compositional changes in both the major and minor species. The percent differences of O, O_2 and N_2 from the base case given in Figure 1, are shown in Figure 2b for the two cases. At 100 km both O_2 and N_2 decrease by about 40% when the trace gases are doubled and increase by 40% when the trace gases are halved. Atomic oxygen increases by about 20% in the mesosphere because of changes in chemistry and downward diffusion from the thermosphere caused by the thermal restructuring in that region. In the upper thermosphere near 300 km, O decreases by 40% when the trace gases are doubled and increases by 40% when they are halved. The NO and $N(^4S)$ densities in Figure 2c also show variations in response to the thermal restructuring as do other important mesosphere and thermosphere minor species, e.g., O_3, CO and H, as shown in Figure 2d. The concentrations of CO and H vary with the respective CO_2 and CH_4 source variations, and O_3, H, NO and $N(^4S)$ respond to temperature and compositional variations through temperature sensitive chemical rate coefficients and vertical transport. These calculations did not vary the CO concentration at the lower boundary and thus both curves tend toward a zero percent difference at the lower boundary. The upper thermospheric H concentrations varies primarily in response to variations in CH_4 [Ehhalt, 1986]. The calculated height of the constant pressure surface at the base of the exosphere ($Z = +5$) varies between 451 km, 427 km, and 398 km as trace gases are halved, kept at the base concentration and doubled respectively.

Discussion

Variations in lower atmospheric concentrations of CO_2 and CH_4 are shown here to have an important influence on the global mean thermal and compositional structure of the mesosphere and thermosphere. As these gases increase into the 21st century both the mesosphere and thermosphere will cool drastically relative to present day conditions. The cooling is caused primarily by enhanced CO_2 emissions. Both the NO and O

cooling rates are essentially unchanged since the enhanced densities are offset by colder temperatures. Compositional profiles will change in response to this projected cooling. In particular, exospheric hydrogen will increase with increasing CH_4 [Ehhalt, 1986] as does H_2O in the mesosphere. Noticulent cloud events may increase with the greater H_2O and colder mesopause temperatures [Thomas et al., 1989]. The concentration of CO would increase throughout the mesosphere with increased CO_2 concentrations, whereas NO would decrease in the lower thermosphere with colder temperatures and less chemical production from $N(^4S)+O_2$. The density of the thermosphere at a given height will decrease with the colder temperatures and thus reduce the drag on satellites from present day values. Correspondingly, the ionospheric structure will also be altered with lowered E- and F-region peak densities and smaller topside plasma scale heights. Thus, global change from trace gas increases is not confined to the lower atmosphere alone but also extends into the mesosphere, thermosphere and ionosphere regions. The projected changes should also lead to some alterations in global circulation, latitudinal distributions of temperature and composition and the response of the system to solar and auroral variability.

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