

Effects of Carbon Dioxide on the Upper Atmosphere

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Human activity has caused subtle changes in the Earth's atmosphere over the past several decades, due to increased emissions of gases such as carbon dioxide (CO₂) and methane (CH₄). These anthropogenic changes in "greenhouse gases" have the potential for increasing temperature in the lower atmosphere due to their ability to absorb infrared radiation. The far-reaching consequences of these changes are now being seen at extremely high altitudes in the outer atmosphere of the Earth, especially in the thermosphere, the high-temperature, near-vacuum region from ~90 to ~500 km, which is where many satellites are in orbit.

Roble and Dickinson [1989] predicted that a consequence of increasing CO₂ levels would be to decrease the temperature of the upper atmosphere. This is the opposite effect to the response of the lower atmosphere. The reason for this apparent paradox is that CO₂ and other multi-atom molecules can emit infrared radiation as well as absorb it. In the lower atmosphere, especially in the troposphere (below ~15 km), CO₂ absorbs radiation coming from the Earth, which excites it to higher vibrational states. Before it can re-emit the radiation, it undergoes collisions with other atmospheric gases, transferring the vibrational energy into heat. Any emission that does occur is likely to be re-absorbed by CO₂ at other altitudes. But in the stratosphere (~15 to ~50 km) and mesosphere (~50 to ~90 km) the atmosphere becomes increasingly transparent to infrared radiation as densities decrease, and the radiation-excitation-collision process runs in reverse. Instead of absorbing radiation, CO₂ molecules are vibrationally excited by collisions, and then, before additional collisions can remove the vibrational energy, they spontaneously emit in the infrared, which causes radiational cooling of the upper atmosphere.

In the stratosphere, changes in CO₂ have a minor effect on temperature because the energy balance is dominated by processes involving ozone (O₃). In the mesosphere, CO₂ cooling is significant, but long-term changes are difficult to measure. In the thermosphere, one effect of a cooler atmosphere is to cause global density to decrease as the thermosphere cools and contracts. Roble and Dickinson predicted that this could cause a decrease in density in the outer atmosphere above ~300 km of about 40% for a doubling of CO₂ from pre-industrial levels, which could happen by 2100. Additional studies by other groups have confirmed these calculations using other models. Changes in density of this magnitude could have significant effects, for example, on the orbits of satellites and also space debris, which are affected by drag processes as they pass through the tenuous outer atmosphere. It could also cause changes in the ionosphere, which is the ionized component of the thermosphere, consisting of electrons and positive ions.

The thermosphere goes through natural, cyclical changes in density driven by the Sun's 11-year activity cycle, heating and expanding at solar maximum, cooling and contracting at solar minimum. This makes it difficult to detect the smaller and more gradual changes occurring due to increasing anthropogenic emissions. So it may be surprising that during the last several years, three different groups were able to measure thermospheric density changes by observing the effect of atmospheric drag on the trajectories of satellites, some of which have been in orbit since the dawn of the space age. Keating et al. [2000] evaluated the long-term orbital decay of five

satellites during solar minimum years and found that density was decreasing at ~5% per decade near 350 km altitude. Emmert et al. [2004] derived secular trends in upper thermosphere density using 27 near-Earth orbiting objects for all levels of solar activity during the period 1966-2001. Their results indicated that the secular decline ranged from 2% to 5% per decade in the altitude range 200 km to 700 km, with the trend increasing with altitude. Marcos et al. [2005] analyzed satellite orbits over the period 1970-2000 and detected an average secular density decrease of 1.7% per decade near 400 km. Since it is expected that temperature change will cause cumulatively larger effects on density at higher altitudes, these observations are in reasonable agreement, except that the initial result from Keating et al. indicated somewhat higher trends than either model predictions or other measurements. In order to circumvent the problem of the complicating effects of the solar cycle, Keating et al. confined their study to solar minimum years, which could explain the apparent discrepancy. Emmert et al. also observed that the trends were larger at solar minimum than at higher solar activity levels.

Recent work by Qian et al. [2006] employed an extended and updated version of the Roble and Dickinson model to investigate the interaction of anthropogenic change with the solar cycle. They used daily CO₂ concentration measurements from the observatory at Mauna Loa, Hawaii [Keeling et al., 2005], and solar ultraviolet variations, to calculate the secular change of thermosphere neutral density for the last three decades. Results show that the average density decrease at 400 km should be 1.7% per decade, in excellent agreement with the Marcos et al. [2005] observations. They also modeled the expected effect under solar minimum and solar maximum conditions, finding larger trends at solar minimum and smaller change during solar maximum, which could explain some of the observational discrepancies. This is because at solar minimum, CO₂ is the primary gas that radiationally cools the thermosphere, but at solar maximum, increases in other minor gases cause CO₂ cooling to be less important. Figure 1 shows results from the 30-year simulations, using the measured CO₂ variations, and comparing to a control run with constant CO₂. Changes in CH₄, O₃, H₂O, and other minor gases may also affect the upper atmosphere, especially by increasing hydrogen and therefore water vapor in the mesosphere, but their effect on thermospheric temperature and density is nearly an order-of-magnitude less than that of CO₂.

Changes in the ionosphere should accompany the neutral atmosphere changes, including slight changes in the height and peak density of ionospheric layers, and decreasing ion temperature. Analysis of long-term ionosonde and radar data has proven challenging, but may also reveal trends. These and other possible effects are reviewed in a recent article in *Science* by Lastovicka et al. [2006]. Mesosphere changes are probably occurring but are difficult to prove conclusively because it is not easy to measure temperature accurately and consistently over many decades. But in the thermosphere, where density is a strong function of temperature, theory and observation are in good agreement with regard to density decreases.

Continued monitoring and modeling of upper atmospheric change will be important for understanding the complete picture of global change, and for predicting the trajectories of orbiting objects ranging from the smallest fragments to the International Space Station. A beneficial effect could be that it will take less fuel to maintain the orbits of active spacecraft, but defunct satellites, fragments from explosions, and other miscellaneous objects would have even longer orbital lifetimes, which could exacerbate the accumulation of hazardous space debris.

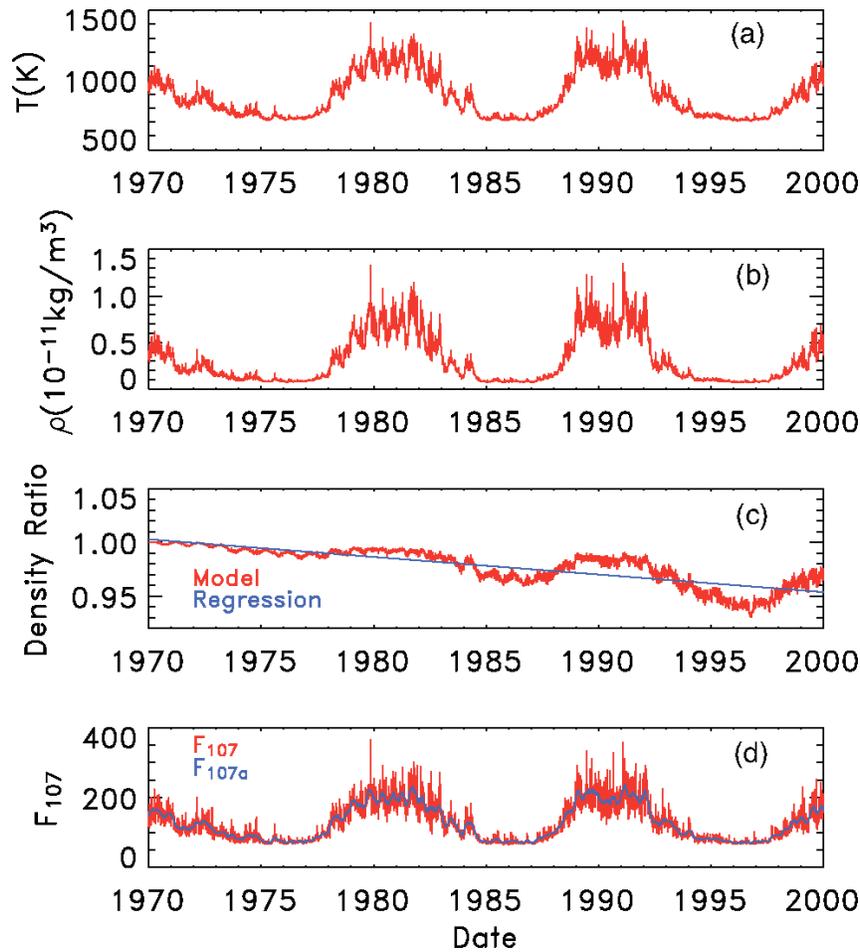


Figure 1. Calculations by Qian et al. [2006] of the thermospheric response to the combined effects of solar activity and anthropogenic change. (a) Global mean temperature at 400 km. (b) Global mean neutral density at 400 km. (c) Red: ratio of thermospheric neutral density from two model runs. First run: density calculated with varying CO_2 and solar ultraviolet variation from 1970 to 2000; Second run: density calculated with CO_2 fixed at 1970 levels and with solar ultraviolet variation from 1970 to 2000. The ratio of the two model runs is calculated to remove the influence of solar activity on density variation. Blue: linear regression to the ratio curve. The linear regression shows the average density decrease for the recent three decades is 1.7% per decade. (d) Red: $F_{10.7}$ index, representing solar activity; Blue: 81-day average $F_{10.7}$ index.

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