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Is thermospheric long-term cooling due to CO_2 or O_3?

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Abstract. While greenhouse gases trap heat emanating from the Earth and thereby heat the surface atmosphere, they act as emitters in the high atmosphere and cool the air there. In 1989 Roble and Dickinson (1989) estimated the cooling that would occur in the thermosphere (250–500 km altitude) due to a doubling of greenhouse gas densities. Ever since, long-term data bases have been scoured for evidence of this thermospheric "global cooling." Here we show evidence that the thermosphere did indeed cool over the period 1966–1987, but the data suggest that the cooling accelerated at a "breakpoint year" around 1979 to a rate far larger than may be attributed to greenhouse cooling. This 1979 breakpoint year appears to coincide with a breakpoint year in ozone (O_3) column density. Further, the cooling was confined largely to the daytime thermosphere while the nighttime showed only a small trend. These results suggest, first, that the greenhouse cooling of the thermosphere may well not be detectable with current data sets and, second, that the long-term cooling that is clearly seen may be due largely to O_3 depletion.

Keywords. Atmospheric composition and structure (Pressure, density, and temperature)

1 Introduction

In 1989 Roble and Dickinson (1989) published a seminal paper predicting changes in atmospheric temperature and density above 60 km altitude for a doubling of the densities of the greenhouse gases carbon dioxide (CO_2) and methane (CH_4) at 60 km. They found a cooling of ≈10 K in the mesosphere (≈60–100 km) and 50 K in the upper thermosphere (≈250–500 km). While greenhouse gases act to trap infrared emissions from the surface and thereby increase atmospheric temperature near the surface, they act as efficient emitters of ambient heat at high altitudes and thereby cause cooling. Here we show evidence that the thermosphere has indeed cooled, but we question the agent of this cooling.

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2 Data and trendline analysis

Figure 1 shows timelines of the annual average of several atmospheric quantities during the years 1960–1995: (1) O_3 column density above Arosa, Switzerland, (2) CO_2 density at Mauna Loa, Hawaii, (3) mean global land-ocean surface temperature change, and (4) the mean temperature in the thermosphere 200–400 km above Saint Santin, France. The Saint Santin radar facility operated during the period 1966–1987 only. Each of these timelines has been fitted by lines of different slope before and after a "breakpoint" year when a change in slope occurred. A least-squares fit was used to determine the optimal slopes and the location of the breakpoint. The probable error of the CO_2 breakpoint year is ≈0.5 years while the probable errors of the other three breakpoint years is ≈3 years.

Also shown, by the dashed line, is the thermospheric cooling predicted by Roble and Dickinson (1989), prorated according to the trend in Mauna Loa CO_2 under the assumption that the temperature response to CO_2 change is linear. This rate of cooling is approximately 0.2 K yr^{-1}.

The O_3 results were extracted from the World Ozone and Ultraviolet Radiation Data Center (www.woudc.org). The CO_2 results were extracted from the Mauna Loa data base (www.esrl.noaa.gov/gmd/ccgg/trends). The surface temperature data were extracted from the Goddard Institute for Space Studies data base (data.giss.nasa.gov/gistemp/graphs). The thermospheric results are essentially those of Donaldson et al. (2010), calculated directly from the Saint Santin data base stored at the National Center for Atmospheric Research in Boulder, Colorado, USA. Their method fits and removes the

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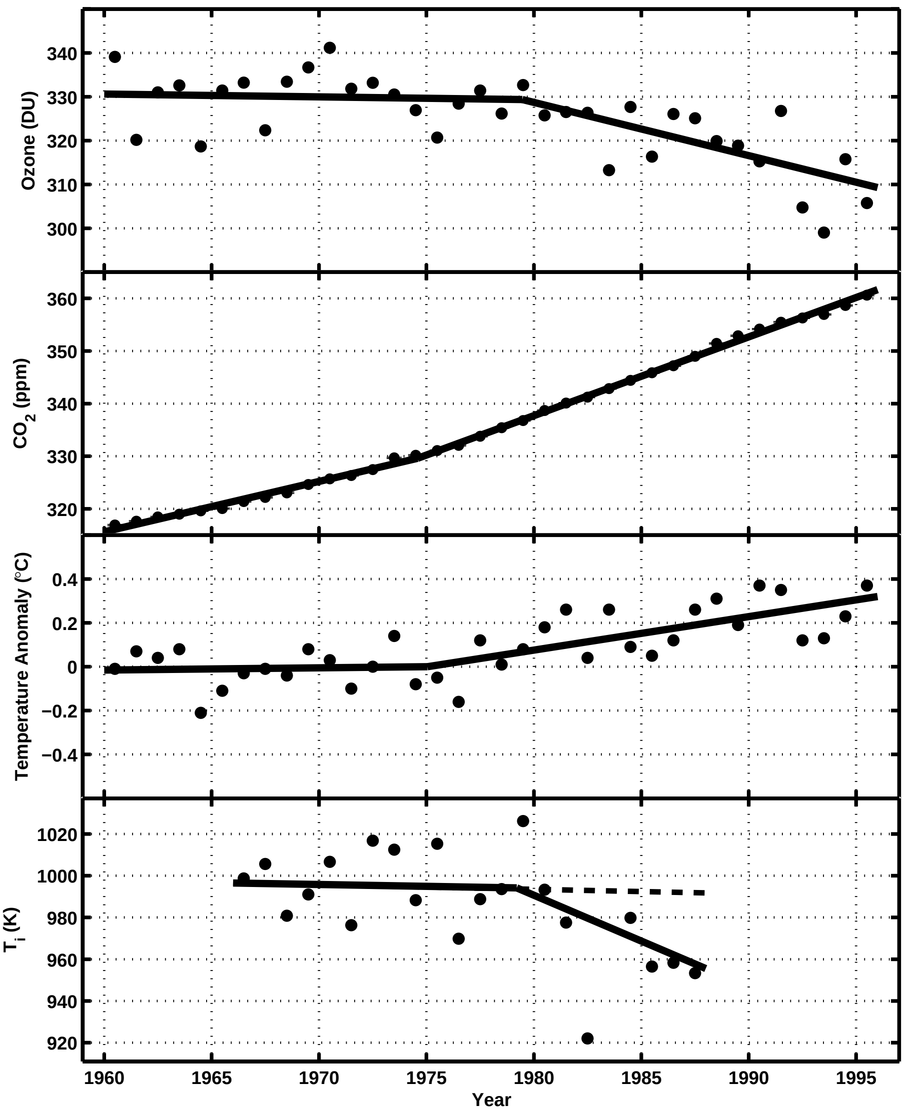

Fig. 1. Long-term trends in four atmospheric parameters. Top to bottom: **(a)** Annual average ozone column thickness over Arosa, Switzerland. **(b)** Annual mean atmospheric carbon dioxide density at Mauna Loa Observatory. **(c)** Global land-ocean temperature change. **(d)** Ion temperature over Saint Santin, France at 200–400 km altitude. The dashed line in the bottom panel is the model prediction of Roble and Dickinson (1989).

solar, magnetic, seasonal, and time-of-day variations in the data to yield a time series which can be binned and averaged to yield the long-term trend shown in Fig. 1. Donaldson et al. (2010) identified this breakpoint timeline for the altitude of 350 km only, using about 14 000 measurements. We have computed the average trendline over the altitude region 200–400 km, over which high-quality data are plentiful and vertical gradients are monotonic and gradual, using about 90 000 measurements. The year-to-year scatter about the trendline was found to be almost identical for the 14 000-point and 90 000-point analyses, indicating that the scatter shown is true year-to-year variability in the thermosphere, not measurement error.

Figure 2 shows the thermospheric data at 350 km altitude now analyzed separately for the time intervals 10:00–14:00 LT (daytime) and 22:00–02:00 LT (nighttime) to show simple linear trends. The daytime thermosphere cooled at $5.6 \pm 0.4\,\mathrm{K\,yr^{-1}}$ while the nighttime cooled at $0.7 \pm 0.5\,\mathrm{K\,yr^{-1}}$.

3 Discussion of trendlines

The Fig. 1 trendlines show interesting features and correspondences. First, it is clear that while CO_2 density and surface temperature rose throughout the period, O_3 density and thermospheric temperature fell. Second, all of the trendlines changed slope in the mid-to-late 1970s, after which change accelerated. Third, greenhouse cooling cannot account for the rapid cooling of the thermosphere after 1979. The Roble and Dickinson (1989) prediction line in the figure shows a change over the life of the Saint Santin radar that is scarcely detectable, given the year-to-year variability shown. Fourth, to the nearest year the CO_2 and surface-temperature breakpoints occurred in 1975 while the O_3 and thermospheric-temperature breakpoints occurred in 1979. In the paragraphs below we consider whether these breakpoint correspondences might represent cause and effect.

We may normally expect surface temperature to rise in response to an increase in CO_2 density, yet the breakpoint in the mid-1970s has received other explanation. Trenberth and Hurrell (1994) showed evidence of a substantial decade-long change in the north Pacific atmosphere lasting from about 1976 to 1988 linked to changes in the frequency and intensity of El Niño versus La Niña events. They noted that the spatial scales of such variations are large, owing to the large scales of atmospheric planetary waves involved, while the time scales are long, owing to the sluggish response of the ocean to surface forcing. It was not clear whether these changes were a manifestation of internal climate variability or whether an external cause (e.g., global warming) may have set favorable conditions for the changes to develop. Such periods of decadal-scale trends are not uncommon. Merzylakov et al. (2009) note that complex nonlinear systems like the atmosphere may well transition from one quasi-stable state to another. Rozelot and Lefebvre (2006) say that there have been periods of warming and cooling since 1861 in surface temperature, with 1910–1945 showing a 0.13 K/decade warming, 1946–1975 showing a 0.01 K/decade cooling, and 1976–2001 showing a 0.21 K/decade warming, with the period 1861–1975 showing remarkable correlation with solar irradiance but the period 1976–2001 showing a complete break in that relationship. Seidel and Lanzante (2004) note that global climate models are able to simulate multi-decadal periods of quasi-linear change with either natural or anthropogenic forcings. So the correspondence of the CO_2 and surface-temperature breakpoints in 1975 may not represent cause and effect but rather just response to a decadal shift in atmospheric behavior.

Might the correspondence of the O_3 and thermospheric-temperature breakpoint years in 1979 represent cause and effect? We must keep in mind in the following discussion that the 3-year uncertainties in these breakpoint-year determinations makes conclusions suggestive rather than definitive, though we also point below to independent evidence of those breakpoint-year determinations. O_3 can act as a greenhouse gas just as CO_2 can, but its decrease in density after 1979 (presumably due to an increase in man-made halocarbon emissions into the atmosphere) would lead to less radiative cooling, not more, and during daytime its radiative heating effect would far outweigh any cooling effect. O_3, in absorbing solar UV radiations, plays a fundamental role in

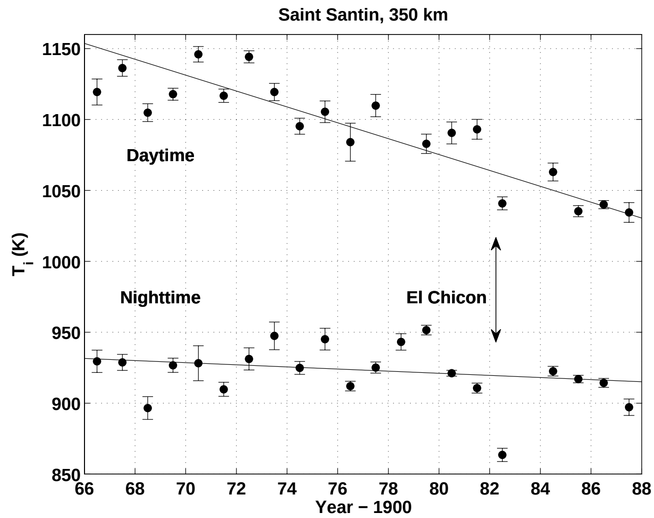

Fig. 2. The linear cooling trend at 350 km above Saint Santin for daytime (10:00–14:00 LT) and nighttime (22:00–02:00 LT). The daytime thermosphere cooled at $5.6 \pm 0.4\,K\,yr^{-1}$ while the nighttime cooled at $0.7 \pm 0.5\,K\,yr^{-1}$. The time of the eruption of El Chichón is noted.

the vertical thermal structure of the atmosphere. The temperature bulge it creates defines the stratosphere on its bottomside and the mesosphere on its topside. A decrease in O_3 density would reduce heating in this region and result in some degree of thermal collapse in the stratosphere and mesosphere and a descent of everything above it (the thermosphere). Akmaev et al. (2006) simulated the response of the upper atmosphere to observed O_3 trends. Even though the trends used were nil above 65 km altitude, the effects of the loss of O_3 heating persisted even to the simulation's upper bound of 200 km. Bremer and Peters (2008) investigated the long-term trend in ionospheric reflection height, which has direct interpretation as a trend in temperature below about 110 km altitude. They found an essential part of the derived trend was correlated with the trend in O_3 content, including a correlated breakpoint feature in 1979 (and another in 1995, when O_3 began a recovery in the atmosphere). This late-1970s breakpoint year has been noted in other work. Labitzke and Kunze (2005) found that stratospheric temperature trends changed around year 1979. Danilov (2009) found that the correlation between daytime and nighttime values of peak ionospheric density showed a clear change in trend "in the vicinity of 1980". Merzylakov et al. (2009) found a breakpoint in the semidiurnal tide above Obninsk and Collm around 1979, when the O_3 trend changed. Zhang et al. (2011) have noted that the thermospheric cooling trend that they see in a 1968–2006 timeline from Millstone Hill did not emerge until the 1980s.

The Fig. 2 trendlines show that the long-term cooling in the thermosphere is largely a dayside phenomenon. The daytime slope is highly significant. We cannot say with any certainty that the nighttime slope of $-0.7 \pm 0.5\,\mathrm{K\,yr^{-1}}$ is different from the Roble and Dickinson "greenhouse" slope of $\approx -0.2\,\mathrm{K\,yr^{-1}}$. The scenario shown in Fig. 2 is consistent with a causative agent of long-term change active only by day. Greenhouse gases are active emitters of thermal energy day and night while O_3 is an active absorber of solar UV only by day. This large difference between daytime and nighttime cooling points to O_3 as the agent of the cooling seen. Greenhouse gas cooling is likely present at a rate undetectable given the year-to-year variability present in the measurements.

We also note in Fig. 2 the time of eruption of El Chichón. That year, 1982, was a cold year in the thermosphere. Volcanic eruptions are known to affect temperature in the mesosphere (e.g., She et al., 2009).

4 Summary

In summary, we can say first that it is common for the atmosphere to transition on decadal time scales from one stable trend to another at a breakpoint-year epoch. We have found two breakpoints in the 1965–1990 period, one around 1975 in CO_2 and surface temperature, one around 1979 in O_3 and thermospheric temperature. The former may have been due to internal atmospheric variability, the latter may have been due to an increase in man-made halo-carbon release into the atmosphere, unrelated to the former. We have argued that the trends in thermospheric temperature seen are too large to be caused by the CO_2 changes seen and that the large day-to-night difference in trend does not point to a greenhouse gas at all. The correspondence in breakpoint year and the essential disappearance of the trend at night both have interpretation in terms of O_3 as the causative agent. Such an interpretation suggests that the cause of the long-term cooling of the thermosphere has been a decrease in heating rather than an increase in cooling. It suggests that part of the daytime bulge in the thermosphere is due to O_3 heating by day in the stratosphere/mesosphere and that the weakening of that bulge was due to the decrease in O_3 density during the period 1979–1995.

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