Calculated and observed climate change in the thermosphere, and a prediction for solar cycle 24

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[1]   The long-term change of thermospheric neutral density has been investigated using satellite drag measurements and through sensitivity studies using upper atmosphere general circulation models. The magnitude of the change has been quantified in both approaches, and the source of the secular change attributed to the concentration changes of greenhouse gases. In this study, we use CO_2 concentration measured at Mauna Loa Observatory and solar variation based on a proxy model to calculate the secular change of thermosphere neutral density for the last three decades, using a global mean upper atmosphere model. Our results show that the average density decrease at 400 km from 1970 to 2000 is 1.7% per decade. To quantify the impact of solar activity on the secular change of neutral density, we also calculated the long-term density change under solar minimum and solar maximum conditions for the same time period. The average trends at 350 km and 450 km are 2.2% per decade and 2.9% per decade for solar minimum conditions, while at solar maximum, they are 0.7% per decade and 0.8% per decade, respectively. These model results are compared to estimates of thermosphere density change derived from satellite drag observations, showing good agreement. In addition, based on a recent forecast of the intensity of solar cycle 24, we predict that the long-term change of thermospheric neutral density from 2006 to the end of solar cycle 24 will be ~2.7% per decade at 400 km. **Citation:** Qian, L., R. G. Roble, S. C. Solomon, and T. J. Kane (2006), Calculated and observed climate change in the thermosphere, and a prediction for solar cycle 24, *Geophys. Res. Lett.*, *33*, L23705, doi:10.1029/2006GL027185.

1.   Introduction

[2]   *Roble and Dickinson* [1989] initiated study of the impact of greenhouse gases on long-term change of the thermosphere and ionosphere using a global mean upper atmosphere model. They concluded that global change will occur in the upper atmosphere as well as the lower atmosphere, and found that a doubling of CO_2 and CH_4 concentrations will cause a ~50 K decrease of thermosphere temperature and a ~40% decrease of atomic oxygen near 300 km under solar minimum conditions. Since then, theoretical models have been used to investigate climatological change in the upper atmosphere [*Rishbeth and Roble*, 1992; *Akmaev and Fomichev*, 1998, 2000]. These model studies have generally supported Roble and Dickinson's original findings. Recently, satellite orbital decay data have been analyzed to estimate the secular change of thermosphere neutral density. *Keating et al.* [2000] evaluated the long-term orbital decay of five Earth satellites during solar minimum years and found a $4.9 \pm 1.3\%$ per decade decline of density near 350 km over 20 years. *Emmert et al.* [2004a, 2004b] 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 upper thermosphere from 200 km to 700 km, with the trend increasing with altitude, largely independent of geomagnetic activity, local time, latitude, and season. *Marcos et al.* [2005] analyzed several satellite measurements over the period 1970–2000 and detected an average secular density decrease of 1.7% per decade near 400 km. *Lean et al.* [2006] calculated density between 200 km and 475 km using orbital data for the three Starshine satellites from 1999 to 2003, and found an average density ~4% lower than calculated by the NRLMSISE-00 model [*Picone et al.*, 2002], which is based partially on data collected in the 1970s and 1980s, indicating a mean density decrease around 2% per decade. These experimental results are reasonably consistent, considering the wide range of altitudes and solar activity levels sampled. Although the Keating et al. results appear to be a considerably larger change than the Marcos et al. finding, the fact that Keating et al. used data from solar minimum years may explain some of the discrepancy, as discussed below.

[3]   Previous model studies have been limited to sensitivity studies of density change using a fixed greenhouse gas concentration. In this study, we use CO_2 measurements at Mauna Loa Observatory and solar EUV variation over the last three decades in a global mean upper atmosphere model to quantify the secular change of upper thermosphere neutral density. To quantify the impact of solar activity on the density trend, we also calculate the trend over the past 30 years assuming solar minimum and solar maximum conditions. The three trends are then compared to density trends derived from satellite drag measurements. In light of a recent prediction of the strength of solar cycle 24 [*Dikpati et al.*, 2006], we also construct a long-term climatological forecast of thermospheric density for solar cycle 24.

2.   Model Description

[4]   The model employed in these studies is a self-consistent global mean model of the mesosphere, thermosphere, and ionosphere. Its original version is described by *Roble et al.* [1987]; extension to the mesosphere and

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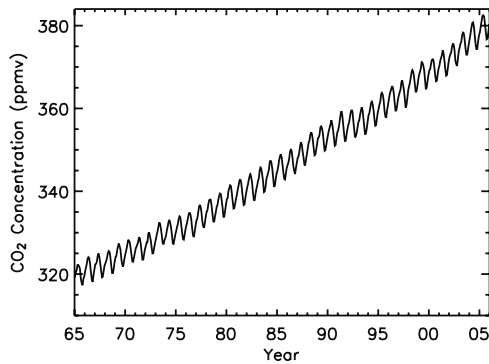
Figure 1. CO_2 concentration from 1965 to 2005 measured at Mauna Loa Observatory.

additional modifications are documented by *Roble* [1995]. The model is a 1D representation of aeronomic processes in the NCAR Thermosphere-Ionosphere-Mesosphere General Circulation Model (TIME-GCM) [*Roble and Ridley*, 1994] over a similar altitude range. Recent improvements include incorporation of a new solar EUV energy deposition scheme [*Solomon and Qian*, 2005] in the model, and updates to cooling rates and odd-nitrogen chemistry [*Roble and Solomon*, 2005; *Bailey et al.*, 2002].

[5] In past studies, the global mean model has been employed with static solar inputs and fixed greenhouse gas mixing ratios at the lower boundary. To investigate a particular scenario, the inputs would be set and the model iterated to equilibrium (usually several weeks with a 6-hour time step, depending on initialization), and the results compared to calculations using alternate inputs. We have now enabled time-varying solar ultraviolet and X-ray inputs, using the EUVAC proxy model [*Richards et al.*, 1994] and the Solomon and Qian parameterization method, and can run the model in a continuous time-dependent fashion using historical records of the solar 10.7 cm radio flux index $F_{10.7}$ as a proxy for solar variation. A time-varying CO_2 mixing ratio at the lower boundary can also be employed.

[6] The CO_2 concentration data used in this study are measurements from Mauna Loa Observatory [*Keeling and Whorf*, 2005]. Figure 1 shows CO_2 concentration from 1965 to 2005. CO_2 concentration has increased consistently from around 320 ppmv in 1965 to around 380 ppmv by the end of 2005. At this location, CO_2 concentration also has a seasonal variation with a fluctuation around 6 ppmv. This mixing ratio is applied to the model as a lower boundary condition at 30 km altitude.

3. Results

3.1. Cyclical and Secular Change Over Three Decades

[7] The time period of secular trends derived from published satellite drag measurements ranges from about 1970 to 2000. Figure 2 shows the global mean thermosphere temperature, density, and density trends at 400 km for a model run covering this period. The $F_{10.7}$ and its 81-day average for this period are also shown. To remove the solar activity influence on density variation, a second model run with constant CO_2 concentration applied at the

lower boundary, fixed at 1970 levels. We then calculated the ratio of density from the first run to the second run. The ratio is shown in Figure 2c. A linear regression gives an average decline of 1.7% per decade. *Marcos et al.* [2005] found that the average decline of density near 400 km during 1970 to 2000 was 1.7% per decade, in very good agreement with our calculation, and roughly consistent with the Starshine results [*Lean et al.*, 2006]. *Emmert et al.* [2004a, 2004b] derived a slightly larger average decline of density near 400 km from 1966 to 2001 of ~3% per decade.

3.2. Secular Change Under Solar Minimum and Maximum Conditions

[8] Model studies [*Roble and Solomon*, 2005] and satellite measurements [*Emmert et al.*, 2004a, 2004b; *Marcos et al.*, 2005] suggest that the density trend in the upper thermosphere depends on solar activity and is smaller for solar maximum conditions and larger for solar minimum conditions. One important mechanism of this dependency is that CO_2 cooling is dominant during solar minimum, while NO cooling becomes more important during maximum due to its increased density. Since the long-term decline of density in the upper thermosphere is mainly caused by
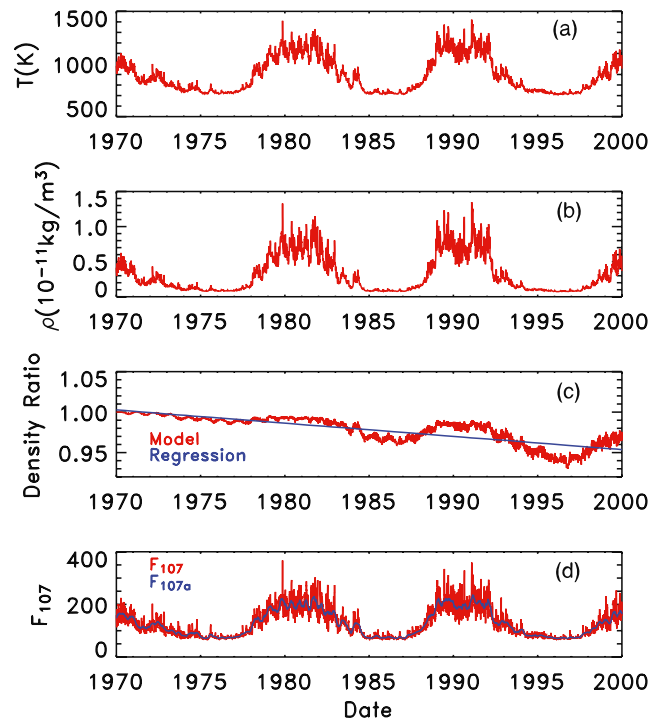
Figure 2. (a) Global mean temperature at 400 km. (b) Global mean neutral density at 400 km. (c) Red: ratio of thermospheric neutral density from two model runs. First run: density calculated with varying CO_2 and solar EUV variation from 1970 to 2000; Second run: density calculated with CO_2 fixed at 1970 levels and with solar EUV 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; Blue: 81-day average $F_{10.7}$ index.
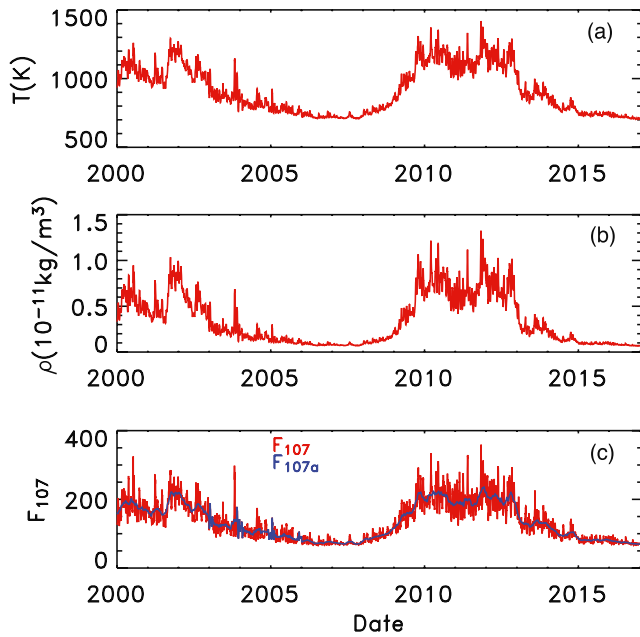
Figure 3. Thermosphere temperature and neutral density from 2000 to the end of solar cycle 24. (a) Predicted thermosphere temperature. (b) Predicted thermosphere neutral density. (c) Measured $F_{10.7}$ from 2000 to 2005 and estimated $F_{10.7}$ from 2006 to the end of solar cycle 24, based on the prediction of *Dikpati et al.* [2006].

increases in CO_2, the change should be larger during solar minimum conditions.

[9] To quantify this, the model was run with the historical CO_2 measured concentrations at the lower boundary but under "perpetual" solar minimum and solar maximum conditions. The $F_{10.7}$ proxy index was set to 70 for the solar minimum run, and to 210 for the solar maximum simulation. These calculations show that under solar minimum conditions, the average decreases were 2.2% per decade at 350 km and 2.9% per decade at 450 km from 1970–2000. Under solar maximum conditions, the average density decreases were only 0.7% per decade at 350 km and 0.8% per decade at 450 km. The density trend increases with height for both solar minimum and solar maximum conditions, and that increase is more apparent during solar minimum due to the lower scale heights. These results compare favorably with the density estimates derived from satellite drag measurements described in section 1, since the larger changes found by Keating et al. used solar minimum data.

3.3. A Thermospheric Density Forecast for Solar Cycle 24

[10] *Dikpati et al.* [2006] have recently predicted the strength of the next solar cycle using a flux-transport solar dynamo model. Their conclusion is that cycle 24 will have a 30–50% larger amplitude than cycle 23. Other recent predictions for solar cycle 24 have been made, using a variety of techniques. *Svalgaard et al.* [2005] and *Schatten* [2005] have predicted that cycle 24 will be weaker than cycle 23, while *Hathaway and Wilson* [2004] predict a

stronger cycle but with an earlier start, and *Sello* [2003] concludes that the amplitude will be similar to cycle 23. It will be interesting to track this over the next several years as solar activity increases, to observe whether the physical modeling approach of Dikpati et al. will make a significant improvement in this field. In anticipation that it will, we apply an approximation of their forecast to thermospheric density modeling.

[11] Since the global mean model uses the $F_{10.7}$ index as a proxy for solar EUV radiation, it is necessary to transform the *Dikpati et al.* [2006] prediction into a realistically varying solar proxy index. The prediction provides an estimate of the intensity of cycle 24, but not the shape or rotational variation within the cycle. In addition, the strength of cycle 24 is predicted in terms of magnetic flux in the solar shear layer, which directly corresponds to sunspot area. Past measurements of sunspots and $F_{10.7}$ suggest that a 30–50% increase of sunspot area corresponds to approximately a 10% increase of $F_{10.7}$ [*Hathaway and Wilson*, 2004]. Based on Figure 2 of Dikpati et al., we elected to employ historical measurements of $F_{10.7}$ during solar cycle 22 as a reasonable approximation of the predicted cycle 24 for the purpose of these calculations. The time sequence used as input to the global mean model uses measured $F_{10.7}$ through the end of 2005, and then extends through the present and future by repeating values from the end of cycle 21 and throughout cycle 22, with the nadir of solar minimum in mid-2007. An estimation of CO_2 concentration for the next 12 years is also required. For this simulation, we estimated future CO_2 levels by linear extrapolation of the present trend.

[12] The calculated thermosphere temperature and neutral density, and the prediction of $F_{10.7}$ for solar cycle 24, are shown in Figure 3. Because the predicted solar activity is based on a cycle amplitude estimate with historical data superimposed, the structure of the prediction should be considered as merely speculative, to represent what a typical large-amplitude even-numbered solar cycle might look like. To extract the long-term change caused by increasing CO_2 concentrations, an additional model run was performed with the lower boundary CO_2 concentration fixed at 2006 levels but with the same predicted solar input. We then calculated the ratio of densities from the two model runs to remove the change caused by the change of solar activity. Figure 4 shows the trend of density change from the beginning of 2006 to the end of cycle 24. A linear regression indicates that the thermosphere density will decrease at 400 km from the present to the end of cycle 24 at a rate of 2.7% per decade, a higher rate than the average decrease of 1.7% per decade for the past three decades.

4. Discussion

[13] Using a global mean model of the mesosphere, thermosphere, and ionosphere, we calculated the long-term change of thermosphere neutral density using CO_2 and solar EUV variation measurements over the recent three decades. It indicates that the average decline of thermosphere neutral density for the recent three decades is 1.7% per decade at 400 km. The results are in good agreement with the observational findings of *Emmert et al.* [2004a, 2004b] and *Marcos et al.* [2005].
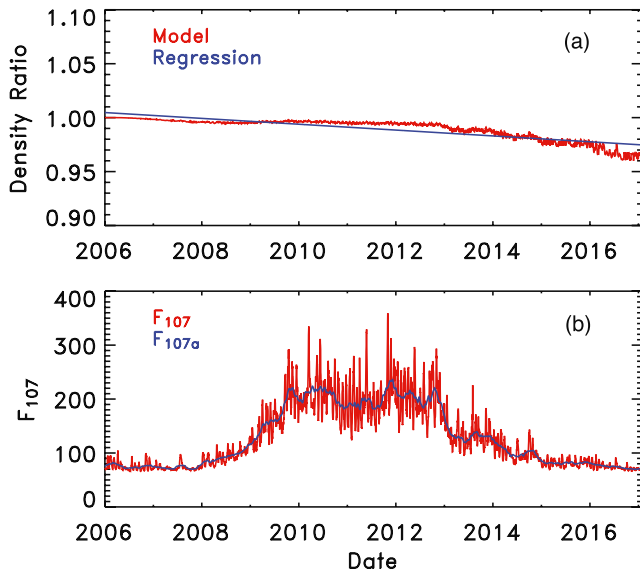
Figure 4. (a) Red: ratio of thermospheric neutral density from two model runs. First run: density calculated with varying CO_2 and varying $F_{10.7}$; second run: density calculated with CO_2 fixed at 2006 levels and varying $F_{10.7}$. The ratio of the two model runs is calculated to remove the influence of solar activity on density variation. Blue: linear regression to the ratio curve. The linear regression suggests that the density decrease from 2006 to the end of solar cycle 24 will be 2.7% per decade. (b) Estimation of $F_{10.7}$ based on the prediction of *Dikpati et al.* [2006]. Red: $F_{10.7}$ index; blue: 81-day average $F_{10.7}$ index.

[14] Assuming solar minimum and solar maximum conditions, the model calculation shows that the decline of thermosphere neutral density during solar minimum conditions is significantly larger than during solar maximum, as observed by *Emmert et al.* [2004a, 2004b] and *Marcos et al.* [2005]. Based on the CO_2 concentration of the past three decades, the average decline during solar minimum condition is 2.9% per decade at 450 km and 2.2% at 350 km; 0.8% per decade at 450 km, and 0.7% per decade at 350 km for solar maximum conditions. Therefore, for solar minimum conditions, our model result agrees well with *Marcos et al.* [2005] but is somewhat smaller than the evaluation of *Keating et al.* [2000]. The fact that CO_2 cooling dominates under solar minimum conditions, while nitric oxide cooling becomes more important at solar maximum, causes CO_2 cooling to have less impact on thermosphere density at solar maximum, and thus a smaller long-term decline of density during solar maximum years.

[15] Based on the intensity prediction for solar cycle 24 by *Dikpati et al.* [2006], we used the $F_{10.7}$ record from solar cycle 22 as an estimation of solar cycle 24 for the purpose of a long-term forecast of thermosphere density. We also extrapolated the CO_2 concentration based on a linear fit to past data to provide a CO_2 concentration at the model lower boundary for solar cycle 24. The model predicts a decrease of thermosphere density at 400 km of 2.7% per decade from 2006 to the end of solar cycle 24. It is larger than the average decline of 1.7% per decade during the 1970–2000

period calculated by the model, and estimated for the same period deduced by *Marcos et al.* [2005], but similar to the 3% per decade decline of *Emmert et al.* [2004a, 2004b] based on 1966–2001 data. The density trends based on model calculations suggest that there might be a slight increase of density decline with time. Since the CO_2 concentration is increasing with time, the impact of CO_2 cooling on thermosphere neutral density also increases with time, which could explain this possible increase in the magnitude of long-term change of thermospheric density.

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