Secular changes in the thermosphere and ionosphere between two quiet Sun periods

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Abstract The solar minimum period between solar cycles 23 and 24 was the longest since the beginning of space-based measurements, and many manifestations of solar activity were unusually low. Thermospheric neutral density was about 30% lower than during the previous solar minimum, but changes in the ionosphere of the two solar minima are more controversial. Solar radiation, geomagnetic activity, and anthropogenic increases in greenhouse gases can all play a role in these changes. In this paper, we address the latter of these potential contributions the degree to which secular change driven by greenhouse gases.

1. Introduction

Thermosphere neutral density has been slowly decreasing for several decades, driven by long-term changes of greenhouse gases, particularly CO₂ [e.g., Laštovička et al., 2006a; Qian et al., 2013]. The observed rate of decrease at 400 km altitude, derived from satellite drag data, has been estimated to be ~2% to ~3% per decade [e.g., Emmert et al., 2004; Marcos et al., 2005; Emmert et al., 2008], but this change is very small compared to the order-of-magnitude fluctuations induced by the solar cycle. From analysis of solar minimum data only, the observed rate of decrease is ~5% per decade [e.g., Keating et al., 2000; Emmert et al., 2008]. However, in the solar minimum period between solar cycles 23 and 24, during 2008–2009, thermosphere neutral density at 400 km was ~30% lower than that of the previous solar minimum [Emmert et al., 2010; Solomon et al., 2010], well below the expected secular trend. Modeling studies indicated that the anomalously low neutral density was mainly caused by lower levels solar extreme ultraviolet radiation, with additional contributions from the very low geomagnetic activity during this solar minimum period [Solomon et al., 2011; Deng et al., 2012].

While the neutral density change between the two minima is widely accepted, changes in the ionosphere are more controversial. The observational evidence was reviewed by Solomon et al. [2013]. Space-based data [e.g., Heelis et al., 2009; Coley et al., 2010; Lühr and Xiong, 2010; Klenzing et al., 2011; Yue et al., 2013], ionosonde measurements [e.g., Chen et al., 2011, 2012; Liu et al., 2011, 2012; Araujo-Pradere et al., 2011; Bilitza et al., 2012; Bremer et al., 2012; Mielich and Bremer, 2013], and radar observations [e.g., Liu et al., 2012] found decreases in daytime F region peak density NₘF₂ and (in some cases) the peak altitude hₘF₂. However, Lean et al. [2011a, 2011b] obtained a small positive trend of global daily average of total electron content (TEC) based on multiple GPS observations between 1995 and 2010, with a regional pattern of larger, positive trends in two low-latitude bands parrelling the magnetic equator and a negative trend in the equatorial Atlantic region. Jee et al. [2014] analyzed TEC measured by the TOPEX and JASON satellites, finding negligible change from 1996 to 2008–2009 on a global mean basis, but a small negative change during the day. Ground-based TEC is measured primarily over land and extends to ~20,000 km altitude, while TOPEX/JASON TEC is measured entirely over water and extends to ~1300 km altitude, so these two data sets may not be directly comparable.
Regardless of the uncertainty in ionosphere changes between the minima of 1996 and of 2008–2009, a key question is how much does secular change contribute to thermosphere and ionosphere differences between the two minima? Although there is wide acceptance of secular cooling of the thermosphere and consequent neutral density decrease, there are still discrepancies among observations and between observations and model simulations. Observed average density trends at 400 km, based on long-term satellite drag data for the past several decades, range from $-1.7 \pm 0.2\%$ per decade [Marcos et al., 2005] to $-2.7 \pm 0.5\%$ per decade [Emmert et al., 2004, 2008]. These studies also found larger trends of $-4\%$ to $-6\%$ from one solar minimum period to the next, in agreement with the first detection of secular change in the thermosphere by Keating et al. [2000], who found a trend of $-4.9 \pm 1.3\%$ per decade, based on solar minimum data alone. However, Holt and Zhang [2008] obtained a long-term cooling trend of 47 K per decade in ion temperature at 375 km at noon, from incoherent scatter radar at Millstone Hill, Massachusetts, for the period 1968 to 2006. According to model calculations, and assuming that ion and neutral temperatures are approximately equal at this altitude, a 2.1 K temperature decrease corresponds to a 2.4\% neutral density decrease at 400 km [Qian et al., 2013]. Therefore, the trend found by Holt and Zhang [2008] is much larger than the trends derived from satellite drag data [cf. Akmaev, 2012]. Zhang and Holt [2013] reanalyzed the same data set and found a smaller cooling trend of $-4\text{ K per decade}$, considering both day and night data, at heights between 200 and 350 km, where ion temperature best approximates neutral temperature. This estimate is in better agreement with the trends derived from satellite drag data but still somewhat larger.

Model simulations are generally consistent with the trends derived from satellite drag data [e.g., Roble and Dickinson, 1989; Akmaev et al., 2006; Qian et al., 2006, 2011]. For example, Qian et al. [2006] used an updated version of the Roble and Dickinson [1989] global mean model but calculated the neutral density trend using measured CO$_2$ concentrations from 1970 to 2000. They obtained an average density decrease of 1.7\% per decade at 400 km, in reasonable agreement with the satellite drag-derived average trends. However, the simulated trend under solar minimum conditions was $-2.6\%$ per decade at 400 km, about half of that obtained from satellite drag data. The reason that simulated trends are smaller during solar active periods than at solar minimum is that nitric oxide (NO) levels in the thermosphere are higher when solar and geomagnetic activity are high, and therefore, there is more radiational cooling from NO, which decreases the relative importance of radiational cooling by CO$_2$.

Trends in the ionosphere are more complex than those in the thermosphere. Since comparisons of ionospheric changes between the two minima have largely concerned F$_2$ peak parameters, we will focus our discussion on these parameters as well. Review of trends in the E and F$_1$ region can be found in Qian et al. [2011]. N$_m$F$_2$ and h$_m$F$_2$ have been investigated extensively using the global network of ionosondes. However, trend magnitudes continue to be controversial, as shown in the analysis by Lattovicka et al. [2006b]. Modeling efforts have also investigated the effects of CO$_2$ cooling on trends in the ionosphere. Qian et al. [2008] showed that on a global average basis and under solar minimum conditions, changes of N$_m$F$_2$ and h$_m$F$_2$ responding to a doubling of CO$_2$ were $-9\%$ and $-14\text{ km}$, respectively. Qian et al. [2009] conducted 3-D model simulations of the effect of increased CO$_2$ concentration on trends of F$_2$ peak parameters under solar minimum and geomagnetic quiet conditions, finding that for doubled CO$_2$, trends of N$_m$F$_2$ are ranged from 0 to $-40\%$, depending on location and local time. The corresponding trends of h$_m$F$_2$ are mostly negative with a magnitude from 0 to $-40\text{ km}$ but can be positive with a magnitude from 0 to $-10\text{ km}$ at night, with maximum positive trends occurring after midnight under solar minimum conditions. Trends in the ionosphere are also affected by geomagnetic forcing. Cnossen and Richmond [2008] examined the effects of secular change of the Earth’s magnetic field from 1957 to 1997 on trends of the F$_2$ peak parameters. They found that the secular change of the Earth’s magnetic field caused changes of h$_m$F$_2$ up to $\pm 20\text{ km}$ and changes of f$_p$F$_2$ up to $\pm 0.5\text{ MHz}$ over the low-latitude Atlantic Ocean and South America, but the effect is small to negligible for the rest of the globe.

It is clear that much progress has been made, yet uncertainties remain in the magnitudes of the secular changes. In addition, most modeling studies have focused on the cooling effects of CO$_2$. Other trace gases such as H$_2$O, CH$_4$, and O$_3$ can also make small contributions to secular changes in the thermosphere [Akmaev et al., 2006; Qian et al., 2013]. Additionally, many past modeling studies have focused on a “year 2100” scenario, with doubled CO$_2$ and significant changes in other anthropogenic gases. Since both the rate of change of anthropogenic gases and the atmospheric response is nonlinear, it is not entirely straightforward to map these model estimates to recent decadal change rates. The purpose of this paper is to estimate secular
Table 1. Minor Species and Their Concentrations (ppmv) Based on Crutzen and Brühl [1993] Used in TIME-GCM Simulations

<table>
<thead>
<tr>
<th>Species</th>
<th>Year 2000</th>
<th>Year 2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₄</td>
<td>0.6</td>
<td>1.34</td>
</tr>
<tr>
<td>CO₂</td>
<td>360</td>
<td>720</td>
</tr>
<tr>
<td>H₂</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>CO</td>
<td>1.1E-2</td>
<td>2.2E-2</td>
</tr>
<tr>
<td>H₂O</td>
<td>4.4</td>
<td>8.8</td>
</tr>
<tr>
<td>NO</td>
<td>2.7E-3</td>
<td>16.0E-3</td>
</tr>
<tr>
<td>NO₂</td>
<td>4.2E-3</td>
<td>8.4E-3</td>
</tr>
<tr>
<td>O₃</td>
<td>8.3</td>
<td>4.15</td>
</tr>
</tbody>
</table>

change rates for recent decades and to obtain an estimate of the secular contribution to changes between the two minima of 1996 and 2008–2009 in both the thermosphere and ionosphere. In addition to information derived from the above review of the observational and modeling evidence, new modeling results using the fully three-dimensional National Center for Atmospheric Research (NCAR) thermosphere-ionosphere-mesosphere electrodynamics general circulation model (TIME-GCM) are used to improve on earlier estimates derived from the global mean version of this model.

2. Model Simulations

2.1. Model Description

The NCAR TIME-GCM is a time-dependent, three-dimensional model that solves the fully coupled hydrodynamic, thermodynamic, and continuity equations for the neutral gas, self-consistently with the ion energy, ion momentum, and ion continuity equations from the upper stratosphere to the thermosphere. It combines all previous features of the NCAR TIME-GCMs, including electrodynamics driven by the neutral wind circulation [Roble et al., 1988; Richmond et al., 1992; Roble and Ridley, 1994]. The TIME-GCM calculates global neutral winds, neutral temperatures, major and minor neutral species composition, electron and ion densities and temperatures, and the ionospheric dynamo electric field. The model assumes hydrostatic equilibrium and performs calculations on pressure surfaces. The pressure interfaces are defined as \( \frac{P}{P_0} \) (where \( P_0 \) is a reference pressure of \( 5 \times 10^{-4} \) mb). The vertical range of the pressure interfaces is from \(-17 \) to \(7\), corresponding to an altitude range of \(-30 \) to \(-600 \) km, depending on solar activity. Older versions of the model had a horizontal resolution of \(5^\circ \times 5^\circ\) and a vertical resolution of \(0.5\) scale height, but the simulations shown here use the double-resolution version, with \(2.5^\circ \times 2.5^\circ\) horizontal resolution and \(0.25\) scale height in the vertical. The external drivers of the model are solar irradiance, either parameterized using the \( F_{10.7} \) index or supplied by measurements [Solomon and Qian, 2001], auroral particle precipitation, an imposed magnetospheric electric field, and the amplitudes and phases of tides from the lower atmosphere specified by the global scale wave model [Hagan et al., 2001]. Gravity wave effects are parameterized based on the linear saturation theory of Lindzen [1981]. \( CO_2 \) is collisionally deactivated by atomic oxygen and cools the upper atmosphere through infrared radiation at 15 \( \mu \)m. The TIME-GCM uses a \( CO_2 \) radiative transfer algorithm developed by Fomichev et al. [1998]. The collisional deactivation rate coefficient is set at \( k = 1.5 \times 10^{-12} \) cm\(^3\) s\(^{-1}\) [Khvorostovsky et al., 2002]. Nitric oxide cooling through deactivation by atomic oxygen and atomic oxygen fine structure cooling are also included, calculated assuming that the resulting emissions are optically thin.

2.2. Model Runs

We conducted two sets of numerical experiments. The first set, consisting of two model runs, is intended to determine how much the change of \( CO_2 \) between 1996 and 2008 could contribute to the changes observed in the thermosphere and ionosphere between these two consecutive solar minimum periods. In the first run, \( CO_2 \) concentration at the lower boundary was set to its 1996 level (363 ppmv); in the second run, \( CO_2 \) concentration was set at its 2008 level (386 ppmv). The second set of numerical experiments consisted of three model runs. The purpose of these experiments is to quantify the response to a doubled \( CO_2 \) case and to determine how much other trace gases might contribute to secular changes in the thermosphere and ionosphere. The first run is the base case with gas concentrations at \(-30 \) km approximating year 2000 levels, as shown in Table 1. In the second run, only \( CO_2 \) concentration was doubled compared with year 2000, whereas the third model run is for a year 2100 scenario [Crutzen and Brühl, 1993], with \( CO_2 \) doubled, and other trace gas concentrations as shown in Table 1. All model runs were conducted for solar minimum \( (F_{10.7} = <F_{10.7} > = 70) \) and geomagnetic quiet conditions at March equinox. In each case, the model was run for two model years to assure that vertical profiles of \( CO_2 \) (and all other minor species) reached equilibrium through upward diffusion and transport after being changed at the model lower boundary.
3. Secular Change Rates in the Thermosphere

We conducted the first set of model runs described in section 2.2 to examine how much the change of CO₂ concentrations between 1996 and 2008 contributes to the changes in the thermosphere and ionosphere between these two recent solar minima. Figure 1 shows the profiles of global mean changes of neutral temperature, neutral density, and electron density due to the increase of CO₂. Neutral temperature decreases about 1 K in the mesosphere. In the lower thermosphere from ~100 to ~140 km, neutral temperature apparently increases, with a maximum increase of ~0.8 K at ~120 km (Figure 1a). This apparent increase of neutral temperature is due to the lowering of constant pressure surfaces, when the thermosphere cools and contracts, in the presence of a large positive vertical gradient of neutral temperature in this altitude range. Local cooling by CO₂ is actually the largest in this altitude range. To illustrate the difference of temperature changes with respect to altitude and pressure, the profile of global mean neutral temperature change is also plotted in pressure coordinates (Figure 1b). Decrease of neutral temperature is the largest at about the ~4.5 pressure level, which, ironically, is near 120 km. In the upper thermosphere, neutral temperature decreases by 4.2 K (Figures 1a and 1b), whereas neutral density decreases by 5.8% (Figure 1c), due to the change of CO₂ concentration between 1996 and 2008. The per decade density trend is therefore ~−4.8%, since there are 12 years between 1996 and 2008. This density trend is significantly larger than results from global mean version of the TIME-GCM obtained by Qian et al. [2006] and is similar to the observed density trends of ~4% to ~6% per decade under solar minimum conditions [Keating et al., 2000; Emmert et al., 2004, 2008; Marcos et al., 2005].

The second set of numerical experiments described in section 3 examines the CO₂ doubling case and the potential effects of other greenhouse gases. Figures 2a and 2b show zonal mean temperature and density changes due to the doubling of CO₂ as a function of latitude and altitude, whereas Figures 2c and 2d show the temperature and density changes due to changes of all gases shown in Table 1. The combined effects of gases other than CO₂ only slightly increase temperature and density changes. This confirms the results of Qian et al. [2013], who conducted model simulations considering effects from changes of gas concentrations of CO₂, CH₄, H₂O, and O₃ from 1983 to 2003, using the National Center for Atmospheric Research (NCAR) Whole Atmosphere Community Climate Model and the global mean version of the TIME-GCM. Therefore, CO₂...
is the main forcing for the density trend in the upper thermosphere. Based on the results from long-term satellite drag data sets, and the modeling results mentioned above, at 400 km, we estimate that the contribution of secular change to global mean neutral density decrease between the two recent solar minima is less than ~6%.

4. Secular Change Rates in the Ionosphere

Figure 1d shows the profile of global mean changes of electron density due to the increase of CO2 concentration between 1996 and 2008. Electron density changes are negligible in the E region and F1 layer and small in the F2 layer, with the largest global mean decrease ~1.4%. This result is consistent with previous model results [e.g., Qian et al., 2008, 2009]. Figure 3 shows changes of hmF2 and NmF2 due to the change of CO2 concentration between 1996 and 2008, at 12:00 SLT, under solar minimum and geomagnetic quiet conditions, at March equinox. Changes of both hmF2 and NmF2 are negative at noon on a global mean basis, being −1.5 km and −1.5%, respectively. Assuming an average NmF2 of 5 × 10^6 cm^−3 under solar minimum conditions, the corresponding global change of f0F2 is −0.15 MHz between the recent two solar minima in a 12 year period, which is about −0.13 MHz/decade. Laitovička et al. [2006b] found a negative average secular change of f0F2 in the order of −0.1 MHz/decade at noon, using various methods on an ionosonde data set. The model result is consistent with their results. Changes of hmF2 and NmF2 are negative in most regions, except that there are positive changes of hmF2 and NmF2 in the low-latitude region of the longitude sector between 0° and 70°W (Figures 3a and 3b). The largest negative changes of hmF2 and NmF2 are at low magnetic latitudes and along the magnetic equator. Changes of hmF2 range from +11 to −11 km, whereas changes of NmF2 are between +6% and −9%, depending on geographic location. Changes of hmF2 and NmF2 due to doubling of CO2 at 12 local time, simulated by the second set of numerical experiments, are all negative, with a morphology similar to that shown in Qian et al. [2009]. Based on these model simulations, the main difference between the changes of hmF2 and NmF2 due to CO2 changes in a 12 year period versus the
changes due to a doubling of CO2 is that changes of \( {h_m}^2 \) and \( {N_m}^2 \) are positive in the low-latitude region of the longitude sector between \( \sim 0^\circ \) and \( 70^\circ \)W, whereas they are negative in the CO2 doubling case. This difference suggests that \( {h_m}^2 \) and \( {N_m}^2 \) respond to the amount of CO2 change nonlinearly. The combined effect from the rest of the gases shown in Table 1 does not change the morphology of the changes of \( {h_m}^2 \) and \( {N_m}^2 \) but slightly increases the magnitudes of these changes.

Trends in the \( F_2 \) peak parameters depend not only on geographic locations but also on local time, season, and solar activity. Qian et al. [2009] found that, similar to the thermosphere, trends of the \( F_2 \) peak parameters are larger under solar minimum conditions than those under solar maximum conditions. Here we examine the local time variation of the trends of the \( F_2 \) peak parameters under solar minimum conditions. Figure 4 shows comparisons of changes of \( {h_m}^2 \) and \( {N_m}^2 \) at 12:00 SLT and 03:00 SLT, under solar minimum and geomagnetic quiet conditions, at March Equinox, due to the change of CO2 concentration between 1996 and 2008. The zonal mean changes of \( {h_m}^2 \) are negative at all magnetic latitude at 12 local time, whereas at 03 local time, zonal mean changes of \( {h_m}^2 \) become positive at low magnetic latitudes. This positive change of \( {h_m}^2 \) is due to neutral wind transport, which lifts the \( F \) region and compensates for the lowering of \( {h_m}^2 \) due to cooling and contraction [Qian et al., 2009]. On the other hand, changes of \( {N_m}^2 \) become more negative at 03 local time compared to that at 12 local time, with the largest change near the equatorial anomaly region in the Northern Hemisphere, reaching \( \sim 7\% \).

Trends in the ionosphere are also affected by evolution of the geomagnetic field. Based on the model simulations by Cnossen and Richmond [2008], the secular changes of \( {h_m}^2 \) are up to \( \pm 20 \) km, and changes of \( f^2 \) are up to \( \pm 0.5 \) MHz in the vicinity of the South Atlantic anomaly region, due to the secular change of the Earth’s magnetic field from 1957 to 1997, and the effect is small to negligible for the rest of the globe. These changes are expected to be small on a decadal basis but still need to be considered when evaluating ionospheric trends at stations near the low-latitude Atlantic Ocean and South America.
5. Conclusions

Secular changes in the thermosphere and ionosphere have been studied using long-term data sets as well as upper atmosphere models. Secular change in the thermosphere is mainly caused by increasing CO₂ concentration, with other radiatively active gases such as CH₄, H₂O, and O₃ playing minor roles. These other gases may have more significant effects in the lower and middle atmosphere, but note that the “year 2100” scenario shown in Table 1 represents rather extreme changes to stratospheric chemistry that may be unlikely to occur, with the exception of CO₂ increase, which appears to be relentless. Secular changes in the ionosphere are not only affected by radiatively active gases but also affected by geomagnetic forcing and, on longer time scales, by the evolution of the geomagnetic field. Consequently, the ionosphere exhibits complex changes with local time, geographic locations, season, and solar activity.

Significant uncertainties remain in terms of the magnitudes of the secular changes in both the thermosphere and ionosphere. Observational and modeling studies indicate that the changes are largest under solar minimum conditions. Here we analyzed the secular changes in the thermosphere and ionosphere under solar minimum conditions based on results from previous observational and modeling studies, as well as new results from TIME-GCM simulations. We estimate that the contribution of secular change to global mean neutral density decrease between the two recent solar minima of 1996 and 2008–2009 is less than −6%. Based on our model simulations, on a global average basis, the contributions of secular change to the changes of \( N_{m}F_2 \) and \( h_{m}F_2 \) between the two recent solar minima were about −1.5% and −1.5 km, respectively, at local noon. At local noon, the largest positive and negative secular changes of \( N_{m}F_2 \) between the two minima occurred in the low magnetic latitude region. They were estimated to be +6% and −9%, respectively. The largest local noon positive and negative changes of \( h_{m}F_2 \) between were estimated to be +11 km and −11 km, also occurring at low magnetic latitude.

The rate of thermospheric density decrease under solar minimum conditions simulated in this study is significantly higher than that in previous work using a global mean version of the same model and is in better agreement with measurements derived from satellite drag observations. This is likely due to a more realistic treatment of the CO₂ profile in the 3-D model, which includes neutral winds and tidal motions in addition to the eddy diffusion and molecular diffusion mechanisms for vertical transport. Despite this upward revision of model estimates of the secular change rates, they are still much smaller than the observed changes in the thermosphere and ionosphere seen during the 2008–2009 extreme solar minimum. This supports the conclusion that solar activity in some form must have been the primary cause of these changes.

References

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