Geomagnetic Activity Effects on CO$_2$-Driven Trend in the Thermosphere and Ionosphere: Ideal Model Experiments With GAIA

Huixin Liu$^1$, Chihiro Tao$^2$, Hidekatsu Jin$^2$, and Takamichi Abe$^1$

1Department of Earth and Planetary Science, Kyushu University, Fukuoka, Japan, 2National Institute of Information and Communications Technology, Koganei, Japan

Abstract We examine impacts of geomagnetic activity (GA) on CO$_2$-driven trend in the ionosphere and thermosphere using the Ground-to-topside Atmosphere Ionosphere model for Aeronomy whole atmosphere model with GAIA. The model reveals three salient features. (1) Geomagnetic activities usually weakens the CO$_2$-driven trend at a fixed altitude. Among the IT parameters analyzed, the thermosphere mass density is the most robust indicator for CO$_2$ cooling effect even with GA influences. (2) Geomagnetic activities can either strengthen or weaken the CO$_2$-driven trend in hmF$_2$ and NmF$_2$, depending on local time and latitudes. This renders the widely used linear fitting methods invalid for removing geomagnetic effects from observations. (3) An interdependency exists between the efficiency of CO$_2$ forcing and geomagnetic forcing, with the former enhances at lower GA level, while the latter enhances at higher CO$_2$ concentration. This could imply that the CO$_2$-driven trend would accelerate in periods of declining GA, while magnetic storms may have larger space weather impacts in the future with increasing CO$_2$. These findings provide a preliminary model framework to understand interactions between the CO$_2$ forcing from below and the geomagnetic forcing from above.

1. Introduction

Model simulations have predicted global cooling in the thermosphere (Roble & Dickinson, 1989) and corresponding changes in the ionosphere (Rishbeth & Roble, 1992) in response to increasing CO$_2$ concentration. The cooling trend has been confirmed by observations, notably by thermosphere density derived from satellite drag (e.g., Emmert et al., 2004; Keating et al., 2000) and ion temperature in the F$_2$-region derived from incoherent scatter radars (e.g., Ogawa et al., 2014; Zhang et al., 2016). However, finding trend in ionospheric parameters such as the height of the maximum electron density of the F$_2$ region (hmF$_2$) and the peak electron density (NmF$_2$) has proved to be more challenging, due to their high sensitivity also to many other drivers like the solar and geomagnetic activity (GA), Earth’s magnetic field, stratospheric ozone, atmospheric dynamics (see, e.g., Crossen & Maute, 2020; Laštovička, 2013; Laštovička et al., 2012; Qian et al., 2011, and references therein). The extraction of CO$_2$-driven trend requires careful removal of effects from all other drivers, which can cause potential errors and uncertainties in the derived trend as comprehensively summarized in Laštovička and Jelinek (2019). The effects of GA are often removed using linear fitting method (e.g., Bremer, 1998; A. D. Danilov & Konstatinova, 2014; Miellch & Bremer, 2013, and references therein). However, due to complications in the process of geomagnetic storms (e.g., variability in response time and recovery time, the choice of geomagnetic indices) such removal method may also cause contamination in the derived CO$_2$-trend, particularly when daily (or even monthly during period of frequent geomagnetic storms) data are used.

On the other hand, Mikhailov and Marin (2000) and Mikhailov (2006) found that secular variations of hmF$_2$ and NmF$_2$ obtained without removing the GA effect show a local pattern that can be explained by long-term changes in the GA in the 20th century, indicating that GA impacts could override the CO$_2$-impact in that period. This promotes us to ask how the two drivers (CO$_2$ and GA) interact with each other and what are their combined impacts on the thermosphere and ionosphere? Since changes in CO$_2$ are of lower atmosphere origin while that in the GA is of solar/magnetosphere origin, this question directly relates in a broader context to interactions between external drivers of the thermosphere-ionosphere (TI) system from above and below, which is a critical issue underaddressed.
All model simulations reported so far (Liu et al., 2020; Qian et al., 2011; Rishbeth & Roble, 1992; Solomon et al., 2018) examined in depth the CO₂ impact on the TI, but offered no clue on these questions. The fluctuating nature of geomagnetic activities makes it difficult to simulate and complicated to interpret their interaction with the CO₂ forcing (even low GA can sometimes significantly impact the upper atmosphere as shown by Cai et al., 2020; Fuller-Rowell et al., 2011; Goncharenko et al., 2006). Therefore, as the first model attempt to diagnose the complex coupling processes, we aim to extract basic features of the CO₂-geomagnetic interaction using idealized numerical experiments as described in the next section. Though simplified, ideal experiments are essential steps toward reproducing observations with more sophisticated simulations, as they help to gain physical insight and also validation of the model to capture core processes.

2. The GAIA Model and Experimental Setup

The Ground-to-topside Atmosphere Ionosphere model for Aeronomy (GAIA) model is a 3D whole atmosphere model of the Earth’s troposphere, stratosphere, mesosphere, thermosphere and ionosphere, covering the altitude range from the ground to ∼600 km for the neutrals and to 3,000 km for the plasma (Jin et al., 2011). It has a horizontal resolution of 2.8° × 2.8° (latitude × longitude), and a vertical resolution of 0.2 scale height for the neutral atmosphere. The ionosphere part of the model has a horizontal resolution of 1.0° × 2.5° (latitude × longitude), and a vertical resolution of 10 km between 0 and 600 km altitudes, and of 100 km between 600 and 3,000 km.

To examine interactions between the CO₂ and GA forcing, we performed six GAIA simulations as shown in Table 1 with combinations of different CO₂ concentrations and GA levels set by the cross-polar cap potential drop (CPCP). Two levels of CO₂ concentration are used, at 345 ppm and its doubled value of 690 ppm. Three levels of GA are set with CPCP at 30 kV (Kp ≈ 2−), 55 kV (Kp ≈ 3+), and 90 kV (Kp ≈ 6) to represent quiet, moderately disturbed and highly disturbed geomagnetic conditions, respectively. By doing so, we also examine how the interaction vary with different GA levels. The moderately disturbed case is close to the observed long-term changes in GA from Kp ≈ 2 to Kp ≈ 3+ (see, e.g., Mikhailov & Marin, 2000).

All simulations were run for 2 months from May to June under constant solar minimum conditions with F10.7 = 80 sfu to avoid solar influences. The outputs in June are used for the following analysis. It takes about 10 days for GAIA to reach stable-state conditions, which is determined primarily by the eddy diffusion coefficient in the lower thermosphere. June was focused as CO₂ cooling effect has been shown to be strongest in this month (Liu et al., 2020). Impacts of increasing CO₂ and GA are obtained by taking differences between different runs as shown in Table 2. For convenience, we will refer to them later on simply as the CO₂ impact, GA impact, and the combined impact.

3. Results

In this section, we examine the following three aspects: (1) the combined impacts of increasing CO₂ and GA on the thermosphere; (2) the combined impacts on the ionosphere; (3) the interdependence of the efficiency of CO₂ forcing and GA forcing.

3.1. Combined Impacts in the Thermosphere

The combined impacts of double-CO₂ and increasing GA are obtained from Run4 − Run1 for Kp ≈ 3+ and Run6 − Run1 for Kp ≈ 6, respectively, and labeled as C&S@Kp ≈ 3+ and C&S@Kp ≈ 6 in all figures (please refer to Table 2 for detailed descriptions on model runs and labels). The double-CO₂ impacts under quiet geomagnetic conditions (CQ) are also shown for comparison.
We first examine the combined impacts on globally averaged thermospheric quantities shown in Figures 1a and 1b. It is apparent that the combined impacts (C&S) have similar shape to $C_Q$ but with smaller magnitudes. For instance, the thermosphere cooling ($\Delta T_n$) reduces from $-80$ K at quiet conditions to $-61$ K for $Kp \approx 3^+$ and to $-30$ K for $Kp \approx 6$ at about 300 km height. The corresponding reduction of mass density $\Delta \ln(\rho)$ also drops from $-0.75$ to $-0.65$ and $-0.45$, respectively. This weakening is what we would expect from the heating effect of increasing GA (Liu & Lühr, 2005), which counteracts the CO2 cooling effect. We note that perturbation values for $C_Q$ here are slightly different from those shown in Liu et al. (2020), likely due to a minor version up of GAIA, but the patterns remain unchanged. Since we focus on changes between $C_Q$ and C&S, differences between model versions are irrelevant here.

Figure 2 presents the latitude-height structure of thermosphere temperature, density, and meridional wind. Figures 2d, 2e, 2g, and 2h show that the weakening of temperature and density perturbations are more severe at high latitudes, due to stronger Joule heating caused by elevated GA. The meridional wind perturbation $\Delta V$ (Figures 2f and 2i), on the other hand, does not show such monotonic weakening. It shows a strengthening of the southward $\Delta V$ in the Northern Hemisphere but a weakening in the Southern Hemisphere, hence indicates equatorward winds in both hemispheres driven by increasing GA (e.g., Fejer et al., 2000). Comparing the three parameters in Figure 2, it is clear that the thermosphere density is the only one that

![Figure 1](image-url)

**Figure 1.** Double CO2 impacts under quiet geomagnetic conditions ($C_Q$) and combined impacts ($C&S@Kp = 3^+$ and $C&S@Kp = 6$) on globally averaged thermosphere temperature ($\Delta T_n$), thermosphere mass density in log space ($\Delta \ln(\rho)$), and electron density ($\Delta N_e$). Values are shown for June. In $\ln(\rho)$ instead of $\rho$ is plotted to better visualize the variation over extended heights. Corresponding model runs used to obtain these impacts are described in Table 2.
retain the negative sign at all latitudes and altitudes in the combined trend even at high GA level of Kp ≈ 6, demonstrating it as a more robust indicator for the CO2 cooling impact.

3.2. Combined Impacts in the Ionosphere

In this section, we first examine the combined impacts on the zonal mean ionospheric quantities, then have a closer look at impacts on hmF2 and NmF2, which are more frequently used in observations.

Figure 2. The latitude-height distribution of the CO2 impacts and combined impacts on the thermosphere temperature (left column), thermosphere density (middle column), and meridional wind (right column, positive northward). Upper row: CO2 impacts under quiet conditions; middle row: combined impacts at Kp ≈ 3+; bottom row: combined impacts at Kp ≈ 6. The thermosphere density remains negative at both low and high geomagnetic activity levels, implying its being a more robust indicator of CO2 impact than other parameters.
3.2.1. Impacts on the Zonal-Mean Plasma Density and Temperature

Figure 3a shows the double-CO$_2$ impact on plasma density (Ne) under quiet conditions. It is consistent with simulation results shown in Rishbeth and Roble (1992) and Qian et al. (2011), with negative trend in the topside (above the white zero line) but positive trend at lower altitude (below the zero line). When combined with GA impacts, we see that the negative trend in the topside gets weaker at Kp $\approx 3$+ (Figure 3d) and even reverses to positive in polar regions and around 30°N above 300 km at Kp $\approx 6$ (Figure 3g). The positive trend is also weakened, as best seen in the equatorial ionization anomaly region. This weakening effect of GA on CO$_2$ trend in the plasma density is also concisely revealed in the globally averaged height profiles (Figure 1c).

Figure 3. Same as Figure 2 but for electron density (Ne), ion (Ti) and electron temperature (Te).
Now let us examine the impacts on plasma temperatures. Figure 3b shows that the double CO₂ impact under quiet conditions in ΔTi. It exhibits a sandwich pattern, being dominantly negative in the F₂-region, positive in the topside and bottom-side (transition altitudes depend on latitudes as indicated by the white lines). The positive trend at bottom-side and negative trend in the F-region is consistent with observations reported by Zhang et al. (2016) at middle and high latitudes (see their Figure 12), though the model seems to show an overall downward shift in altitude (e.g., the transition from negative to positive occurs around 140 km height in models but at 180 km in observations). The topside positive trend, however, is opposite to results of...
Zhang et al. (2016). But it agrees with observations at EISCAT reported in Ogawa et al. (2014) and TIEGCM model results in Qian et al. (2011). On the other hand, the negative ΔTe trend above 200 km height (Figure 3c) is consistent with Zhang et al. (2016) (their Section 5.4) but opposite to model results of Qian et al. (2011). This lack of consistency among different studies indicate that more efforts are needed to clarify the CO₂ trend in plasma temperatures in both observations and model simulations even under quiet conditions.

Figures 3e, 3f, 3h, and 3i present the combined impacts on plasma temperatures for Kp ≈ 3+ and Kp ≈ 6, showing ΔTi and ΔTe are overall more positive than those in Figures 3b and 3c. GA effects can reverse the negative ion temperature trend in the polar lower thermosphere (below 250 km) to positive even at moderate level with Kp ≈ 3+ (Figure 3e). Similar sign reversal occurs in the electron temperature around 60°N above 200 km (Figures 3f and 3i). The impact on Ti trend is consistent with that shown in Zhang et al. (2016) (their Figures 5), which is one of the very few studies mention the GA impact on temperature trend. GA impacts on Te trend have not been investigated using observations so far. These GAIA results demonstrate that trends in plasma temperatures are very sensitive to geomagnetic activities and it will be challenging to separate CO₂ and GA impacts.

3.2.2. Impacts on the hmF₂ and NmF₂

Figure 4a presents double-CO₂ impact on hmF₂ under quiet conditions in local time (LT)-latitude frame. Negative trend is seen at all latitudes and local times, consistent with simulation results by Rishbeth and Roble (1992), but different from that by Qian et al. (2009) which showed positive hmF₂ in the postmidnight Southern Hemisphere (see their Figure 3b). With increasing GA levels, the combined (C&S) impact on hmF₂ (Figures 4d and 4f) generally retains the negative sign except for in limited regions indicated by positive patches. The positive ΔhmF₂ at middle latitudes is likely to be driven by equatorward winds shown in Figures 2f and 2i, while that at nighttime low latitudes is more likely driven by vertical plasma drift. As shown in Figure 5, the combined impact enhances the upward drift trend at the equator during 18–03 LT at both moderate and high geomagnetic levels, uplifting the ionosphere hence weakening the negative hmF₂ trend at night. On the other hand, the combined impacts also strengthens the downward drift at dawn (04–08 LT), thus enhances the negative trend there. So, we see that higher GA can either weaken or strengthen the CO₂-driven trend in hmF₂. This is quite different from the monotonic weakening seen at fixed altitudes in previous sections. The same can be said to the NmF₂ discussed below.

Figure 4b shows that the CO₂ impact under quiet conditions in NmF₂. It shows an overall positive trend at northern (summer) middle latitudes but a negative trend at southern middle latitudes. In tropical regions between about 30°S and 30°N, the sign of the trend shows strong local time dependence. This complex pattern in NmF₂ trend produced by GAIA differs significantly from that by the TIEGCM, which shows monotonic negative trend at all local time and latitudes (Qian et al., 2009, their Figures 3a).

Figures 3e and 3h, respectively depict combined impacts on NmF₂ at moderate and high GA levels. We see that the combined impact departs significantly from the CO₂ impact at quiet times (Figure 4b) already at moderate geomagnetic level (Figure 4e), with enhanced LT and latitudinal variations. It exhibits interchanging positive and negative values in both hemispheres. The dominating negative trend at middle (poleward of 45°N) and high latitudes (blue regions in Figure 4e) are consistent with that found in observations (e.g., Mikhailov, 2006) including long-term GA effects. The complex pattern in ΔNmF₂ and its high sensitivity to GA makes it a more challenging parameter to use for CO₂-driven trend studies than hmF₂ or the ΔNe at 400 km discussed below.
In comparison to $\Delta NmF_2$, $\Delta Ne$ at 400 km height shows a much simpler pattern, with almost monotonically negative values for CO$_2$ impact except for near 08 and 18 LT during quiet time (Figure 4c). With increasing GA, the negative trend in daytime tropical regions retains at both Kp $\approx 3^+$ and Kp $\approx 6$ (Figures 4e and 4i), which may imply more robust CO$_2$-driven trend in these regions. The relatively simpler pattern than those in NmF2 makes Ne at 400 km more suitable for CO$_2$ trend study.

3.3. Interdependence of the Efficiency of CO$_2$ Forcing and Geomagnetic Forcing

We examined in previous sections the combined impacts of increasing CO$_2$ and GA on the TI system. Here we explore their interaction from a different point of view by asking two questions: (1) Does the efficiency of CO$_2$ forcing depend on the level of GA? (2) Does the efficiency of geomagnetic forcing depend on the level of CO$_2$ concentration? By efficiency, we simply refer to the perturbation magnitude caused by a change in each forcing.

To answer these questions, in addition to CO$_2$ impact under quiet geomagnetic condition (C$_Q$) used in previous sections, we also obtain the CO$_2$ impact at moderate and high GA levels (labeled as C@Kp $\approx 3^+$ and C@Kp $\approx 6$). The model runs used to extract these impacts are given in Table 2. Since the GA level remains fixed for each pair of model runs, these impacts are the pure CO$_2$ impacts caused by the doubling of CO$_2$ concentration but at different background GA levels (not to confuse with the combined effect C&S in previous sections). Similarly, we obtain the pure geomagnetic impacts (for Kp $\approx 3^+$ and Kp $\approx 6$) at both the base and double CO$_2$ levels ($S_{C0}$ and $S_{C2}$).

Impacts on globally averaged thermospheric temperature, thermospheric density and electron density are presented in Figure 6. We see that for the same doubling of CO$_2$ concentration, its impact (in absolute values) tends to become smaller with increasing GA levels (upper row in Figure 6), suggesting lower efficiency of CO$_2$ forcing toward higher GA levels.

The lower half of Figure 6 shows the dependence of GA impacts on the background CO$_2$ level. Larger impacts are seen at double CO$_2$ level for both moderate and high GA levels (e.g., solid lines are at larger values than dashed lines), implying higher efficiency of geomagnetic forcing at higher CO$_2$ level. Such effect, if confirmed, could potentially lead to higher magnetic storm effects in the future with increasing CO$_2$ concentrations (even if geomagnetic activities remain the same).

4. Discussions

Using ideal experiments with the whole atmosphere model GAIA, we explored the interaction between CO$_2$ and GA forcing and their combined impacts on the TI system. The analysis revealed several features that worth discussion.

1. Geomagnetic activities tend to weaken the CO$_2$-driven trend in the thermosphere temperature, density and electron density when seen at fixed altitudes (Figures 1–3). In spite of this weakening, however, the thermosphere density retains a negative trend at all latitudes and altitudes (Figures 2e and 2h), demonstrating it being the most robust indicator for CO$_2$ cooling among all parameters. This robustness practically originates from the fact that the steady-state thermosphere mass density at a fixed altitude is largely controlled by the integrated temperature (via scale height) below that altitude down to the mesopause whose height subsequently depends on the lower atmosphere temperature down to the ground surface. As GA effects are generally limited to regions above $\sim$100 km, its impact on the thermosphere density is relatively small compared to that of CO$_2$ which affects the temperature throughout the whole atmosphere. This robustness is probably one of the reasons why CO$_2$ impact has been most consistently revealed in the thermosphere density than in other parameters, even if there were potential contamination from geomagnetic effects (Mikhailov, 2006).

2. Geomagnetic activities can either strengthen or weaken the CO$_2$ impacts on hmF2 and NmF2, depending on local time and latitudes/season (see Figure 4). This complex pattern and its seasonal variation renders the widely used linear fitting methods invalid to remove GA effects in the observed hmF2 and
NmF2, which could lead to globally inhomogeneous contamination of GA in the derived trend (see review by Laštovička et al., 2012).

3. The NmF2 trend produced by GAIA under quiet conditions shows both positive and negative trends depending on local time and latitudes (Figure 4b). This contrasts to the monotonic negative trend simulated by the TIEGCM model (Qian et al., 2009), but is more consistent with observations. For instance, the overall positive trend in summer and negative trend in winter at middle latitudes agrees with observations reported by A. Danilov (2015). Although detailed comparison between GAIA and TIEGCM are required to clarify their differences, the more realistic NmF2 pattern produced by GAIA likely owes to its better capturing coupling processes between the lower and upper atmosphere as a whole atmosphere model (in comparison to TIEGCM with lower boundary at about 90 km), which affects the tides and circulation in the thermosphere (Liu et al., 2020). The more complicated local time and latitude dependence of NmF2 trend and its high sensitivity to geomagnetic activities (see Figures 4b, 4e, and 4h) make it a very challenging parameter to use for CO2 trend studies.

4. The efficiency of CO2 forcing drops at higher GA level (upper row in Figure 6). This gives us an interesting deduction: for the same amount of CO2 change, the cooling trend will decelerate in periods of increasing GA but accelerate in periods of decreasing GA. Consequently, the CO2-driven trend will be nonlinear even for a linear increase of CO2 concentration. Particularly in periods of decreasing GA, the decline of GA itself will produce an apparent cooling trend. This would add up to the already accelerating CO2-driven trend and make it appearing even more pronounced. Such a deduction is not inconsistent

Figure 6. CO2 impacts at different geomagnetic activity levels (upper row) and geomagnetic activity impacts at different CO2 levels (lower row) on the global-averaged thermosphere temperature, thermosphere mass density, and electron density during June. Dashed lines in the lower row represent geomagnetic impacts at base CO2 level, while solid ones those at double CO2 level. It is seen that efficiency of CO2 forcing is reduced at higher geomagnetic activity levels, and that of geomagnetic forcing is enhanced at double CO2 level. (Please refer to Table 2 for corresponding model runs.)
with the increasing CO₂ impact observed since about 2000, when the GA has been declining (Laštovička et al., 2012).

In summary, even simple numerical experiments used this study have revealed complex characteristics of the interaction between CO₂ and geomagnetic forcing on the TI. More realistic experiments with the observed evolution of CO₂ concentration and GA are necessary to reproduce observations. Finally, it goes without saying that these results represent only the physical picture from GAIA. It would be interesting to see results from other models, as model comparisons are essential to elucidate processes evolved in the interactions between external drivers of the TI system from above and below.

Data Availability Statement

The data used in this study are publicly available at https://doi.org/10.5281/zenodo.3862006.

References

Bremer, J. (1998). Trends in the ionospheric E and F regions over Europe. Annales Geophysicae, 16, 986–996.
Cai, X., Burns, A. G., Wang, W., Qian, L., Solomon, S. C., Eastes, R. W., et al. (2020). The two-dimensional evolution of thermospheric ΣO/N, response to weak geomagnetic activity during solar-minimum observed by GOLD. Geophysical Research Letters, 47(18), e88838. https://doi.org/10.1029/2020GL088838
Crossen, I., & Maute, A. (2020). Simulated trends in ionosphere-thermosphere climate due to predicted main magnetic field changes from 2015 to 2065. Journal of Geophysical Research: Space Physics, 125(3), e27738. https://doi.org/10.1029/2019JA027738
Danilov, A. (2015). Seasonal and diurnal variations in fF2 trends. Journal of Geophysical Research, 120, 3868–3883. https://doi.org/10.1002/2014JA020971
Danilov, A. D., & Konstantinova, A. V. (2014). Relationship between fF2 trends and geographic and geomagnetic coordinates. Geomagnetism and Aeronomy, 54, 323–328.
Emmert, J. T., Picone, J. M., Lean, J. L., & Knowles, S. H. (2004). Global changes in the thermosphere: Compelling evidence of a secular decrease in density. Journal of Geophysical Research, 109, A02301. https://doi.org/10.1029/2003JA010176
Fejer, B. G., Emmert, J. T., Shepherd, G. G., & Solheim, B. H. (2000). Average daytime F region disturbance neutral winds measured by UARS. Initial results. Geophysical Research Letters, 27, 1859–1862.
Fulsher-Rowell, T., Akmaev, R., Wu, F., Fedrizzi, M., Viereck, R. A., & Wang, H. (2011). Did the January 2009 sudden stratospheric warming cool or warm the thermosphere? Geophysical Research Letters, 38, L18104. https://doi.org/10.1029/2011GL048985
Goncharenko, L., Sahai, J., Crowley, G., Paxton, L. J., Zhang, Y., Coster, A., et al. (2006). Large variations in the thermosphere and ionosphere during minor geomagnetic disturbances in April 2002 and their association with IMF By. Journal of Geophysical Research, 111(A3), A03303. https://doi.org/10.1029/2004JA010683
Jin, H., Miyoshi, Y., Fujiwara, H., Shinagawa, H., Terada, K., Terada, N., et al. (2011). Vertical connection from the tropospheric activities to the ionospheric longitudinal structure simulated by a new Earth’s whole atmosphere-ionosphere coupled model. Journal of Geophysical Research, 116, A01316. https://doi.org/10.1029/2010JA015925
Keating, G. M., Tolson, R. H., & Bradford, M. S. (2000). Evidence of long term global decline in the Earth’s thermospheric densities apparently related to anthropogenic effects. Geophysical Research Letters, 27(10), 1523–1526. https://doi.org/10.1029/2000GL007371
Laštovička, J. (2013). Trends in the upper atmosphere and ionosphere: Recent progress. Journal of Geophysical Research: Space Physics, 118(6), 3924–3935. https://doi.org/10.1002/2013JA019049
Laštovička, J., & Jelínek, Š. (2019). Problems in calculating long-term trends in the upper atmosphere. Journal of Atmospheric and Solar-Terrestrial Physics, 189, 80–86. https://doi.org/https://doi.org/10.1002/jastp.201904011
Laštovička, J., Solomon, S. C., & Qian, L. (2012). Trends in the neutral and ionized upper atmosphere. Space Science Reviews, 168, 113–145. https://doi.org/10.1007/s11214-011-9799-3
Liu, H., & Lühr, H. (2005). Strong disturbance of the upper thermospheric density due to magnetic storms: CHAMP observations. Journal of Geophysical Research, 110, A09S29. https://doi.org/10.1029/2004JA010908
Liu, H., Tao, C., Jin, H., & Nakamoto, Y. (2020). Circulation and tides in a cooler upper atmosphere: Dynamical effects of CO₂ doubling. Geophysical Research Letters, 47, e2020GL087413. https://doi.org/10.1029/2020GL087413
Mielich, J., & Bremer, J. (2013). Long-term trends in the Ionospheric F2-region with different solar activity indices. Annales Geophysicae, 31, 291–303.
Mikhailov, A. V. (2006). Ionospheric long-term trends: can the geomagnetic control and the greenhouse hypotheses be reconciled. Annales Geophysicae, 24, 2533–2541.
Mikhailov, A. V., & Marin, D. (2000). Geomagnetic control of the foF2 long-term trends. Annales Geophysicae, 18, 653–665. https://doi.org/10.1007/s00585-000-0653-2
Ogawa, Y., Motoba, T., Buchert, S. C., Hågström, L., & Nozawa, S. (2014). Upper atmosphere cooling over the past 33 years. Geophysical Research Letters, 41(15), 5629–5635. https://doi.org/10.1002/2014GL060591
Qian, L., Laštovička, J., Roble, R. G., & Solomon, S. C. (2011). Progress in observations and simulations of global change in the upper atmosphere. Journal of Geophysical Research, 116, A00H03. https://doi.org/10.1029/2010JA016317
Qian, L., Solomon, S. C., & Kane, T. J. (2009). Seasonal variation of thermospheric density and composition. Journal of Geophysical Research, 114, A01312. https://doi.org/10.1029/2008JA013643
Rishbeth, H. (1992). Cooling of the upper atmosphere by enhanced greenhouse gases - modeling of thermospheric and ionospheric effects. Planetary and Space Science, 40(7), 1011–1026. https://doi.org/10.1016/0032-0633(92)90041-A
Roble, R. G., & Dickinson, R. E. (1989). How will changes in carbon dioxide and methane modify the mean structure of the mesosphere and thermosphere?. Geophysical Research Letters, 16(12), 1441–1444. https://doi.org/10.1029/GL016i12p01441
Solomon, S. C., Liu, H.-L., Marsh, D. R., McInerney, J. M., Qian, L., & Vitt, F. M. (2018). Whole atmosphere simulation of anthropogenic climate change. Geophysical Research Letters, 45(3), 1567–1576. https://doi.org/10.1002/2017GL076950

Zhang, S.-R., Holt, J. M., Erickson, P. J., Goncharenko, L. P., Nicolls, M. J., McCready, M., & Kelly, J. (2016). Ionospheric ion temperature climate and upper atmospheric long-term cooling. Journal of Geophysical Research: Space Physics, 121(9), 8951–8968. https://doi.org/10.1002/2016JA022971