Journal of Atmospheric and Solar-Terrestrial Physics 71 (2009) 1592–1601

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

The effect of carbon dioxide cooling on trends in the F2-layer ionosphere

Liying Qian *, Alan G. Burns, Stanley C. Solomon, Raymond G. Roble

High Altitude Observatory, National Center for Atmospheric Research, 3080 Center Green Drive, Boulder, CO 80301, USA

ARTICLE INFO

Article history:
Accepted 8 March 2009
Available online 20 March 2009

Keywords:
Ionospheric trends
Greenhouse effect
Photochemical forcing
Dynamical forcing
Composition (O/N_2)
Plasma transport

ABSTRACT

The effect of carbon dioxide (CO_2) cooling on trends of h_mF_2 and N_mF_2 are investigated using a coupled thermosphere and ionosphere general circulation model. Model simulations indicate that CO_2 cooling not only causes contraction of the upper atmosphere and changes of neutral and ion composition but also changes dynamics and electrodynamics in the thermosphere/ionosphere. These changes determine the altitude dependence of ionospheric trends and complex latitudinal, longitudinal, diurnal, seasonal, and solar cycle variations of trends of h_mF_2 and N_mF_2. Under the CO_2 cooling effect, trends of N_mF_2 are negative with magnitude from 0% to $\sim-40\%$ for doubled CO_2, depending on location, local time, season, and solar activity. The corresponding trends of h_mF_2 are mostly negative with a magnitude from 0 to -40 km, but can be positive with a magnitude from 0 to ~10 km at night, with maximum positive trends occurring after midnight under solar minimum conditions.

1. Introduction

Long-term changes in the upper atmosphere and ionosphere have been of great interest since Roble and Dickinson (1989) suggested that global cooling will occur in the upper atmosphere in conjunction with global warming in the troposphere due to long-term increase of greenhouse gas concentrations, particularly carbon dioxide (CO_2). This cooling is caused by collision-induced infrared radiation by CO_2 and other heterogenous molecules as the atmosphere above the tropopause becomes increasingly transparent to infrared radiation. Thus, instead of causing warming as in the troposphere, the "greenhouse effect" in the upper atmosphere reduces temperature and causes the thermosphere to contract, reducing its density as a function of altitude. This has practical importance due to its influence on satellite drag. In addition, determination of long-term changes in the upper atmosphere and ionosphere has important scientific interest. It can facilitate understanding of global change in the lower atmosphere since global change in the lower atmosphere and upper atmosphere/ionosphere are closely linked, and it can be easier to detect global changes in the upper atmosphere and ionosphere due to larger signal to noise ratio (Laštovička et al., 2006a). Significant progress has been made after nearly two decades of observational and modeling studies (e.g., Akmaev and Fomichev, 1998, 2000; Akmaev et al., 2006; Beig, et al., 2003; Bremer et al., 2004; Clilverd et al, 2003; Danilov and Mikhailov, 1999; Emmert et al., 2004; Gruzdev and Brasseur, 2005; Keating et al., 2000; Laštovička and Bremer, 2004; Laštovička, 2005; Laštovička et al., 2008; Marcos et al., 2005; Mikhailov and Marin, 2000, 2001; Qian et al., 2006, 2008; Rishbeth, 1990, 1997; Rishbeth and Roble, 1992; Xu et al., 2004). Consistent results have been obtained regarding long-term trends of mesospheric temperature, electron density in the lower ionosphere and F_1-region, *hmE* and *NmE*, and thermospheric neutral density (Laštovička et al., 2006a, 2008). These results support the hypothesis of cooling and contraction of the upper atmosphere as a result of increased greenhouse gas concentrations.

However, controversies and discrepancies remain for detection of trends of F_2 peak parameters (h_mF_2 and N_mF_2), regarding methods of data analysis, the magnitudes of the trends, and interpretation of the causes of the trends. Since these trends of h_mF_2 and N_mF_2 are relatively weak compared to the strong natural variability due to solar and geomagnetic activity, different analysis methods resulted in discrepancies of more than one order of magnitude (Laštovička et al., 2006b). There are two interpretations of the cause of these trends of h_mF_2 and N_mF_2: geomagnetic origin and greenhouse gas cooling effects. Mikhailov et al. (2002) found a small negative residual trend of foF_2 with a natural origin related to long-term variations in solar and geomagnetic activity, but no indication of any manmade effects. Mikhailov (2006) further indicated that thermosphere cooling due to the greenhouse gases is not noticeable in the foF_2 trends due to the weak dependence of N_mF_2 on neutral temperature and, therefore, foF_2 trends are completely controlled by long-term variations of geomagnetic activity. On the other hand, Bremer (1992) found a negative trend in h_mF_2 for a mid-latitude station over time; this supports global cooling of the thermosphere due to greenhouse

* Corresponding author. Tel.: +1 303 497 1529; fax: +1 303 497 2180.
E-mail address: lqian@ucar.edu (L. Qian).

1364-6826/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jastp.2009.03.006

gases. Danilov (2002) developed a method of determining of long-term trends of non-geomagnetic origin, and found a negative trend in foF_2 for the period 1958–1995, which is substantially larger than that for the period of 1948–1985, which supports its anthropogenic origin. Attempts were also made to reconcile the greenhouse and geomagnetic activity causes of these trends. It was suggested that there is simultaneous greenhouse control of the trend in h_mF_2 and geomagnetic control of the trend in foF_2 (e.g., Mikhailov, 2006).

In addition, trends of F_2 peak parameters exhibit variations with geographic location, local time, season, and solar activity. Controversies exist regarding these variations. Bremer (1998, 2001) obtained h_mF_2 and foF_2 trends of different signs for 31 European stations, with negative trends west of 30°E but positive trends east of 30°E. He suggested that trends of F_2 parameters cannot be explained by the increasing greenhouse effect alone and that dynamical effects seem to play an important role. Danilov and Mikhailov (1999) found negative trends for all individual stations they selected, and detected a strong and well pronounced dependence of the foF_2 trends on geomagnetic latitude but no longitudinal dependence, which is contrary to Bremer's finding (1998, 2001). Mikhailov and Marin (2000) found diurnal variations of foF_2 trends, with foF_2 having its minimum trend at local noon and its maximum at night. Danilov (2008) found long-term variations in the relation between daytime and nighttime foF_2 and evoked long-term variations of thermospheric meridional wind to explain these variations. Furthermore, variability in trends of F_2 peak parameters has also been used as evidence of the origin of these trends. Mikhailov and Marin (2000, 2001) and Mikhailov et al. (2002) argued that trends of foF_2 due to greenhouse gas cooling should be positive and should not have complex latitudinal, longitudinal, and diurnal variations, and that latitudinal and diurnal variations of foF_2 trends are evidence of geomagnetic control of the foF_2 trend.

So what are the signs and magnitudes of trends of the F_2 peak parameters and what has been causing their long-term trends? It is likely that both natural trends of solar and geomagnetic activity and anthropogenic trends through the greenhouse gas cooling effect have contributed to long-term trends of the F_2 peak parameters. It is important to understand how the trends of the F_2 peak parameters are influenced by each forcing process in order to determine contributions from each forcing type and identify the driving mechanisms of these trends. In data analysis, it is difficult to separate contributions from forcing of natural origin and the greenhouse effect. For example, it is difficult to explain the origin of complex features of trend dependence on geographic location, local time, season, and solar activity. Modeling studies can be a great tool to separate contributions from the two forcing types and to understand the distribution of trends with location and variations with local time, season, and solar activity. Furthermore, possible dynamic influences on trends of F_2 peak parameters has been speculated about and used to explain the observed features of trend variations (e.g., Bremer, 1998; Danilov, 2008). In this paper we will use a three-dimensional general circulation model to examine dynamic influences on these trends.

Qian et al. (2008) used a one-dimensional model to investigate trends in the global mean ionosphere. In this paper, we will use a three-dimensional upper atmospheric general circulation model to investigate how the three-dimensional ionosphere, particularly foF_2 and h_mF_2, responds to increased CO_2 concentrations in the atmosphere. Specifically, the model will be used to examine the geographic pattern of these trends, their diurnal and seasonal variations, and the dependence of these trends on solar activity. The model will also be used to determine dynamical influences on trends and their variability. Section 2 describes the three-dimensional upper atmosphere general circulation model; Section 3 shows model simulation results; Section 4 provides some discussion; and Section 5 concludes the study.

2. Model description

The model used for this study is the National Center for Atmospheric Research (NCAR) Thermosphere–Ionosphere-Electrodynamic General Circulation Model (TIEGCM). The TIEGCM is a first-principles numerical model that solves the Eulerian continuity, momentum, and energy equations for the coupled thermosphere/ionosphere system (Dickinson et al., 1981, 1984; Roble and Ridley, 1987; Roble et al., 1988; Richmond et al., 1992; Richmond, 1995). It utilizes a spherical coordinate system fixed with respect to the rotating Earth, with latitude and longitude as the horizontal coordinates and pressure surfaces as the vertical coordinate. The pressure interfaces are defined as $z = \ln(P_0/P)$, where P_0 is a reference pressure of $5 \times 10^{-4}\,\mu$b. The vertical range of these pressure surfaces is from −7 to 7, and thus covers an altitude range of about 97–600 km, depending on solar activity. The vertical resolution is 2 model grids per pressure scale height; the horizontal resolution is 5° latitude by 5° longitude, and the model time step is about 3 min. Output of the model are neutral, electron, and ion temperatures; neutral and ion winds; concentrations of major species O, O_2, and N_2; concentrations of minor species $N(^4S)$, $N(^2D)$, NO; concentrations of ions O^+,O_2^+, N_2^+, N^+, NO^+; electron density; and geopotential heights of pressure interfaces.

The external forcing of the TIEGCM are solar irradiance, mainly in the extreme ultraviolet (EUV) and ultraviolet (UV) regions; geomagnetic energy input in the form of auroral energetic particle precipitation and ionospheric convection driven by the magnetosphere–ionosphere current system; perturbation at the lower boundary of the model by waves representing the interaction between the thermosphere/ionosphere system and lower atmosphere processes; and a specified upward or downward plasma flux at the upper boundary representing the interaction of the system with the plasmasphere. In this study, the EUVAC solar proxy model (Richards et al., 1994) was used as solar input. Ionospheric convection driven by the magnetosphere–ionosphere current system is specified by the empirical model of Heelis et al. (1982). Auroral particle precipitation and its ionization and dissociation are calculated by an analytical auroral model described by Roble and Ridley (1987). The migrating semi-diurnal and diurnal tides are specified at the lower boundary using the Global Scale Wave Model (GSWM) (Hagan and Forbes, 2002, 2003). The effect of gravity wave breaking in the mesosphere–lower-thermosphere (MLT) region is included by specifying eddy diffusivity at the lower boundary that declines with altitude. Effects of planetary waves and non-migrating tides are not considered.

Since the goal of this paper is to examine and separate contribution of the greenhouse gas cooling effect on the global distribution of ionospheric trends, we conducted all model runs under geomagnetic quiet conditions. Since CO_2 is the main cooler of the upper atmosphere, we consider the effect of changes of CO_2 concentrations. Changes of other radiatively active gases, such as stratospheric ozone depletion and possible stratospheric and mesospheric water vapor increases, may also slightly affect long-term changes of the ionosphere since Akmaev et al. (2006) have demonstrated the effects of ozone depletion and water vapor increase on lower thermospheric temperature and density. However, this secondary effect is not treated here. The model was run with base (365 ppmv) and doubled CO_2 concentrations (730 ppmv), for both solar minimum and solar maximum, near the June solstice. The 365 ppmv characterizes present-day CO_2