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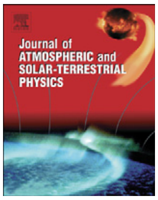

Modeling the effect of sudden stratospheric warming within the thermosphere–ionosphere system

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ABSTRACT

This paper presents an investigation of thermospheric and ionospheric response to the sudden stratospheric warming (SSW) event, which took place in January 2009. This period was characterized by low solar and geomagnetic activity. Analysis was carried out within the Global Self-consistent Model of Thermosphere, Ionosphere and Protonosphere (GSM TIP). The experimental data of the atmospheric temperatures obtained by Aura satellite above Irkutsk and ionosonde data over Yakutsk and Irkutsk were utilized as well. SSW event was modeled by specifying the temperature and density perturbations at the lower boundary of the GSM TIP model (80 km altitude). It was shown that by setting disturbances in the form of a stationary planetary perturbation $s=1$ at the lower boundary of the thermosphere, one could reproduce the negative electron density disturbances in the *F* region of ionosphere during SSW events. Our scenario for the 2009 SSW event in the GSM TIP allowed to obtain results which are in a qualitative agreement with the observation data.

1. Introduction

Interaction between the stratospheric and thermospheric layers is a challenging problem. One of the interesting examples of this interaction is sudden stratospheric warming (SSW). In principle, some of the underlying mechanisms responsible for the coupling in stratosphere, thermosphere and ionosphere are currently known, but the detailed physical processes involved in the SSW event remain poorly understood (Chau et al., 2011). During SSW, the stratospheric temperatures increase by tens of degrees, normal polar vortex changes its location and shape, or breaks up (O'Neill, 2003). Upward propagating planetary waves are mostly of zonal wave numbers 1 and 2. Although SSW has been traditionally known as a stratospheric event, it is also associated with phenomena at both lower and higher altitudes. Thus, in the mesosphere-lower thermosphere (MLT) region, large variations connected with SSW are confirmed in observational studies and theoretical simulations. During winters, the SSW is usually accompanied by MLT cooling (Matsuno, 1971; Labitzke, 1981; Walterscheid et al., 2000; Cho et al., 2004). Progress in experimental techniques concerning SSW effects at MLT altitudes allowed to observe, for example, these effects in OH airglow temperature (Walterscheid et al., 2000), lidar, meteor radar (Hoffmann et al., 2007) and SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) instrument on the TIMED (Thermosphere Ionosphere Mesosphere Energetics and Dynamics) satellite (Siskind et al., 2005) data. Series of instrumental observations show significant variations of the thermospheric temperature at the middle latitudes (Goncharenko and Zhang, 2008): warming in the lower (about 120 km) and cooling in the upper (above 150 km) thermosphere. The coupling mechanisms were investigated also with modeling studies using the TIME-GCM model (Thermosphere Ionosphere Mesosphere Electrodynamics General Circulation Model) (Liu et al., 2002, 2005, 2010) from 30 km to about 600 km altitude and WAM model (Whole Atmosphere Model) (Fuller-Rowell et al., 2010, 2011) from 0 to 600 km altitude.

The primary mechanism causing SSW seems to be planetary waves (PW) originating in stratosphere and propagating upwards to MLT region. These PW interact with the mean-flow and can produce significant changes of MLT dynamics and temperature (Hernandez, 2003; Liu and Roble, 2005). The waves with large periods are able to penetrate to the altitudes above the lowermost thermosphere and were observed in the ionosphere (Altadill et al., 2001; Pancheva et al., 2002; Danilov and Vanina, 2004). Moreover, PW in the MLT region may produce modification of the diurnal and semidiurnal tidal modes and hence change the atmospheric dynamo electric field, especially at low latitudes. The above mentioned electrodynamic response was simulated

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and reported in papers by (Liu et al., 2002, 2010; Fuller-Rowell et al., 2010, 2011). Although TIME-GCM simulations by Liu et al. (2010) have underestimated variations in vertical ion drift during SSW, simulations using WAM model with CTIP model have produced results closer to the experimental data (Fuller-Rowell et al., 2010, 2011).

As it has been noted in the paper of Chau et al. (2011), the global ionospheric response to SSW was investigated in many studies in which FORMOSTAT3/COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate) data were used. Analysis of thermospheric density observed by CHAMP (Challenging Minisatellite Payload) and GRACE (Gravity Recovery and. Climate Experiment) satellites (Liu et al., 2011) showed decrease in density during SSW in January 2009. Density has a minimum on January 24, 2009, e.g. some days after temperature maximum in high-latitude stratosphere. The greatest density decrease is at ~20°S and ~40°N. Since density is closely connected with thermospheric temperature Liu et al. (2010) concluded that this density variations may be caused by cooling in the upper thermosphere by ~50 K.

Recent years, total electron content (TEC) measurements have been widely used for studying the ionospheric behavior at quiet and disturbed conditions (Lastovicka, 2002; Lilensten and Blelly, 2002). In particular, the detailed analysis of TEC variations during SSW periods can be found in Goncharenko et al. (2010 a,b), and Chau et al. (2010). Using the TIME-GCM model Liu et al. (2010) clearly demonstrated that the quasi-stationary planetary waves present at the lower boundary (30 km) at high latitudes modify the total electron content. The daytime TEC changes predicted by TIME-GCM remain much smaller than that observed in the experiments. Discrepancy between theoretical results and observation data is usually associated with either inadequate model inputs or mathematical simplifications of some physical processes. Hence, a capability of an individual theoretical model to describe adequately the experimental data is a good test of the mathematical model. We performed model calculations using the first principles Global Self-Consistent Model of the Thermosphere, Ionosphere and Protonosphere (GSM TIP) in order to investigate a capability of the model GSM TIP to reproduce variations of ionospheric parameters during strong SSW event. The model outputs have been compared with the observation data above Yakutsk (62°N, 130°E), and Irkutsk (52°N, 103°E) stations for January 2009.

2. Brief description of the model

The Global Self-consistent Model of the Thermosphere, Ionosphere and Protonosphere (GSM TIP) (Namgaladze et al., 1988, 1991; Korenkov et al., 1998) was developed in the WD IZMIRAN (West Department of Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio wave propagation of the Russian Academy of Sciences). It was used for simulations of the time-dependent global structure of the near-Earth space environment from 80 km to 15 Earth radii. In the thermospheric block of the model, global distribution of the neutral gas temperature (T_n) and of N_2, O_2, O, NO, N(^{4}S), and N(^{2}D) concentration, as well as the three-dimensional circulation of the neutral gas and N_2^+, O_2^+, and NO^+, and also their temperature (T_i) and velocities (V_i), are calculated in the range from 80 to 526 km in the spherical geomagnetic coordinate system. In the vertical dimension, the thermospheric code uses 30 layers, with each layer approximately equal to a half thickness of scale height. The minimum distance between knots is 3 km nearly low boundary and increases to 40 km at 526 km altitude. In the ionospheric section of the model, global time dependent distributions of ions, electron temperatures (T_i, T_e), vector velocity (V_i), and O^+ and H^+ ion concentrations are calculated in the magnetic dipole coordinate system from 175 km in the northern hemisphere to 175 km in the southern hemisphere. In this case, the ionosphere code for atomic ions does not require the upper boundary condition. Additionally, the model also provides the two-dimensional electric field potential distribution for dynamo and magnetospheric origin. The calculation of electric fields in the GSM TIP model has recently been modified by Klimenko et al. (2006, 2007).

The solution of the full system of equations of the model is performed numerically on a global grid with resolutions of 5° in latitude and 15° in longitude as specified in the spherical geomagnetic coordinate system; the time step is 2 min. The model inputs are (1) the solar EUV and UV spectra (10–1760 Å), (2) the precipitating electron fluxes, and (3) the amplitudes and spatial distribution of Region 1 field aligned currents or a cross-polar cap potential difference and Region 2 field aligned currents. The transformations between all coordinate systems in the model are given by standard equations. The GSM TIP model has been described in detail by (Namgaladze et al., 1988, 1991; Korenkov et al., 1998). Current simulation uses the empirical model by Zhang and Paxton (2008) for high-energy particle precipitation. In this model, the energy and energy flux of precipitating electrons depend on a 3-h *Kp*-index, instead of functional dependences based on the morphological representations in earlier GSM TIP studies.

3. Statement of the problem and SSW model

During sudden stratospheric warming (SSW) events the sudden enhancement of neutral temperature and planetary wave activity are observed at altitude of 30–40 km. This meteorological event occurs most often in the winter period in northern hemisphere. In our calculations, the parameters of a sudden stratospheric warming are specified at the GSM TIP lower boundary of the thermosphere (at an altitude of 80 km) as a superposition of boundary conditions for a quiet period and some disturbance of neutral temperature and density. The thermospheric low boundary conditions for the temperature, density and wind velocity for a quiet period correspond to the COMMA-LIM (Cologne Model of the Middle Atmosphere – Leipzig Institute for Meteorology) model (Fröhlich et al., 2003). These lower boundary conditions were obtained for January. Fig. 1 (at top) shows the global distribution of neutral temperature at a height of 80 km according to COMMA-LIM model.

We use simulation results in order to understand the thermosphere/ionosphere response to SSW event. Usually both PW1 and PW2 are present in the stratosphere, and their amplitudes are highly variable in both space and time. Now it is well known that SSW of 2009 was forced by PW2 in the stratosphere. In the literature devoted to SSW 2009 event, the various scenarios of SSW were discussed. The study (Fuller-Rowell et al., 2010; Goncharenko et al., 2010b) points out that during the SSW 2009 PW with zonal number $s=1$ is changed in the stratosphere, and in study (Goncharenko et al., 2010a; Fuller-Rowell et al., 2011), the same conclusion was made for the PW with $s=2$. Note that the type of wave disturbances at mesospheric altitudes during the SSW is not discussed in these studies. However, after analyzing zonal temperature structure observed by MIPAS during the January 2009 SSW, Funke et al. (2010) found a pronounced wave 1 pattern in the entire middle and upper atmosphere with maximum amplitudes at around 50 km and 140 km. This conclusion is indirectly confirmed by Pedatella and Forbes (2010). We consider the stratospheric warming at the mesopause as a result of the stationary planetary perturbation with zonal wave number $s=1$. The selecting wave