Journal of Atmospheric and Solar-Terrestrial Physics 71 (2009) 2017–2026

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

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

Quantifying the effect of thermospheric parameterization in a global model

David J. Pawlowski *, Aaron J. Ridley

Department of Atmospheric, Oceanic and Space Sciences, University of Michigan, Ann Arbor, MI 48109-2143, USA

ARTICLE INFO

Article history:
Received 12 May 2009
Received in revised form
4 September 2009
Accepted 11 September 2009
Available online 20 September 2009

Keywords:
Thermosphere
Global climate model
Parameterization

ABSTRACT

Global climate models have become useful tools for studying the important physical processes that affect the Earth's upper atmosphere. However, the results produced by all models contain uncertainty that stems for the manner in which the model is driven, as well as in the treatment of the internal physics and numerics. In order to fully understand the scientific value of the model results then, it is necessary to have a quantitative understanding of the uncertainty in the model. In this study, the global ionosphere–thermosphere model is used to investigate how uncertainty in the use of parameters in a large scale model can affect the model results. Eight parameters are studied that ultimately have an effect on the thermospheric temperature equation. It is found that among these, uncertainty in the thermal conductivity, NO cooling, and NO binary diffusion coefficients most strongly translate to uncertainty in the temperature and density results. In addition, variations in the eddy diffusion coefficient are shown to result in significant uncertainty in the thermospheric composition, and ultimately the electron density.

1. Introduction

The necessity to understand the dynamics of the governing physical processes that occur in the Earth's upper atmosphere is constantly growing due to the human dependence on space-borne technology. While observations of the ionosphere and thermosphere are an important tool for developing deeper understanding of the physics of the system, continuous, global observations of the upper atmosphere, at high temporal resolution, for all of the state variables are not available. This leads the community to turn to models, which can simulate the behavior of the system under a wide range of conditions, globally, and on time scales of a few seconds. However, models are limited by the numerical schemes they are built on, as well as the physics that are included in them and the implementation of that physics. Each of these limitations introduce uncertainty into the results, and when modeling the upper atmosphere and using the results to develop an understanding of the physical processes taking place, it is important to understand the specific sources of this uncertainty, as well as the effect the uncertainty has on the results.

Perhaps the most important source of uncertainty stems from the fact that the ionosphere–thermosphere system is highly externally driven. In other words, given adequate time, the initial conditions of the system should have little to no effect on the end state of the system. This is primarily a result of the coupling between the Earth's upper atmosphere and the magnetosphere as well as the sun (e.g., Kamide and Baumjohann, 1993; Lu et al., 1995; Khazanov et al., 2003). Dynamics in these two external systems have a profound effect on the state of the ionosphere and thermosphere. Thus, when attempting to model the system, it is critical to accurately account for the forcing due to these sources. For example, it would be impossible to sustain an ionosphere with out specifying the solar radiation flux, regardless of the initial ionospheric conditions. There is a great deal of work throughout the community attempting to accurately specify the important sources of energy and momentum to the upper atmosphere (Fuller-Rowell and Evans, 1987; Barth et al., 2003; Woods et al., 2005; Solomon and Qian, 2005; Chamberlin et al., 2007; Ridley, 2005) and several studies have investigated how these sources of energy affect the global structure of the thermosphere (e.g., Roble et al., 1987; Roble, 1995; Killeen et al., 1997).

The uncertainty introduced into the results by external forcing can be quite substantial depending on the manner in which the forcing is specified. For example, it is possible to drive the solar flux within a model empirically, based on measurements of the flux at 10.7 cm (e.g.,Hinteregger et al., 1981; Richards et al., 1994; Woods and Rottman, 2002; Solomon and Qian, 2005). However, this $F_{10.7}$ proxy calculates the flux across the entire EUV spectrum (1–150 nm) based on measurements at only one wavelength. Further, the $F_{10.7}$ is only obtained once per day. (Woods et al., 1998) shows that parts of the soft X-ray and EUV flux can change by an order of magnitude or more in just a few minutes. Similar uncertainties can be introduced into the model results by the high-latitude drivers.

* Corresponding author. Tel.: +1 734 709 0311; fax: +1 734 647 3083.
E-mail address: dpawlows@umich.edu (D.J. Pawlowski).

1364-6826/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jastp.2009.09.007

In addition to the external drivers, there are other sources of uncertainty. In some cases, there is underlying physics in the system that is important and needs to be accounted for, but is not completely understood. In other cases, the physics may be understood, but it may be too complicated to take into account given the scale of problem trying to be solved. In either case, models must approximate the real system through the use of parameterizations. In today's global circulation models (GCMs) of the Earth's upper atmosphere, dozens of parameters are used to specify a variety of rates and coefficients. Parameters are used to specify sources in the energy equation, such as heating efficiencies and conductivities, the momentum equation, such as diffusion coefficients, and the mass continuity equation, such as reaction rates. While many of these parameters have been studied in detail, whether through laboratory or computational experiments, the use of any of them is subject to some uncertainty, since it is impossible to test each parameter in all possible scenarios.

It is unrealistic to expect that models always provide the correct answer to every problem, and it is in uncovering why the answer is wrong that new physics can be deduced. In order to better understand the results from a model and to use the results to provide insight into the physical processes that are not understood, it is important to evaluate the inherent uncertainty in the results. This is done here using the global ionosphere–thermosphere model (GITM) to investigate the uncertainty associated with the use of parameterizations on the results. Specifically, the effect of eight of the most important atmospheric parameters on the results is studied under solar minimum and solar maximum conditions. In addition, the time-dependent effects of the parameters are studied during a geomagnetic storm.

2. Model conditions

GITM is a 3D spherical model that solves for the coupled ionosphere-thermosphere system. GITM has several features that make it different from other global models of this region. First, GITM solves the momentum equation without making the assumption of hydrostatic equilibrium. This allows for significant vertical flows to develop in a self-consistent manner (Deng et al., 2008), as well as for the use of an altitude-based vertical coordinate system. The horizontal domain is block based, which allows for efficient parallel processing as well as for the resolution to be very flexible. As a result, GITM has been run at resolutions as high as 1.25° longitude $\times 1.25^{\circ}$ latitude. Another consequence of the horizontal block-based domain is that GITM can be run in one-dimensional (1D) mode. In 1D, GITM can be run on a personal computer very quickly, which is ideal for debugging and long term climatological studies. Ridley et al. (2006) further explains the model in detail, including the core numerical algorithms, and a validation study has been performed by Pawlowski et al. (2008) using incoherent scatter radar data.

2.1. Parameters

For this study, the uncertainty involved with the use of eight different thermospheric parameters is investigated. The parameters examined are the thermal conductivity (Schunk and Nagy, 2000), eddy diffusion coefficient (Blum and Schuchardt, 1978; Brasseur and Offermann, 1986; Fuller-Rowell and Rees, 1992; Fukao et al., 1994), homopause altitude (Blum and Schuchardt, 1978; Hall et al., 2008), NO binary diffusion coefficient (Colegrove et al., 1966), N_2 photodissociation branching ratio (Rees, 1989; Schunk and Nagy, 2000), NO^+ recombination branching ratio (Torr et al., 1976; Rees, 1989; Marsh et al., 2004), O^+ recombination rate, and the nitric oxide (NO) dilution factor for NO cooling (Kockarts, 1980). These represent only a subset of the parameters involved in the model. One of the reasons that these parameters have been selected is that each of them has some inherent uncertainty. The goal of this study is to show how this uncertainty affects the results.

The other reason these parameters are selected is because each of them are significant with regards to the calculation of the neutral gas temperature. In GITM, the chemical source terms are included in the vertical temperature equation, which is given by

$$\frac{\partial \mathcal{T}}{\partial t} + u_r \frac{\partial \mathcal{T}}{\partial r} + (\gamma - 1)\mathcal{T}\left(\frac{2u_r}{r} + \frac{\partial u_r}{\partial r}\right) = \frac{k}{c_v \rho \overline{m}_n}\mathcal{L}, \tag{1}$$

where $\mathcal{T} = P/\rho$, u_r is the bulk (mass-density weighted) vertical velocity, γ the ratio of specific heats, k the Boltzmann's constant, c_v the specific heat at constant volume, ρ the mass density, P the pressure, and $\overline{m}_n$ the average mass of the neutrals. The $k/\overline{m}$ on the right side of Eq. (1) is required to relate the normalized temperature, $\mathcal{T}$, to the thermal energy source term, $\mathcal{L}$, which is the total of the thermal energy sources, and is calculated by

$$\mathcal{L} = Q_{EUV} + Q_{NO} + Q_O + Q_p \frac{\partial}{\partial r}\left((\kappa_c)\frac{\partial T}{\partial r}\right) + N_e \frac{\overline{m}_i \overline{m}_n}{\overline{m}_i + \overline{m}_n} \nu_{in}(\mathbf{v} - \mathbf{u})^2. \tag{2}$$

$Q_{EUV} Q_p$, Q_{NO}, and Q_O are the EUV heating, particle heating, and NO and O cooling terms respectively, κ_c is the thermal conductivity, and the final term is a frictional or Joule heating term.

Each of the terms in Eq. (2) contributes to the total uncertainty in the model, since each term itself contains some uncertainty. The solar, particle, and Joule heating terms are directly driven by external forcing (i.e., magnetospheric electric fields, particle precipitation, as well as the solar EUV flux), therefore, most of the inherent uncertainty in the results due to these terms is not contained in GITM specifically. However, the radiative cooling and the conductive terms are dependent on the internal dynamics of the model, and thus uncertainty in these terms can be quantified. Each of the parameters addressed in this study have an effect on one of these three terms, either though a coefficient used directly in the calculation of the temperature, or because the parameter either directly or indirectly causes compositional changes, which affects the radiative cooling rates. In order to quantify the effect that each of these parameters has on the upper atmosphere, GITM is run several times for each parameter. Each time, the value of the parameter is changed within the limit of published values. Table 1 summarizes these values.

3. Results

3.1. Steady-state simulations

As a first look at the effect of these different parameter values, GITM is run under solar minimum and solar maximum conditions to see how the results differ when the model is in steady-state. In these simulations, GITM is initialized using MSIS and IRI profiles and then run for 24 h. In the solar minimum case, GITM is run with a $f_{10.7}$ of 87.8 W/(m^{2}Hz) and during the solar maximum case, GITM is run with a $f_{10.7}$ of 240.6 W/(m^2 Hz). The high-latitudes are driven by constant values which are the same for solar minimum and solar maximum. The hemispheric power index (HPI) is specified to be 1.0 and the cross polar cap potential patterns are specified by the Weimer model (Weimer, 1996) using interplanetary magnetic field values of $B_y = 0.0$ nT and $B_z = -2.0$ nT and a radial solar wind velocity of 400 km/s. In all cases, all inputs are identical between the runs except for the particular parameter being investigated.