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Thermospheric neutral density response to solar forcing

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Abstract

Recent measurements by the Solar EUV (Extreme Ultra Violet) Experiment (SEE) aboard the Thermosphere–Ionosphere–Mesosphere Energetics and Dynamics satellite (TIMED) provide solar EUV spectral irradiance with adequate spectral and temporal resolution, and thus the opportunity to use solar measurements directly in upper atmospheric general circulation models. Thermospheric neutral density is simulated with the NCAR Thermosphere–Ionosphere–Electrodynamic General Circulation Model (TIEGCM) using TIMED/SEE measurements and using the EUVAC solar proxy model. Neutral density is also calculated using the NRLMSISE-00 empirical model. These modeled densities are then compared to density measurements derived from satellite drag data. It is found that using measured solar irradiance in the general circulation model can improve density calculations compared to using the solar proxy model. It is also found that the general circulation model can improve upon the empirical model in simulating geomagnetic storm effects and the solar cycle variation of neutral density.

Keywords: Thermospheric neutral density; Density variation; General circulation model; Empirical model; Solar energy deposition; Solar spectral irradiance

1. Introduction

Investigation of variations of thermospheric neutral density is important for understanding Sun–Earth connections, the interaction of the upper atmosphere and the ionosphere, and space environment applications such as determination of satellite orbits. Thermospheric neutral density varies on time scales ranging from hours to decades in response to solar irradiance, geomagnetic activity, lower atmospheric processes, and anthropogenic trace gases. Solar EUV heating is the primary energy source to the thermosphere and thus governs the basic temperature, density, and composition structure of the thermosphere. As a result, thermospheric neutral density is mainly modulated by changes of solar EUV heating, from solar cycle variation of ~11 years and solar rotational variation of ~27 days, to diurnal variation and short-term episodic variation from solar flares.

Solar EUV measurements started in the 1960s and have been sparse in both spectral and temporal coverage, and many of the measurements have insufficient spectral resolution (see the review by Woods et al. (2004)). Among the measurements, the Atmospheric Explorer (AE) mission and related calibration rocket flights have provided the most comprehensive measurements in terms of spectral and temporal coverage from 1974 to 1981. These measurements provide the basis for some of the widely used reference spectra and solar proxy models [e.g. Hinteregger et al., 1981a,b; Richards et al., 1994].

Aeronomic calculations in numerical models of the thermosphere–ionosphere system require accurate specification of solar spectral irradiance to fully account for the influence of solar input on thermospheric composition, energetics, and dynamics. Due to the inadequacy of spectral and temporal coverage of EUV measurements, solar proxy

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models have been used as solar input for upper atmospheric general circulation models. For example, the NCAR TIEGCM uses the EUVAC proxy model (Richards et al., 1994) as the default for solar input. However, the recent TIMED/SEE provides the opportunity to use measured solar spectral irradiance in numerical models. The TIMED/SEE measures solar spectral irradiance from 0.1 to 194 nm (Woods et al., 2005). It uses two types of instruments: an XUV Photometer System (XPS) and a EUV Grating Spectrograph (EGS). The XPS measures solar irradiance from 0.1 to 34 nm with a resolution of 5 to 10 nm, and the EGS measures irradiance from 27 to 194 nm with 0.4 nm spectral resolution. The TIMED satellite was launched on December 7, 2001. It has a circular orbit of 625 km in altitude with 74.1° inclination. Its period is about 90 min per orbit. The TIMED/SEE measures solar spectrum once per orbit, i.e., about 15 times per day. The data products are daily-averaged solar spectral irradiance from 0 to 195 nm with 1 nm resolution (Level 3 data), and orbital solar spectral irradiance in the same format as the daily averaged spectra (Level 3A). In this study, version 8 of level 3 data is employed.

The calculation of solar EUV energy deposition depends on both the specification of solar EUV spectral irradiance and the method employed to calculate ionization, dissociation, and heating rates. Solomon and Qian (2005) developed a new solar EUV energy deposition scheme for upper atmospheric general circulation models that includes accurate parameterization of photoelectron effects. It has low spectral resolution but adequate accuracy that is suitable for global three-dimensional and time-dependent general circulation models.

In this study, we use the NCAR TIEGCM to investigate thermospheric neutral density response to solar forcing. TIMED/SEE measurements and the solar proxy model EUVAC (Richards et al., 1994) are used as solar input for the TIEGCM. Model calculations are then compared to measurements of thermospheric neutral density derived from satellite drag data. It will be investigated whether using measured solar spectral irradiance can improve model calculations of thermospheric density compared to using solar proxy models. In addition, density calculated by the NRLMSISE-00 (Picone et al., 2002) (subsequently “MSIS00”) will be compared to density from the TIEGCM and satellite drag derived neutral density, to evaluate the capability of the TIEGCM and the MSIS00 in quantification of thermospheric neutral density.

2. The TIEGCM model

The TIEGCM model has been developed, evolved, and improved over time (Dickinson et al., 1981, 1984; Roble et al., 1987a; Roble et al., 1988; Richmond et al., 1992). It solves continuity, momentum, and energy equations of the coupled thermosphere and ionosphere system self-consistently. It assumes hydrostatic equilibrium and uses pressure coordinates which extend from ~97 to ~600 km depending on solar activity. The vertical resolution is two grids per pressure scale height and the horizontal resolution is 5° latitude by 5° longitude. The coupling of the model domain with the lower atmosphere is applied by using the Global Scale Wave Model (GSWM, Hagan and Forbes, 2002, 2003) to specify the lower boundary tides, and a simple eddy diffusivity parameterization. Solar energy deposition is calculated using a scheme developed by Solomon and Qian (2005). Auroral precipitation is parameterized by an empirical model (Roble and Ridley, 1987b) and the high latitude ionospheric convection pattern is specified using the empirical model developed by Heelis et al. (1982). Dynamo effects of the thermospheric neutral wind and the feedback of the dynamo electric field and currents on neutral and plasma dynamics is included using an ionospheric dynamo model (Richmond et al., 1992). Either measured solar spectra or solar proxy models can be used as solar input. Geomagnetic input is parameterized by the geomagnetic index K_p.

3. Thermospheric neutral density data

Measurements of neutral density in the thermosphere are obtained from satellite drag data that has been computed (Bowman et al., 2004a) for the Air Force High Accuracy Satellite Drag Model (HASDM) program using the Jacchia, 1970 empirical model (J70) (Jacchia, 1970, 1971). The satellite used in this study is satellite #12388. It is a low-Earth orbit spherical radar calibration satellite. It has a moderately eccentric orbit with perigee near ~400 km and apogee currently near ~1525 km. Its inclination is 83°. The data are daily averaged neutral densities at the perigee locations, i.e., the perigee altitude, local solar time, and latitude. The daily drag density values have been shown to be accurate to within 2–4% by comparisons of the daily drag values using numerous calibration satellites in a wide variety of orbits. In this study, modeled densities from the TIEGCM and the MSIS00 are sampled at satellite perigee locations to be compared to satellite drag derived density.

4. Comparison of the EUVAC and the TIMED/SEE as solar input for the TIEGCM

The EUVAC is an empirical solar EUV spectral irradiance model for aeronomic calculations. It is based on the F74113 reference spectrum (Heroux and Higgins, 1977; Heroux and Hinteregger, 1978) and the solar cycle variation of solar spectral irradiance measured by the EUV Sensor (EUVS) aboard the AE-E satellite. The F74113 spectrum was measured on April 23, 1974 by a rocket flight at low solar activity. The EUVAC covers solar EUV from 5 to 105 nm and this wavelength range is divided into 37 bins. Solar spectrum for a given solar activity is scaled based on solar radio flux at 10.7 cm ($F_{10.7}$ index) and its 81-day average ($F_{10.7A}$):