Journal of Atmospheric and Solar-Terrestrial Physics 147 (2016) 50–58

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

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

Thermospheric atomic oxygen concentrations from WINDII $O^+(^2P \rightarrow {}^2D)$ 732 nm emission: Comparisons with the NRLMSISE-00 and C-IAM models and with GUVI observations

Gordon G. Shepherd *, Young-Min Cho, Victor I. Fomichev, Oleg V. Martynenko

Centre for Research in Earth and Space Science, York University, Toronto, Ontario, Canada M3J 1P3

ARTICLE INFO

Article history:
Received 1 March 2016
Received in revised form
28 June 2016
Accepted 29 June 2016
Available online 29 June 2016

Keywords:
Interferometer
Airglow
Atomic oxygen
Thermosphere
Satellite
Models

ABSTRACT

Thermospheric atomic oxygen concentrations have been retrieved from observations by the Wind Imaging Interferometer (WINDII) $O^+(^2P \rightarrow {}^2D)$ 732 and 733 nm emissions and are compared with results obtained by the Global Ultraviolet Imager (GUVI). Although the observations compared were taken ten years apart, the periods were selected on the basis of solar activity, using the Canadian Ionosphere and Atmosphere Model (C-IAM) to bridge the time gap. Results from all of these were compared with those from the Naval Research Laboratory Mass Spectrometer and Incoherent Scatter (NRLMSISE-00) model. Comparisons were made on the basis of $F_{10.7}$ solar flux, day of year, local time, season, latitude and longitude. The WINDII local time variations showed enhanced values for the Northern spring season. Latitude and longitude plots showed smooth variations for NRLMSISE-00 and large variations for both WINDII and GUVI observations; in particular a depression in atomic oxygen concentration around 40 °S latitude and 100 °E longitude that is tentatively identified with a longitudinal wave 1 that does not propagate in local time but has an annual variation. The averaged values showed the WINDII values to be 0.75 that of NRLMSISE-00 compared with 0.80 for GUVI. Thus the WINDII values agreed with those of GUVI to within 6%, although taken 10 years apart.

1. Introduction

Atomic oxygen is a major atmospheric constituent in the upper atmosphere, playing a role in almost all processes and being the dominant constituent above about 200 km. In spite of this it is only recently that its absolute concentrations have become known with some confidence. This is because the methods of accurate measurement are few, comprising remote sensing airglow observations and in-situ measurements with mass spectrometers. The Atmosphere Explorer (AE) satellites (Spencer et al., 1973) conducted an ambitious series of observations intended to determine all the important parameters of the upper atmosphere and they established clear directions towards this goal. One of the approaches used was highly elliptical orbits so that a range of altitudes would be observed on each orbit. However this did not yield true vertical profiles since different altitudes were sampled at different locations. Circular orbits were also employed to explore specific altitudes in detail. The VAE (Visible Airglow Experiment) on AE (Hays et al., 1973) was a photometer that included the O^+ $(^2P \rightarrow {}^2D)$ 732.0 and 733.0 nm emissions. The simulated results agreed well with the observations (Yee et al., 1981), using the atmospheric composition provided by Hedin et al. (1977). Sunil Krishna and Singh (2009) modeled the 732.0 nm volume emission rates and compared the profiles with those of VAE for individual orbits of AE-C. They obtained good agreement using the ultraviolet solar fluxes of Solar2000 (also known as the Solar Irradiance Platform – SIP) by Tobiska et al. (2000).

In recent years the SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY) (Kaufmann et al., 2014), Optical Spectrograph and InfraRed Imaging System (OSIRIS) (Sheese et al., 2011), Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) (Smith et al., 2010) and Wind Imaging Interferometer (WINDII) (Russell et al., 2005) instruments have made major progress in determining atomic oxygen concentrations in the mesosphere and lower thermosphere (MLT) region, using the O_2, OH and $O(^1S)$ airglows from roughly 80–120 km. These measurements are not discussed here.

Many researchers requiring atomic oxygen concentrations in their analyses make use of the NRLMSISE-00 (hereinafter

* Corresponding author.
E-mail addresses: gordon@yorku.ca (G.G. Shepherd), youngmin.joshua.cho@gmail.com (Y.-M. Cho), victor.i.fomichev@gmail.com (V.I. Fomichev), oleg.marttinen@gmail.com (O.V. Martynenko).

http://dx.doi.org/10.1016/j.jastp.2016.06.015

NRLMSIS) (Picone et al., 2002) empirical model, which combines measurements with the constraints of physical processes. The Bates-Walker equations (Walker, 1965) represent the basic profiles of the temperature and of species number density as analytic functions of altitude. These equations are an exact solution for thermal and diffusive equilibrium. The observations are incorporated into the model with these constraints. The observational input with respect to atomic oxygen came from the AE mass spectrometer measurements while that for O_2 came from the Solar Maximum Mission (SMM), from occultation of solar UV emissions. However, the resulting [O] and [O_2] are not independent as mass spectrometers sometimes provide ambiguous measurements of the two.

The $O^+(^2P \rightarrow ^2D)$ 732.0 and 733.0 nm daytime airglow emissions were observed with the Wind Imaging Interferometer (WINDII) instrument on the Upper Atmosphere Research Satellite (UARS). Preliminary results from the WINDII observations and their comparison with the emission rates produced by the Canadian Ionosphere and Atmosphere Model (C-IAM) were presented by Shepherd et al. (2014). The C-IAM (Martynenko et al., 2014) used for the comparison is a whole atmosphere model that extends from the surface to the inner magnetosphere and is able to describe the impact on the upper atmosphere and ionosphere of self-consistently generated lower atmosphere dynamical variability.

The O^+ emission is produced mainly by photoionization from the ground state of neutral atomic oxygen. Thus, the atomic oxygen concentration can be determined from the solar flux if the quenching rates are accurately known. This article presents the complete WINDII dataset of the derived atomic oxygen concentrations and their comparison with the NRLMSIS and C-IAM model results as well as with measurements from the Global Ultraviolet Imager (GUVI) (Christensen et al., 2003) on board the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) satellite. These derived atomic oxygen concentrations from WINDII add to the existing knowledge of atomic oxygen measurements as well as contribute to the understanding of thermospheric dynamics for short- and long-term periods.

The GUVI instrument viewed the $O(^5S \rightarrow ^3P)$ 135.6 nm daytime ultraviolet emissions, in addition to the Lyman–Birge–Hopfield N_2 bands. The details of the retrieval of atomic oxygen are described by Meier et al. [2015] but the approach is similar to that for the WINDII O^+ in that solar input produces airglow emission excited from atomic oxygen so that observations of the airglow emission allow atomic oxygen to be retrieved. However there are important differences in that for the O^+ 732 nm emission the excitation is solar photon ionization from ground state O while for the daytime 135.6 nm emission the dominant process is by the excitation of ground state atomic oxygen by solar-produced photoelectrons. For the 732 nm emission the only complication is the quenching of the O^+ ^2P before radiation; the 135.6 nm emission analysis must also consider the multiple scattering of the resonance transition as well as subsequent absorption by molecular oxygen in the atmosphere. These differences make the WINDII comparisons with GUVI a valuable contribution towards a definitive determination of atomic oxygen concentrations in the thermosphere; a comparison made here against the background of the NRLMSIS and C-IAM models.

2. Observations

The Wind Imaging Interferometer (WINDII) (Shepherd et al., 1993) on the UARS satellite observed various airglow emissions in the thermosphere from 1991 to 2003, including the $O(^1S)$ 557.7 nm emission, the $O(^1D)$ 630.0 nm emission and the $O^+(^2P \rightarrow ^2D)$ 732.0 and 733.0 nm emissions (Shepherd et al. 2012). The UARS spacecraft maintained an altitude of 585 km in a near-circular orbit of 57° inclination. In order to measure both components of the horizontal wind WINDII had two fields of view viewing the Earth's limb sideways with respect to the orbit plane, one at 45° from the velocity vector and the other at 135°. The spacecraft had a sun-facing side; WINDII was mounted on the shadowed side so that both of its fields of view pointed away from the sun. Each day the local time viewed by WINDII advanced by 20 min so during the course of 36 days the local time for the ascending portion of an orbit would move from dusk to dawn (dayside) while that for the descending portion would advance from dawn to dusk (nightside). Every 36 days it was necessary to yaw the spacecraft through 180° in order to keep the sun on the sun-facing side. This reset the local time, causing a 1200 LT jump for the observations. As a consequence the WINDII observations were made from 42° latitude (geographic coordinates are used exclusively in this article) in one hemisphere to 72° in the other, reversing hemispheres every 36 days. The images from the two fields of view of WINDII were combined side-by-side onto one CCD detector, whose altitude range was roughly fixed from 80 km up to 300 km, varying somewhat around the orbit. The Michelson interferometer that was the heart of WINDII was phased stepped to obtain winds from the phase shifts of the interferometer pattern, but for purely emission rate observations as employed in this study all phase steps were averaged together. Although WINDII operated until 2003 (when GUVI began operations) it's operations were more limited after 1994 because of battery degradation and so priority was given to the $O(^1S)$ emission because of the high quality of the winds from this emission.

Retrieval of the O^+ emission rate was complicated by the doublet structure and the fact that the OH Meinel $P_1(2)$ line at 731.63 nm is transmitted through the same filter and it is only recently that data have been analyzed successfully (Shepherd et al., 2014), making a new data set of WINDII O^+ from 1992 to 1994 available that are used for this study. The GUVI observations and their analysis are described by Meier et al. [2015]. For this study Version 13 of the GUVI data was employed.

3. Model and methods

Shepherd et al. (2014) describe the retrieval of O^+ 732 nm volume emission rate profiles from the WINDII data, and their comparison with selected profiles determined using the C-IAM model, with good agreement. From a previous study Martynenko et al. (2014) employed the C-IAM model to simulate the wave 4 pattern of the nonmigrating tide as seen in the nighttime 135.6 nm ionospheric emission resulting from the $O(^5S \rightarrow ^3P)$ nighttime transition of excited atomic oxygen and is the result of the radiative recombination reaction of O^+ with electrons.

For the present retrieval of [O] the concentration in the model was iterated on the [O] values to bring the C-IAM O^+ emission profiles into agreement with the WINDII 732 nm observations. The equation for the 732 nm volume emission rate (V_{732}) at altitude z and solar zenith angle α can be expressed as:

$$V_{732}(z,\ \alpha) = \left\{ \eta A\ P(z,\alpha) \right\} \left\{ A + k_O\left[O(z)\right] + k_{N2}\left[N_2(z)\right] \right\}^{-1}, \quad (1)$$

where P(z, α) represents the local $O^+(^2P)$ photo-ionization production rate, A is the inverse radiative lifetime of the $O^+(^2P)$ state ($0.216\ s^{-1}$, (Seaton and Osterbrock, 1957)), $\eta = 0.445$ is the branching ratio for the transitions $O^+(^2P \rightarrow ^2D)$ at 732 nm, k_O and k_{N2} are the quenching rates of $O^+(^2P)$ by O ($5 \times 10^{-11}\ cm^3\ s^{-1}$) and N_2 ($1.8 \times 10^{-10}\ cm^3\ s^{-1}$), respectively as specified by Stephan et al. (2003)]. The photoionization production rate of the $O^+(^2P)$ state occurs at wavelengths less than approximately 66.6 nm and