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Effect of solar activity on the morphology of 7320 Å dayglow emission

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Abstract. A comprehensive model is developed to study the 7320 Å dayglow emission. The emission profiles are obtained with the help of the recently developed Solar2000 EUV (Extreme Ultra Violet) flux model. These emission profiles are used to construct the morphology of this emission between equator and 45° N in the Northern Hemisphere. A span of five years (2001–2005) is chosen to study the effect of solar activity on the morphology of this emission. The morphology is studied on 3 April which lies under the equinox conditions. In 2001, the solar F10.7 index on the chosen date was as high as 223.1 which is the case of solar maximum. It is found that the intensity of this emission does not vary linearly with the F10.7 solar index. The morphology shows that the region of maximum emission expands towards the higher latitudes as the F10.7 index increases.

Keywords. Atmospheric composition and structure (Airglow and aurora; Thermosphere – composition and chemistry)

1 Introduction

Over the decades, the airglow measurements have been instrumental in understanding the structure and dynamics of upper atmosphere. Different constituents of the atmosphere have their characteristic airglow emissions. The atomic oxygen is a very important constituent of the upper atmosphere. It plays a crucial role in the atmospheric chemistry at mesospheric and thermospheric altitudes. The highly varying density of atomic oxygen at the thermospheric altitudes has been of a prime interest for researchers over a long period of time. The airglow emission such as 6300 Å is less likely

to be useful in the measurement of atomic oxygen at thermospheric altitudes as this line results from the forbidden transition which originate from the long-lived, low energy states and it is subject to many chemical excitations and deactivation processes (Bahsoun-Hamade et al., 1994). However, the 5577 Å emission may be used to understand the atomic oxygen density if one uses the proper inversion techniques. These inversion techniques are more complex due to the reaction $N_2(A^3\Sigma_u^+)$+O which is one of the significant sources of the production of $O(^1S)$ state (Culot et al., 2005). The atomic oxygen airglow emissions at 8446 Å and 7320 Å occur at thermospheric altitudes (above 150 km) and have been suggested to be potential indicators to monitor the atomic oxygen density at these heights. The 7320 Å airglow emission, which occurs from metastable $O^+(^2P)$ by the photoionization of neutral atomic oxygen with the solar extreme ultra violet (EUV) photons, gets quenched by O, N_2 and thermal electrons. McDade et al. (1991) has suggested a mechanism to extract atomic oxygen density as well as the solar EUV fluxes from this emission.

The atomic oxygen 7320 Å is a very weak emission which generally occurs at the 220–250 km altitude region. This emission was first observed by Carlson and Suzuki (1974). The photoionization of atomic oxygen by extreme solar ultraviolet radiation produces the $O^+(^2P)$, hence, this emission can directly give us the information about the thermospheric atomic oxygen density and solar EUV flux. Yee et al. (1982) have developed a technique to deduce the exospheric temperatures from this emission and according to McDade et al. (1991) the thermospheric oxygen densities and ionization frequencies can be obtained by the inversion of 7320 Å airglow measurements. Torr et al. (1990a), Fennelly et al. (1991), Rusch et al. (1977), Meriwether et al. (1978) have also suggested that this emission could be a potential source to infer atomic oxygen densities. The auroral feature of this emission was reported by satellite-based observation by Cogger et al. (1987).
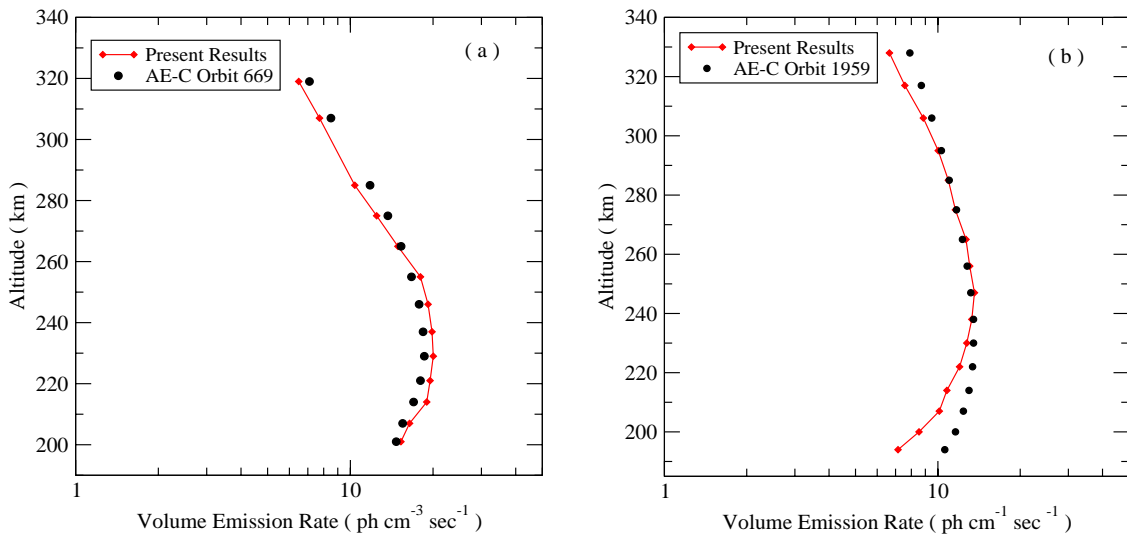
Fig. 1. Comparison of modeled Volume Emission Rates with the AE-C satellite data. AE-C orbit 669 upleg **(a)** and AE-C orbit 1959 **(b)**.
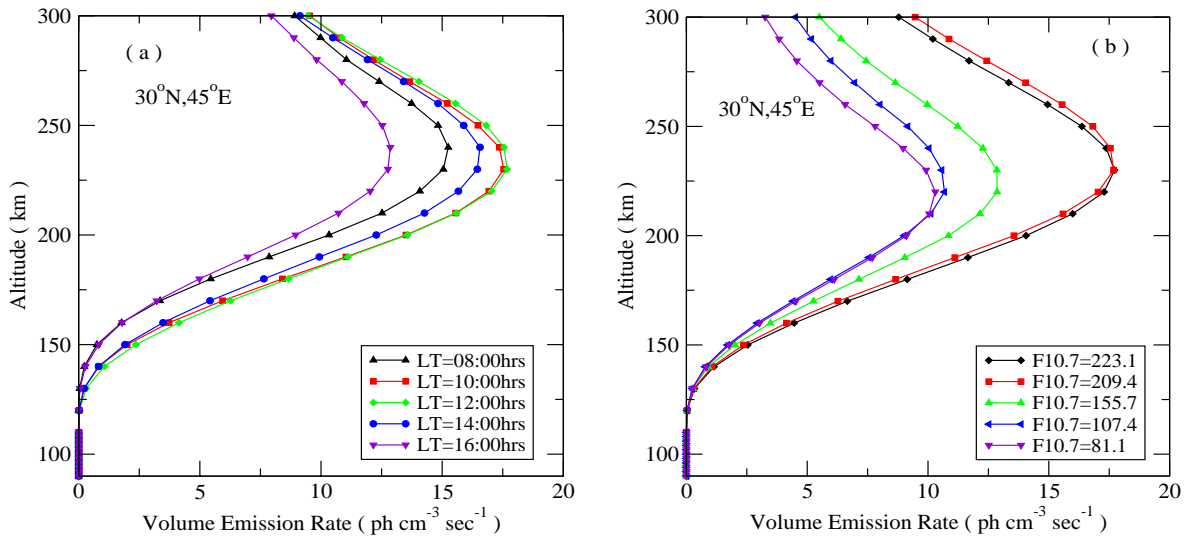

Fig. 2. Diurnal variation of the Volume Emission Rate (VER) of 7320 Å dayglow emission on 3 April 2002 **(a)**. Variation of VER of 7320 Å on 3 April at 30° N 45° E with F10.7 solar index **(b)**.

The $O^+(^2P)$ undergoes quenching by reacting with different constituents of the atmosphere. Walker et al. (1975) gave a preliminary estimate of quenching of $O^+(^2P)$ ions in the atmosphere, Rusch et al. (1977) have quantified the various quenching mechanisms by which the $O^+(^2P)$ ion is lost in the atmosphere. These quenching parameters were reevaluated by Chang et al. (1993) and Stephan et al. (2003). Abreu et al. (1980) have reported the measurements of 7320 Å emission during the solar cycle 21 in which they have studied the photoionization rate of $O^+(^2P)$ – determined using the measurements of $O^+(^2D-^2P)$ emission. A morphological study

of 7320 Å was reported (Yee et al., 1982) in which it has been shown that the intensity of 7320 Å shows a strong correlation to the solar activity. The modeled results of 7320 Å were first reported by Torr et al. (1990a) in which they have modeled the diurnal and seasonal variations near solar minimum over a wide range of latitudes and longitudes using their midlatitude interhemispheric model. The study of Torr et al. (1990a) is based mainly on EUV solar flux for solar minimum conditions and they have used F74113 solar fluxes in the model. Now, it is a well established fact that these fluxes are not consistent with the airglow measurements and do not account for

the variability of solar activity. The limitations of Abreu et al. (1980) are that these are only for solar zenith angle greater than 60, which include only early morning and early evening local times.

The solar irradiance in the EUV range is a fundamental parameter for modeling the chemistry and dynamics of upper atmosphere. Since there are no measured values of EUV flux available under variable solar conditions, one has to use models which would reproduce the solar flux. Hinteregger et al. (1973) have made measurements of solar flux over the wavelength range 140–1850 Å for the day 74 113. Torr and Torr (1985) gave SC#21REF which was for the period of July 1976 and February 1979. The F74113 fluxes given by Hinteregger were measured at the solar minimum and SC#21REF is for moderate low solar activity. The F74113 fluxes are generally 20–30% lower than SC#21REF fluxes for wavelengths greater than 800 Å and about the same between 300 and 800 Å but by a factor 2 larger below 300 Å. This is an inconsistent behaviour and it would not be possible to reconstruct the exact fluxes for any given day. Several researchers (Torr et al., 1990a; Tyagi and Singh, 1998; Lancaster et al., 2000; Singh et al., 2004) have reported the modeled results of dayglow emissions using different scaling techniques for Hinteregger et al. (1973, 1977) and Tobiska solar fluxes (Tobiska, 1991), however, these studies could not explain the dayglow emission measurements. Consequently a more consistent solar EUV flux model is required to model the dayglow emissions. The latest solar EUV flux model, Solar2000 also known as Solar Irradiance Platform (SIP) as developed by Tobiska et al. (2000), has not been fully tested in the airglow studies. Subsequently, one should test this model in the study of airglow emissions.

In the present study, the latest solar EUV flux model, as developed by Tobiska et al. (2000), is used to develop a comprehensive model to study the 7320 Å dayglow emissions. The morphology of this emission is presented between 0 and 45° N latitude in the Northern Hemisphere. The calculations of Volume Emission Rate (VER) and intensities are done between the years 2001 and 2005. The date of 3 April is chosen because it is very close to equinox conditions. This date is also very important in the sense that it was a solar maximum day with F10.7 solar index as high as 223.1 on 3 April 2001. The minimum value of F10.7 on 3 April 2005 was 81.1. It has provided a good opportunity to study the morphology of 7320 Å emission for a wide range of solar activity.

2 Model

The atomic oxygen 7320 Å dayglow is a weak emission generally observed above 200 km. This emission is due to the radiative loss of $O^+(^2P)$ in the following way.
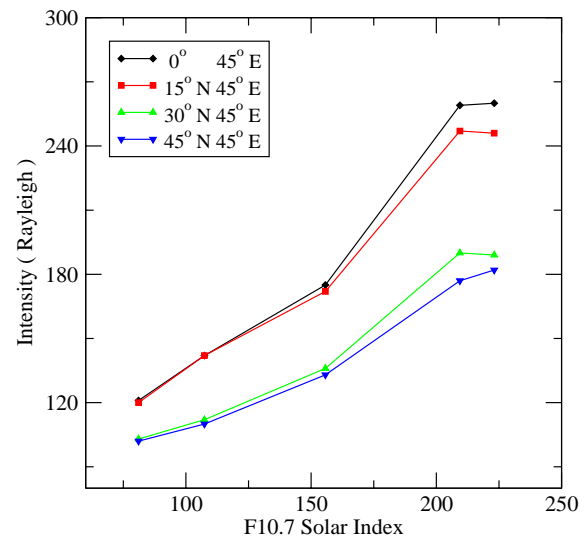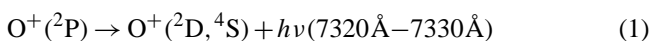
$$O^+(^2P) \rightarrow O^+(^2D, ^4S) + h\nu(7320\text{Å} - 7330\text{Å}) \qquad (1)$$

Fig. 3. Integrated column intensity variation with the solar activity at different locations in the Northern Hemisphere.

The metastable $O^+(^2P)$ ions have a lifetime of 4–5 s. There are two pairs of doublets associated with the $(^2D-^2P)$ transition. The doublet at 7320 Å is contributed by transition from $^2P_{1/2}$ and $^2P_{3/2}$ to $^2D_{5/2}$ and transition to $^2D_{3/2}$ would result in the formation of 7330 Å. According to Seaton and Osterbrock (1957) the 7320 Å emission is nearly 1.31 times stronger than the emission at 7330 Å. The main sources of production of $O^+(^2P)$ ion are by direct photoionization excitation of atomic oxygen caused by absorption of solar extreme ultra violet photons with wavelengths less than 666 Å.

$$O + h\nu(\lambda < 666\text{Å}) \rightarrow O^+(^2P) \qquad (2)$$
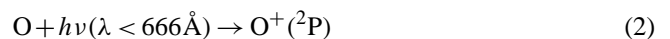
The secondary source of production is photoelectron impact ionization of ground state atomic oxygen atoms

$$O + e^- \rightarrow O^+(^2P) + 2e^- \qquad (3)$$

It has been suggested by Cogger et al. (1987), McDade et al. (1991), Chang et al. (1993) and Rusch et al. (1977) that depending on the solar zenith angle, the secondary source contributes only 15–20% to the total production of $O^+(^2P)$. Further, at higher altitudes (above 250 km), there may be a possible source of $O^+(^2P)$ due to the photoelectron impact on $O^+(^4S)$. Unfortunately no cross-section data is available in the literature for this process. Consequently, it is not possible, at present, to estimate the contribution of this process to the production of $O^+(^2P)$. This process could be studied in future once the excitation cross section is available. The production rates, due to the two processes, can be written as
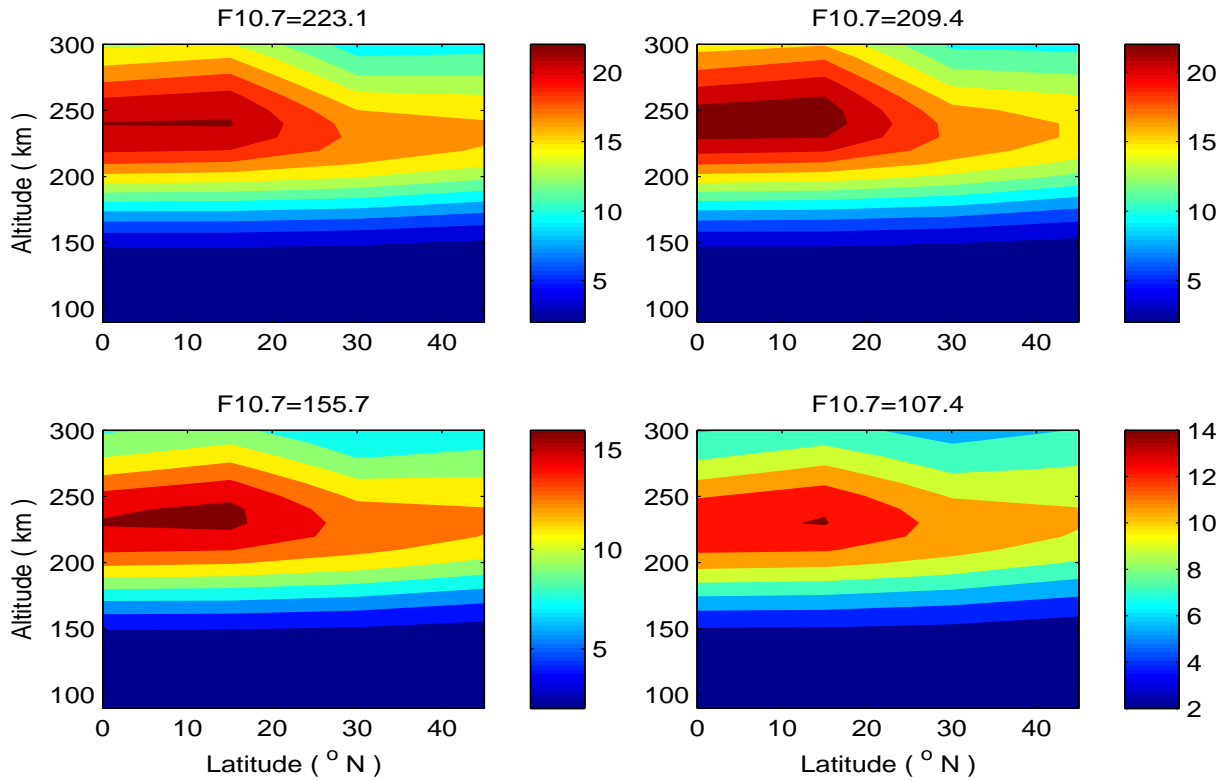
Fig. 4. Modeled morphology of 7320 Å between 0° and 45° N on 3 April for different solar activity levels at 10:00 h local time.
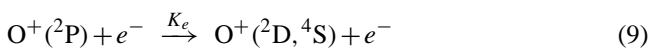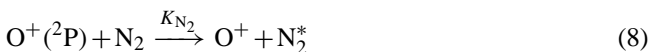
$$R_1(z) = [O] \sum_\lambda I_Z(\lambda, \alpha) \sigma_{O^+(^2P)}(\lambda) \tag{4}$$

$$R_2(z) = [O] \int_{E_{th}}^{\infty} \sigma_e(E) \Phi(E, Z, \alpha) dE \tag{5}$$

Here $I_Z(\lambda, \alpha)$ is the solar EUV flux at wavelength (λ) and the solar zenith angle (α), $\sigma_{O^+(^2P)}$ is the photoionization cross section of photo electron impact excitation of $O^+(^2P)$. E_{th} is the threshold energy for the production of $O^+(^2P)$. The total production rate of $O^+(^2P)$ can now be written as

$$P[O^+(^2P)] = R_1(Z, \alpha) + R_2(Z, \alpha) \tag{6}$$

Thus, the $O^+(^2P)$ produced is lost by radiation in the thermospheric altitudes and at relatively lower altitudes it is quenched by interacting with [O], [N$_2$] and [e] as mentioned in the following reaction mechanisms.

$$O^+(^2P) + O \xrightarrow{K_O} O^+ + O \tag{7}$$

$$O^+(^2P) + N_2 \xrightarrow{K_{N_2}} O^+ + N_2^* \tag{8}$$

$$O^+(^2P) + e^- \xrightarrow{K_e} O^+(^2D, ^4S) + e^- \tag{9}$$

Here K_O, K_{N_2} and K_e are the reaction rate coefficients for the above mentioned reactions. The values of these coefficients are summarized in Table 1.

Table 1. Reaction rate coefficients.

K_O	5.2×10^{-11} cm^3 s^{-1}	Stephan et al. (2003)
K_{N_2}	4.8×10^{-10} cm^3 s^{-1}	Rusch et al. (1977), Chang et al. (1993)
K_e	$1.89 \times 10^{-7} (T_e/300)^{0.5}$	Henry et al. (1969)

The quenching factor is given by

$$Q_{O^+(^2P)} = \frac{A_{2P}}{A_{2P} + K_O[O] + K_{N_2}[N_2] + K_e[e]} \tag{10}$$

Here [O], [N$_2$] and [e] are densities of atomic Oxygen, Nitrogen and electron, respectively. These parameters are calculated from NRLMSIS-00 (Picone et al., 2002) model. A_{2P} is taken to be 0.281 s^{-1} which is the loss frequency of $O^+(^2P)$ due to all radiative transitions (Seaton and Osterbrock, 1957). The volume emission rate of 7320 Å is

$$V_{7320} = 0.781 \cdot Q_{O^+(^2P)} \cdot P[O^+(^2P)] \tag{11}$$

here 0.781 is the branching ratio taken from theoretical transition probabilities calculated by Seaton and Osterbrock (1957). The column intensity (Rayleigh) is obtained by integrating the volume emission rate over the vertical column of altitude.
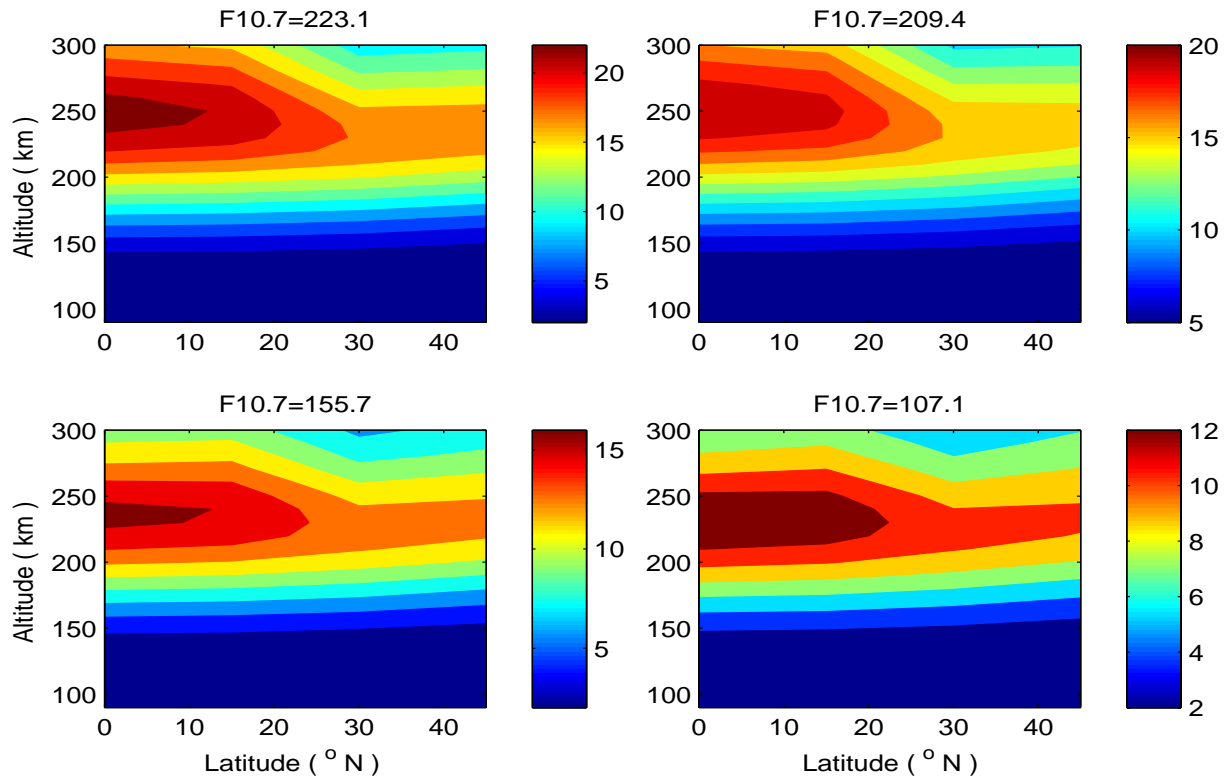
Fig. 5. Modeled morphology of 7320 Å between 0° and 45° N on 3 April for different solar activity levels at 12:00 h local time.

The cross sections for the photoelectron impact ionization reaction is taken from the work of Jackman et al. (1977) which is based on the differential scattering cross section as given by Green and Sawada (1972). The differential cross section is given by the following expression.

$$S_i(E,T) = \frac{A(E)\Gamma^2(E)}{[T - T_o(E)]^2 + \Gamma^2(E)} \tag{12}$$

where

$$A(E) = \left(\frac{K}{E} + K_B\right)\ln\left(\frac{E}{J} + J_B + \frac{J_c}{E}\right)$$

$$\Gamma(E) = \frac{\Gamma_s E}{(E + \Gamma B)}$$

and $T_o(E) = T_s - \frac{T_A}{(E + T_B)}$

With T as the energy of secondary electron and E the energy of primary electron, we used the total scattering cross section of $O^+(^2P)$ state as

$$\sigma = A(E)\Gamma(E)\arctan\frac{(T - T_0)}{\Gamma(E)} \tag{13}$$

Here $K, K_B, J, J_B, J_c, \Gamma, \Gamma_B, \Gamma_s, T_A, T_O, T_B$ are different for different gases and they are adjustable. For the $O^+(^2P)$ state we have taken I_i=18.50, k=1.31, K_B=0.0, J=1.78,

J_B=0, J_B=0, Γ_s=13.0, Γ_B=−0.815, T_S=6.41, T_A=3450.0 and T_B=162.0. The neutral atomic and molecular densities of oxygen and nitrogen are obtained from NRLMSIS – 00 model (Picone et al., 2002), electron densities, neutral and electron temperatures have been obtained from IRI – 07 model (Bilitza et al., 2008). The solar Extreme Ultra Violet radiation fluxes are obtained from the Solar Irradiance Platform, also known as Solar2000 (Tobiska et al., 2000). These parameters have been incorporated in the model as given by Singh et al. (1996) to obtain the Volume emission rate. The photoelectron impact ionization of atomic oxygen is the main source of the production of this emission. The photo electron fluxes have been calculated for the atmospheric density distributions relevant to each case using the model of Richards and Torr (1983) with updates to the electron impact cross sections for O and O_2. The total O_2 excitation cross section is taken from the work of Kanik et al. (1993).

3 Results and discussion

The $O^+(^2P)$ transition at 7320 Å has very little observational history in the literature. Rusch et al. (1977) have reported the measurements of this emission using instruments on Atmospheric Explorer C and D satellites for various orbits. The validity of the present model is tested by comparing the results
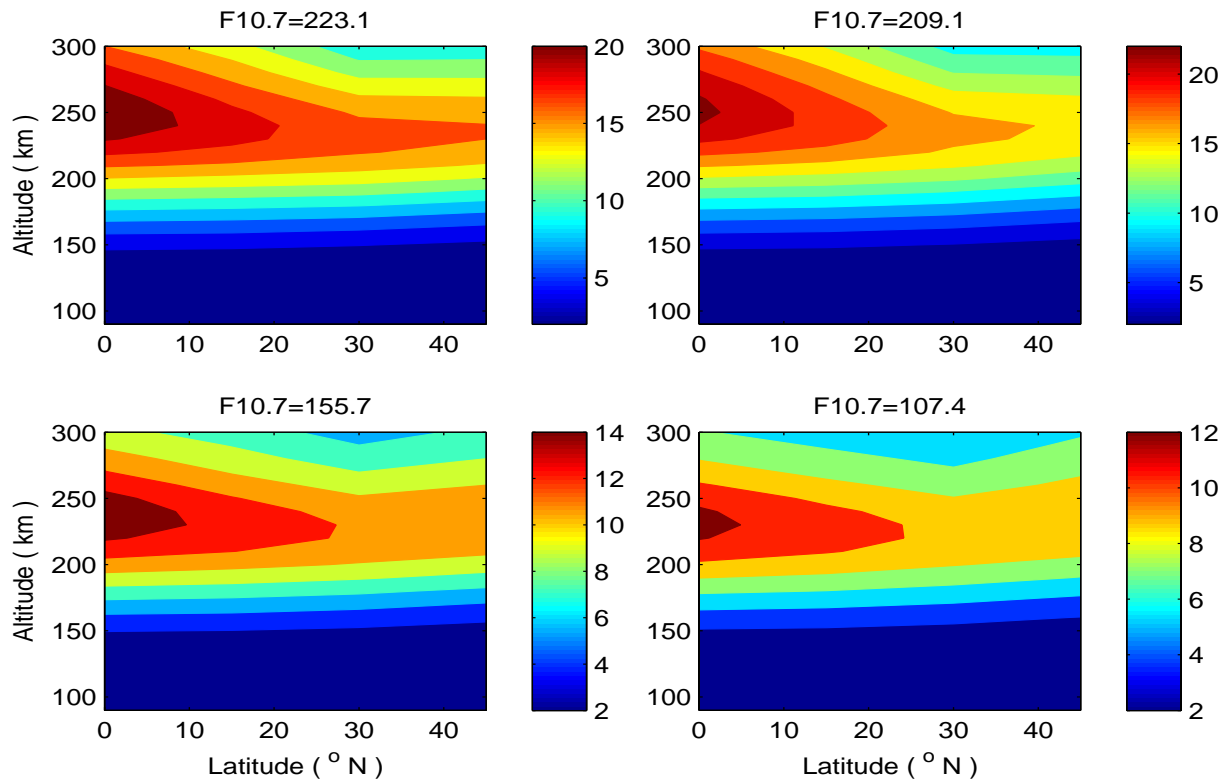
Fig. 6. Modeled morphology of 7320 Å between 0° and 45° N on 3 April for different solar activity levels at 14:00 h local time.

of the total volume emission rate of 7319–7330 Å with the measured two cases as reported by Rusch et al. (1977). Figure 1a and b shows the comparison of modeled results with the observations carried by AE satellite over upleg orbit 669 on 14 February 1974 and orbit 1959 on 8 June 1974, respectively. From these figures, it is evident that the modeled emission rates are very consistent with the observations (within 10%) at all altitudes, except at altitudes below 230 km in Fig. 1b where the emission rate is nearly 20–30% lower than the observed values. The possible reason for the lower value of emission rate may be due to the solar flare activity on 8 June 1974. On this day solar bursts were found to be in progress. In the present calculations, we have used F10.7 solar index as 92.2 which is an average value for a day. Since there were solar bursts in progress, large fluctuations in F10.7 solar index were expected. Unfortunately, we do not have the exact value of F10.7 solar index available which could be used in the model under the measurement conditions. It is quite likely that there may be some enhancement in the solar extreme ultraviolet radiation flux during the solar flare activity, which may result in higher production of 7320 Å emission. If this effect is included in the model, one may expect a better agreement between model and measurements.

The consistency between modeled results and the observations indicates that the present model can be used to study

the 7320 Å emission. The model calculations of 7320 Å dayglow volume emission rates are extended to various latitudes to construct the morphology. We have chosen 3 April in the present calculations. This date is chosen because 3 April 2001 was a solar maximum day with F10.7 index as high as 223.1 Further, 3 April lies under equinox conditions. The emission rates are obtained for the consecutive 5 years starting from 2001 until 2005. During this period, the variation of F10.7 index has been reported between 81.1 and 223.1. It provides a good opportunity to study the effect of the variation of solar activity on this emission for this particular date. The emission rates are obtained between equator and 45° N latitudes for a fixed longitude (45° E). Figure 2a illustrates the variation of the emission rate at 30° N for various local times on 3 April 2001. The maximum emission rate is found at local noon time and the peak is found at about 225 km. Figure 2b illustrates the variation of emission rate at various values of F10.7 solar index. These calculations are performed at 30° N and for local time 12:00 h. It is quite noticeable from Fig. 2b that the emission rate is not showing a linear variation with the F10.7 solar index. The emission rate becomes more or less saturated when the F10.7 solar index is above 200. In Fig. 3 the variation of intensity, as a function of F10.7 solar index, is plotted. It is quite evident from this figure that the intensity becomes more or less constant at

higher values of F10.7 solar index (greater than 200) which is about 250 Rayleigh.

The diurnal variation of morphology of 7320 Å dayglow emissions is presented in Figs. 4 to 6. Each figure has four panels which correspond to various F10.7 values at fixed local times. The main feature, which is seen in these figures, is that the region of maximum emission expands towards the higher latitudes as the solar activity increases. However, below 150 km, no appreciable emission is produced. It is also quite evident from these figures that the emission rate of 7320 Å shows very little variation with F10.7 solar index between 150 and 200 km altitudes.

4 Conclusions

A comprehensive model is developed to study the emission rate of 7320 Å dayglow emission. The model is found to be very consistent with the measurements and reproduces the measured emission rate profiles. This agreement shows that the Solar2000 model is quite consistent. The emission rates are used to construct the morphology of this emission between equator and 45° N in the Northern Hemisphere. The present morphology is the first of its kind. It is found that the intensity of this emission does not vary linearly with the F10.7 solar index. The morphology shows that the region of maximum emission expands towards the higher latitudes as the F10.7 index increases. It is also found that the intensity attains a saturation when the F10.7 solar index is greater than 200.

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