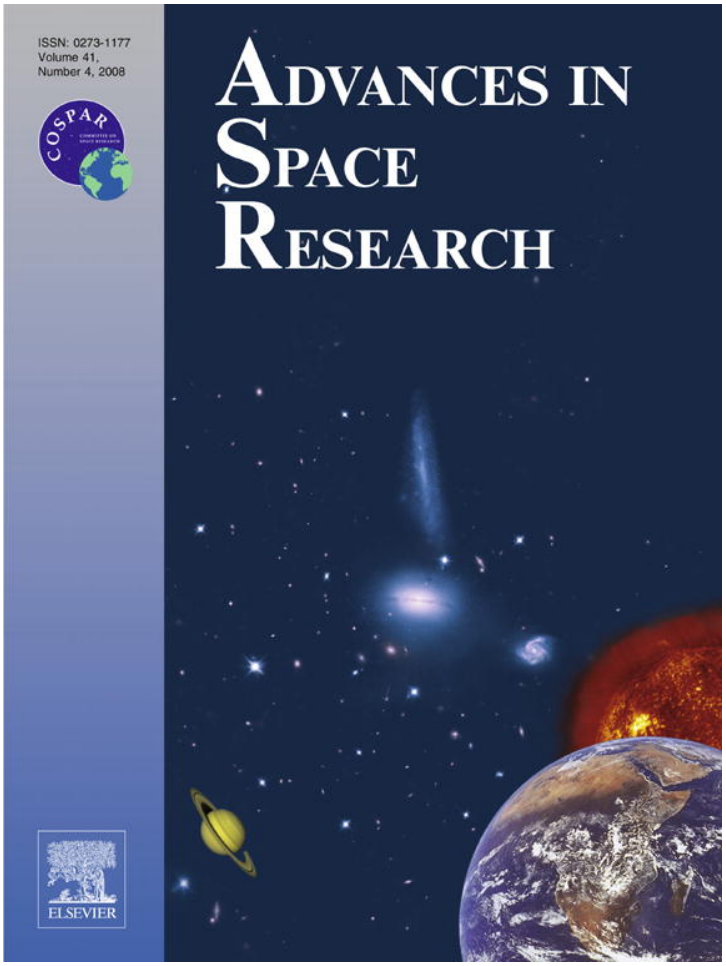

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Behavior of the atomic oxygen 557.7 nm atmospheric emission in the solar cycle 23

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Abstract

We present the results of nightglow observation of the atomic oxygen 557.7 nm line emission in the solar cycle 23. We use the experimental data obtained at Geophysical observatory near Irkutsk (52°N, 103°E), Russia, for the 1997–2006 period. The 557.7 nm emission observations data are compared with atmospheric and solar parameters. We note a difference in correlation coefficients between the 557.7 nm emission intensity and the solar activity indices in different phases of the solar cycle. Airglow observation results are compared with the observational data obtained by other authors.

The obtained results show that the variations of 557.7 nm emission intensity are highly sensitive to atmospheric parameters and could be preliminary associated with the atmospheric dynamics and various disturbances including the effects from lower atmospheric layers.

Probably, manifestation of these disturbances and their contribution to the 557.7 nm emission variations may differ in particular years or cycles of solar activity.

Keywords: Airglow; Solar activity; 557.7 nm emission

1. Introduction

Atomic oxygen 557.7 nm emission appears at heights about 85–115 km, in the mesosphere and lower thermosphere. This is an atmospheric region where both the effects of dynamics as well as disturbances of various nature from the underlying atmospheric layers and the external influence of solar activity can be manifested. According to Fukuyama (1977a), the 557.7 airglow variation should be considered together with thermal and dynamical processes in stratosphere, mesosphere and low thermosphere.

We believe that at large temporal scales identification of 557.7 nm emission variations and separation of manifestations of atmospheric dynamics and solar activity is a sophisticated and still unsolved problem. Results of various authors for different stations and observation periods indicate different levels of the dependence of the 557.7 nm emission intensity on solar activity – from very high, correlation coefficient is up to 0.8 (Fukuyama, 1977a; Givishvili et al., 1996) to medium, correlation coefficient is up to 0.6 (Fishkova et al., 2000) or completely absent (Fukuyama, 1977a). This might be related to the fact that dynamics of the underlying atmosphere may also depend, in some complicated manner, on solar activity and, in some cases, to be a determinative.

This paper presents a combined analysis of 557.7 nm airglow variations and atmospheric and solar parameters in the solar cycle 23.

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2. Observations and data

In this paper we analyzed:

- The 557.7 nm airglow observational data obtained at the Geophysical observatory of the Institute of Solar-Terrestrial Physics (ISTP) (52°N, 103°E) for 1997 through 2005.
- The NOAA/SEC Boulder, USA data on 10.7 cm Solar Radio Flux (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_RADIO/FLUX/).
- Data on zonal temperature anomalies in the middle atmosphere: (http://www.cpc.ncep.noaa.gov/products/stratosphere/strat-trop/).

Airglow measurements were made by the 4-channel zenith photometer in the O(^{1}S) 557.7 nm and O(^{1}D) 630 nm atomic oxygen emission lines and in the near infrared (720–830 nm) and ultraviolet (360–410 nm) spectral intervals. Green and red (557.7 and 630 nm) emission lines were selected with interference – tilting filters ($\Delta\lambda_{1/2} \sim 1$–2 nm). Measurements were recorded with an averaging of ~12 s. The photometers' angular fields of view are 4–5°. Absolute calibration of the measuring channels of equipment was carried out in different periods using reference stars. Channels were subsequently monitored using reference light sources. Airglow observations were made in the moonless night-time during the clear and relatively clear nights for 1–2 weeks per month, mainly in the autumn–winter–spring period. We analyzed observation data for night-time after the evening astronomical twilight and up to the morning one. Thus, the twilight glow was not taken into account. Seasonal variations of this emission during the periods 1991–1993 and 1997–2001, as well as measurement method were presented in Mikhalev et al. (2003).

3. Results and discussion

Fig. 1 shows variations of the following parameters: the monthly mean 557.7 nm nightglow intensities (I_G) (a) and monthly mean $F_{10.7}$ index (b). For comparison, the monthly mean 630 nm nightglow intensities (I_R) for the period of 1999–2005 are presented in Fig. 1c. During the 1999–2005 period the measurements of 557.7 and 630 nm emissions were carried out simultaneously and processed by one and the same procedure. Standard errors of the monthly means for I_G are shown in Fig. 1a.

Many papers investigating the dependence of I_G on solar activity usually mentioned positive correlation with $F_{10.7}$ index (Fukuyama, 1977a; Givishvili et al., 1996; Fishkova et al., 2000). Only few papers noted a negative correlation of these parameters for some observation intervals. For example, correlation coefficients between I_G and $F_{10.7}$ index in Midya et al. (2002) are −0.46 and −0.09 for 1984 and 1985, respectively. Long-term 557.7 nm emission intensity variations in Givishvili et al. (1996) also

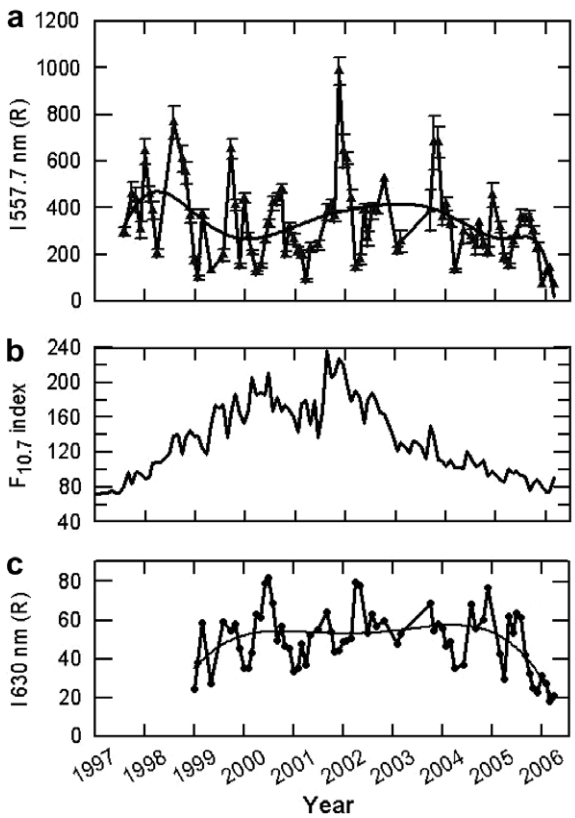

Fig. 1. Variations of: monthly mean 557.7 nm nightglow intensities (I_G) (a); monthly mean $F_{10.7}$ index (b); monthly mean 630 nm nightglow intensities (I_R) (c).

exhibit broken synchronization between the behavior of 557.7 nm emission intensity and $F_{10.7}$ index in some years.

The I_G variations in Fig. 1 show different patterns for the dependence of I_G on solar activity level ($F_{10.7}$ index) over the period under analysis. During the phase of rise of solar activity in 1997–2000 the decrease of green line intensity and accordingly negative correlation between I_G and $F_{10.7}$ index was marked, the correlation coefficient is −0.33. Since the second maximum of solar activity on $F_{10.7}$ index (the end of 2001–the beginning of 2002), the decrease of both $F_{10.7}$ and I_G and accordingly positive correlation between these parameters have been found (correlation coefficient is 0.38). In particular periods (for example, the end of 2003) short-term variations of $F_{10.7}$ index can be compared with the corresponding I_G variations.

In the thermosphere, above 100 km, the atmospheric parameters are more exposed to direct solar radiation than other atmospheric layers and can display solar activity variations (Sahai et al., 1988). It confirms also variations of the monthly mean 630 nm nightglow appearing at F-region heights ~180–250 km (Fig. 1c). At heights where the 557.7 nm emission appears, the dynamics of atmosphere including stratosphere can also be the determinative factor for this emission variations (Fukuyama, 1977a). Atomic oxygen 557.7 nm airglow represents the behavior

of atomic oxygen in heights of appearing of this emission, emission rate goes approximately as the cube of the atomic oxygen concentration (Shepherd et al., 2004). It is known, that I_G has a strong variability in interdiurnal and seasonal variations, during equinox transition. A relation of these variations, their regional (Mikhalev et al., 2003) and longitudinal features (Wang et al., 2002) form an interannual variability. This variability is connected with different processes: variations in atmospheric density (Cook, 1969; Groves, 1972) and prevailing winds at 85–105 km altitudes (Kochanski, 1972), the dissipation variations of diurnal tides and gravity waves (Kulkarni, 1974), the meridional transport of oxygen (Johnson and Gottlieb, 1973; Donahue et al., 1974), the meridional circulation, vertical winds, and diffusion (Angelats and Forbes, 1998), the zonal wind reversal (Shiokawa and Kiyama, 2000), seasonal variations of mesospheric and lower-thermospheric temperature, springtime transition in lower-thermospheric atomic oxygen (Shepherd et al., 1999) and other factors.

Sources of the most of these processes are located in the low atmosphere–mesosphere, stratosphere and troposphere or controlled by these layers. For example, it is known, that the disturbances appearing in stratosphere, can result to disturbances at higher levels, including mesosphere and thermosphere (Fukuyama, 1977a; Shepherd et al., 2004; Hoffmann et al., 2002). Therefore variations I_G as well as variations of mesosphere parameters should been considered taking into account mesosphere's coupling with the lower atmosphere including stratosphere.

For revealing the possible reasons of I_G behavior in 1997–2000 we have analyzed available parameters of underlying atmosphere – zonal temperature anomalies. Zonal temperature anomaly means the deviation of a measurable zonal temperature (averaged on the longitude) from the long-term average, for that latitude.

For investigating interannual and long-term variations of atmospheric emissions and other parameters usually use their annual mean values. It allows to remove large seasonal variations in some parameters. Therefore, further we analyzed annual mean values I_G and zonal temperature anomalies.

Fig. 2 presents the annual mean: intensities of 557.7 nm airglow for October–November (a), I_G (b), $F_{10.7}$ index (c) and zonal temperature anomalies at ~50 km level for 60–90°N latitudes (d).

About the connection of stratospheric and mesospheric temperature and I_G variations can be told the following. The effect of I_G increase during the stratospheric warming in winter and spring periods is well known (Fukuyama, 1977b). It should be noted that contribution of this effect to the monthly mean values of the green line emission intensity I_G for East Siberia, where ISTP Geophysical observatory is located, is more significant one, in comparison with other mid-latitude stations (Mikhalev et al., 2003). Moreover, we noticed that periods where I_G increased at ISTP Observatory during stratospheric warmings (Medvedeva et al., 2006) and

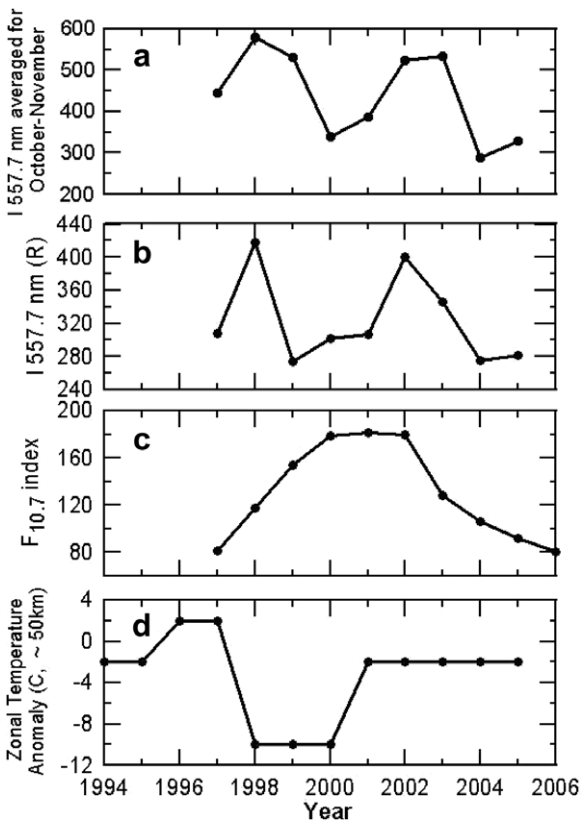

Fig. 2. Variations of: annual mean intensities of 557.7 nm airglow for October–November (a); annual mean 557.7 nm nightglow intensities (b); annual mean $F_{10.7}$ index (c); zonal temperature anomalies for 60–90°N latitudes (d).

the periods of significant zonal temperature anomalies at ~50 km level for 60–90°N latitudes correlated quite well. The dependence of I_G from mesosphere temperatures is noted in many papers (Clemesha et al., 1991). Moreover usually the variations of temperature in mesosphere and stratosphere are correlated with each other at different time scales. For example, the heating of stratosphere in summer is accompanied by coolness of the mesosphere. It was also mentioned a negative correlation between the temperature of stratosphere and mesosphere during the winter stratospheric warming (Offerman et al., 1983). At last, in the day-to-day satellite data of vertical temperature distribution in a stratosphere–mesosphere available from recent time at (http://acdisc.sci.gsfc.nasa.gov/Giovanni/mls/mls.mlsl2.2.shtml) changes of temperature of stratosphere, stratopause or its height were accompanied by changes of temperature at the mesosphere level.

We have analyzed long-term data of middle-atmosphere zonal temperature anomalies for the 1979–2005 period (http://www.cpc.ncep.noaa.gov/products/stratosphere/strat-trop/). The data are presented as color images for each year, with a scale 4 °C. Therefore quantitative data were obtained with the same scale. We used the data for summer months at the highest measurement level (~50 km) because

in the summer the day-to-day variability of mesosphere temperatures is the smallest one.

The annual mean of 557.7 nm airglow intensity was obtained by averaging of monthly mean I_G.

We have also analyzed mean 557.7 nm airglow intensity averaged for October–November. It was noted by Fishkova et al. (2001) that solar activity manifestation in 557.7 nm emission variations depends, among other factors, on the specific season. Maximum correlation between monthly mean 557.7 nm intensity and the solar activity level, remaining ever positive, is registered in the March–April period. It abruptly decreases in summer – in the middle of the year – and increases again toward the autumnal equinox. During the period of October–November maximum intensity, however, the correlation decreases again. The 557.7 nm emitting layer height (Fishkova et al., 2001) has minimum values of 94–100 km during minimum correlation periods in the summer and October–November maximum periods. In this case the dynamics of the underlying atmosphere in the region of the mesosphere and stratosphere can significantly affect the emission variations during the period of the October–November maximum.

Comparison of the annual mean I_G, and $F_{10.7}$ index (Fig. 2) allows to confirm the conclusion obtained after analysis of the monthly mean I_G and $F_{10.7}$ index that positive correlation between I_G and $F_{10.7}$ index on descending phase of 23d solar cycle, in 2002–2005. On the rise phase of the 23d solar cycle, including the peak phase, correlation between the I_G and $F_{10.7}$ index is absent.

Fig. 3 presents the scatter/plot graphs of relationship of the annual mean I_G and the $F_{10.7}$ index for 1997–2001 (a) and 2002–2006 (b) periods; standard errors of the annual means for I_G are shown. For the 1997–2001 period it is impossible to find out direct relationship of I_G and $F_{10.7}$ index, except for the 1997–1998 period. On the contrary, during the descending phase of the solar cycle in the 2002–2006 period there is direct relationship between I_G and $F_{10.7}$ index exceeding the measurements error.

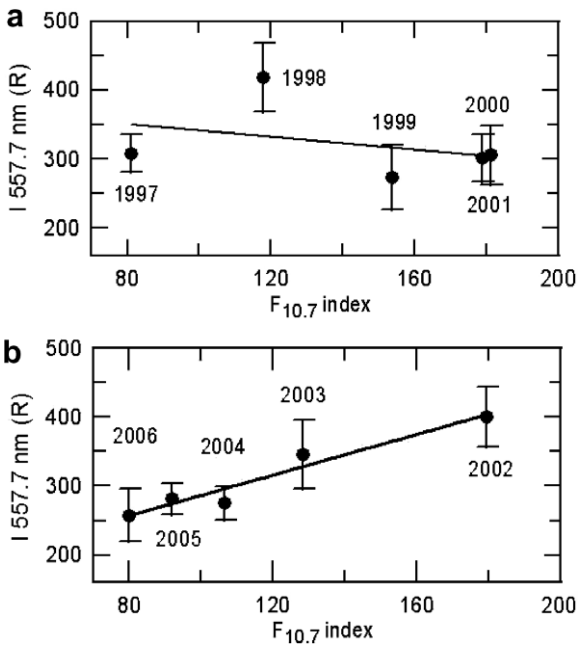

Fig. 3. Relationship of the annual mean I_G and the $F_{10.7}$ index for 1997–2001 (a) and 2002–2006 (b) periods.

It is possible to explain the I_G behavior shown in Fig. 2 as a result of super-position of irregular fluctuation with a period of about 3–5 years on the I_G basic variation depending on solar activity (~11 years). Fig. 2d shows the presence of atmosphere parameters fluctuations at stratosphere and mesosphere level. Their periods are ~2–3 years. In this case, it is necessary to explain the 1-year delay between disturbances of temperature and I_G. Probably, it is caused by the procedure of averaging of annual values of these parameters.

Concerning I_G variations with period of 11 years it is possible to notice the following. Usually in the I_G long-term variations at mid-latitudes there are variations with periods of 11 years (~20–30%), ~5.5 years (~5%) and quasi-biennial (~10%) (Semenov and Shefov, 1997). At equatorial latitudes the basic is quasi-biennial harmonic (Fukuyama, 1977a). I_G variations in Fig. 2 can be interpreted by variations with period close to 5.5 years. Their amplitude consists ~20% (~±70 R) from the average I_G (~340 R). In that case the I_G fluctuation with a period of 5.5 years is the basic harmonic. The appearance of 5.5 years harmonic as basic can also be result of an intensification of the influence of the underlying atmosphere in the analyzed interval of time, in this frequency range. On the zonal temperature anomalies plot (Fig. 2d) the 5.5-year period is well seen. It is necessary to note especially that zonal temperature anomalies in 1998–2000 in the region of ~50 km heights are the largest for the last 25 years. This suggests that broken thermal behavior in the middle atmosphere in the 1998–2000 period extended even higher reaching the 557.7 nm emission airglow heights. For the same period El Nino phenomena and peak global temperature anomalies (<http://www.globalwarmingart.com/wiki/Image: Short_Instrumental_ Temperature _Record_png>) were also observed. El Nino phenomena is connected with disturbance of the global atmosphere circulation. According to Fukuyama (1977a), the 557.7 airglow variation should be considered together with thermal and dynamical processes in stratosphere, mesosphere and low thermosphere.

Fluctuations of the 557.7 nm emission with ~5.5 years periods and close to them were also mentioned in other papers (Semenov and Shefov, 1997). Particularly, according to Fukuyama (1977a) at mid-latitude station Sendai (38°N, 140°E) for 19–20 solar cycles the prevailing period of I_G long-term variations was less than solar activity period, its value was ~6–7 years. In this case, the conclusions of Megrelishvili (1981) based on long-term twilight airglow observations are interesting. According to Megrelishvili (1981), main components of the twilight atmosphere in the 40–300 km height range have long-period oscillations with periods of 4.5–6 and 11 years. Oscillations with

5–6-year periods dominated below 100 km, while oscillations with 11-year periods dominate above 100 km. The amplitude of 5–6-year oscillations decreases with height.

4. Conclusions

Presence of anomalies in the thermal behavior of the lower mesosphere in the 1998–2000 period, indications that stratospheric thermal and dynamical processes during the periods of temperature disturbances sufficiently influence the 557.7 nm emission variations, and the behavioral pattern of other parameters at heights, where 557.7 airglow appears allow us to make the following preliminary conclusions:

1. During solar cycle 23, the correlation between the 557.7 nm emission intensity and solar activity ($F_{10.7}$ index) had a different pattern during different phases of the 23d solar cycle. During the increasing phase of the 23d solar cycle the negative correlation between monthly mean intensity of atomic oxygen 557.7 nm emission and $F_{10.7}$ solar radio flux was revealed. The correlation became positive during the descending phase.
2. Negative correlation between monthly mean 557.7 nm airglow intensities and $F_{10.7}$ index during the increasing phase of the 23d solar cycle was associated with anomalous thermal and dynamical processes in the middle atmosphere in the 1998–2000 period.

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