Investigation of temperature dependence of 557.7 nm atmospheric airglow intensity

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Temporal variations of the 557.7 nm atmospheric airglow intensity and variations of the vertical distribution of the atmospheric temperature for the period from August 2004 till February 2007 have been analyzed. We used the experimental data on the intensity of atomic oxygen emission at 557.7 nm (emitting layer at a height of 85–115 km) obtained at the Geophysical Observatory of the Institute of Solar-Terrestrial Physics near Irkutsk (52°N, 103°E) and the satellite data of the vertical temperature distribution in the stratosphere–mesosphere obtained by MLS (Microwave Limb Sounder) installed aboard the EOS Aura spacecraft. We analyzed the 557.7 nm airglow intensity averaged over night together with the night vertical profiles of the atmospheric temperature. An attempt was undertaken to reveal the regression correlation of the atmospheric 557.7 nm emission intensity with the atmospheric temperature at heights of the stratosphere and mesosphere. Possible mechanisms of the influence of the atmospheric temperature on the 557.7 nm airglow intensity are discussed.

Introduction

The natural airglow of the upper atmosphere depends on the atmospheric density, temperature, and composition at altitudes of emission, on the solar and geomagnetic activity, and on coordinates of an observation site. It has the diurnal and seasonal periodicities.

The green line of atomic oxygen [OI] at $\lambda = 557.7$ nm is an integral characteristic of vertical distributions of temperature and atmospheric constituents participating in excitation of this airglow at its altitudes (85–115 km). In this atmospheric region, the external influence of the solar and geomagnetic activity and the action of the ambient atmosphere characteristics at the airglow altitudes, as well as dynamical and disturbance effects of various nature from lower atmospheric layers, can manifest themselves.

It is still unclear in what way the temperature of the ambient atmospheric gas at altitudes of the 557.7 nm airglow emission affects the airglow intensity. Thus, in Ref. 1 it was stated that the 557.7 nm airglow intensity (I_G) increased as temperature decreased, while in Refs. 2 and 3 the positive correlation is reported.

From the viewpoint of interaction of the upper and low atmosphere, of interest is the correlation between variations of the natural atmospheric airglow and temperature disturbances in the winter stratosphere (stratospheric warming events). It was noted,[4,5] in particular, that the 557.7 nm airglow intensity increases by 50–100% during stratospheric warming events and this effect was explained by activation of the vertical atmospheric circulation, which in some cases reaches altitudes of the mesosphere and the lower thermosphere (the region of the 557.7 nm airglow emission).

Earlier we analyzed variations of the 557.7 nm airglow intensity during stratospheric warming events in the period 1997–2001. The data on the stratospheric temperature at an altitude of 30 km were used as an indicator of stratospheric warming. It was noticed[6] that the contribution of this effect to monthly average values of I_G for Eastern Siberia can be more significant than for other mid-latitudinal regions.

In this paper, we undertake an attempt to reveal the regression correlation between the intensity of green emission in the upper atmosphere according to data of the Geophysical Observatory of the Institute of Solar-Terrestrial Physics (ISTP) SB RAS and the atmospheric temperature at different height levels.

Experimental data

For analysis, we used:

– experimental data on the 557.7 nm atomic oxygen emission observed in the Geophysical Observatory ISTP (52°N, 103°E). Optical measurements were conducted with a Feniks zenith photometer (operating wavelengths of 557.7 and 630 nm and spectral ranges 360–410 and 720–810 nm);

– data on vertical atmospheric temperature profiles obtained with a Microwave Limb Sounder (MLS) set aboard the EOS Aura spacecraft.[7] Aura has a polar orbit with a period of about 100 min and a height of 705 km. Its spatial coverage is nearly global (from –82 to +82° in latitude). Vertical profiles are measured with an interval of ~25 s every 1.5° (~165 km) along the orbital trajectory. The spacecraft makes about 13 flights for 24 hours. The MLS sounder scans the terrestrial limb in the flight

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direction, recording microwave emission at frequencies of 118, 190, 240, 640 GHz, and 2.5 THz. The MLS measurements are used to reconstruct the profiles of the chemical composition, relative humidity and temperature for atmospheric regions from the troposphere and stratosphere to the upper mesosphere as functions of pressure in hPa.

We analyzed the data for the period from August 2004 (EOS Aura satellite was launched on July 15, 2004) to February 2007.

The Geophysical Observatory ISTP conducts regular observations of natural airglow at nighttime, on the average, 1–2 weeks a month. The measurements are usually carried out in clear moonless nights. The total number of nights, at which observations were carried out, for the analyzed period was 252.

The temperature dependence of airglow was analyzed based on the satellite data of atmospheric temperature measured at isobaric surfaces of 10 and 0.001 hPa (altitudes of ~30 and 95 km). We used temperature profiles for the trajectory of descent turns of the satellite (nighttime conditions) over the region of Irkutsk with the preset search radius of 500 km. An analyzed height of 30 km corresponds to the level of most probable occurrence and location of stratospheric warming, and a height of 95 km was selected as the most close to the height of maximum of the 557.7 nm emitting layer, which is ~97 km according to Ref. 8.

Analysis of experimental data, results and discussion

We have considered interdiurnal variations of the night-averaged 557.7 nm airglow intensity and the atmospheric temperature at heights of 30 and 95 km corresponding to nighttime flights of the satellite over the studied region for the period from August 2004 to February 2007 (Fig. 1), as well as the annual average behavior of the 557.7 nm airglow intensity for monthly average values calculated for the years with low solar activity (1997, 1998, 2004–2006) and annual average variations of temperature at the given height levels obtained from satellite data by averaging for every day of the studied period. Variations of the studied parameters are clearly seen in Fig. 1. At the same time, wide interdiurnal variability is seen. Deviations from annual average values are both positive and negative.

Further we analyzed the temperature dependence of the 557.7 nm airglow intensity at deviations of the studied parameters from their average values, that is, by removing regular seasonal variations from time series.

Altitude of 95 km

Figure 2 shows the dependence of ΔI_G on temperature deviations ΔT at a height of 95 km. Figure 2*a* depicts all the data for the studied period.

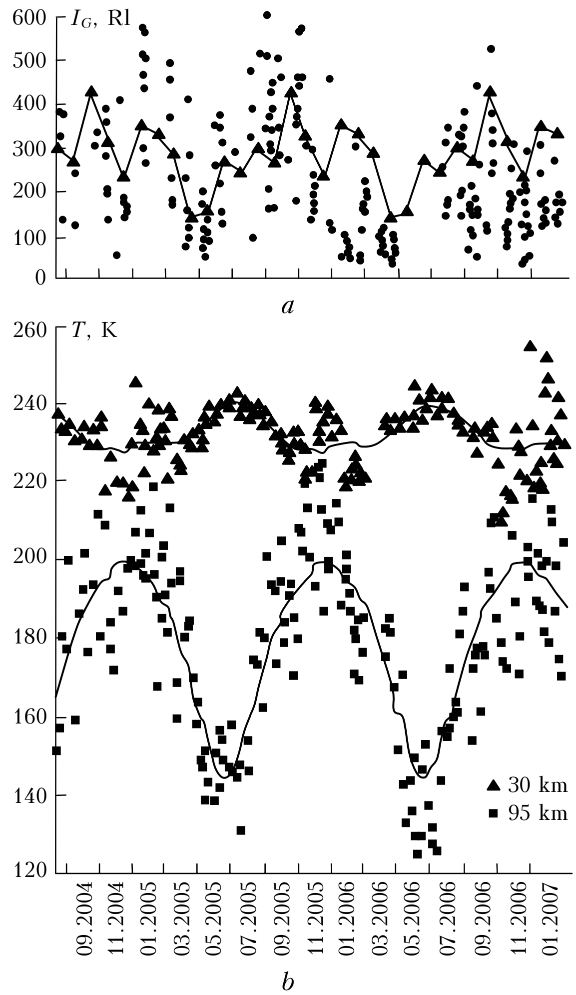

Fig. 1. Interdiurnal variations of the night-averaged 557.7 nm airglow intensity (dots) and the annual average behavior of 557.7 nm airglow intensity (solid curve) from monthly average values calculated for years with low solar activity (*a*); nighttime atmospheric temperature (signs) and annual average temperature variations (solid curves) obtained by averaging for every year in the period from August 2004 to February 2007 at altitudes of 30 and 95 km (*b*).

Figure 2*b* shows separately the winter period (from November to March), while Fig. 2*c* shows the summer period (from April to October). To reveal the correlation between the 557.7 nm airglow intensity and temperature, we used the simplest linear regression method. Figure 2 shows the regression lines obtained by the least-squares method. The regression coefficients are respectively 5.2 for all data, 5.9 for winter, and 3.4 for summer. Thus, the direct regression correlation between deviations of I_G and temperature at a height of 95 km is stronger for winter than for summer. This may be connected with the fact that the height of the maximum of the 557.7 nm emitting layer is characterized by seasonal variations. In winter months for the longitude of the observation site, the height of the emitting layer is closest to 95 km, at which temperature variations were analyzed.[3] For the summer period, the height of the maximum of the emitting layer is somewhat lower than the analyzed level.

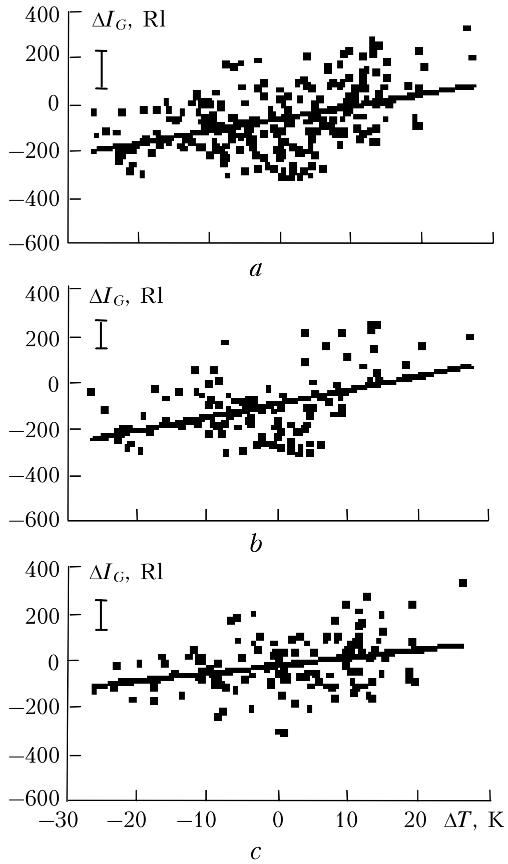

Fig. 2. Deviations of the 557.7 nm airglow intensity ΔI_G as functions of temperature deviations ΔT (signs) and regression lines for a height of 95 km: (*a*) the entire studied period; (*b*) winter period; (*c*) summer period; variances of experimental points from regression lines are shown.

The 557.7 nm airglow emission arises as a result of the forbidden transition $^1S \rightarrow {}^1D$ of atomic oxygen. This emission is believed to be excited according to the Bart mechanism.[9,10] It is a two-stage process:

$$O(^3P) + O(^3P) + M \rightarrow O_2^* + M, \quad (1)$$

$$O_2^* + O(^3P) \rightarrow O_2^* + O(^1S). \quad (2)$$

The rate constant of the reaction with triple collisions (1) is proportional to the coefficient $(300/T)^2$ [Refs. 11–13], and the production of $O(^1S)$ should decrease with the increasing temperature. Consequently, the airglow intensity, taking into account the contribution of the negative temperature dependence of the rate constant of reaction (1) should decrease with the increasing temperature. However, the analysis of experimental data shows the opposite pattern.

Since the reaction with triple collisions of atomic oxygen with molecules of the atmospheric gas is responsible for the 557.7 nm emission, the efficiency of this reaction should increase with the increasing concentrations of the atmospheric constituents taking part in reaction (1). The efficiency of excitation in this case can be determined both by the increasing concentration of the atmospheric constituents stipulating the population of the level ^1S of atomic oxygen (for example, O and O_2) and by the decreasing concentration of the atmospheric constituents deactivating the population of the level ^1S of atomic oxygen (that is, by the change of the ratio between the atmospheric constituents taking part in excitation and quenching the level ^1S).

In Ref. 10, the effect of the change in the concentrations of atmospheric constituents taking part in production of oxygen emissions was estimated numerically using the MSIS-86 model. Both joint variations of the major atmospheric constituents (O_2, N_2, O) and individual variations of atomic oxygen were considered. It was found that the increase in the concentration of the major atmospheric constituents (O_2, N_2, O) leads to a higher intensity of OI emission at 557.7 nm.

Peculiarities of the temperature field in the mesosphere–lower thermosphere cannot be explained only by the influence of radiative factors. Dynamic factors (in particular, warming or cooling upon air descent or ascent), as well as possible heat sources arising due to photochemical reactions, are of great significance.

Thus, we can assume that the contribution to the increase of the airglow intensity due to the increase in the concentration of the major atmospheric constituents resulting from the temperature increase at altitudes near mesopause exceeds that, caused by the negative temperature dependence of the rate constant of reaction (1).

Altitude of 30 km

It is interesting to examine the observed correlations between I_G variations and temperature in the stratosphere, where stratospheric warming events occur in winter months. Figure 3 shows the dependence of ΔI_G on temperature variations at an altitude of 30 km (10 hPa).

The experimental data are presented separately for the whole period (Fig. 3*a*), winter (Fig. 3*b*), and summer (Fig. 3*c*). The regression analysis by the least-squares method was performed for the studied parameters as well. The direct linear regression with the coefficients of 6.6 and 7.6 was found from the considered array of experimental data for winter and for the whole period, respectively. For summer months, no significant regression dependence was revealed between temperature variations at the stratospheric height level considered and I_G (see Fig. 3*c*).

As to the revealed positive correlation between I_G and stratospheric temperature at an altitude of 30 km in the winter period, the following can be said. In this case, we likely cannot argue for the direct dependence of I_G on stratospheric temperature variations. The analysis of the temperature conditions of the strato-mesosphere and the data on 557.7 nm airglow in the upper atmosphere points to manifestation of the well-known effect of the increased winter variability of mesospheric parameters[14] in the considered period. This effect shows itself in intensification of the wave activity of different time scales in the middle and upper atmosphere and is usually accompanied by a set of phenomena: sudden winter stratospheric warming events, intensification of vertical transport and turbulent processes, disturbance of atmospheric circulation, etc.

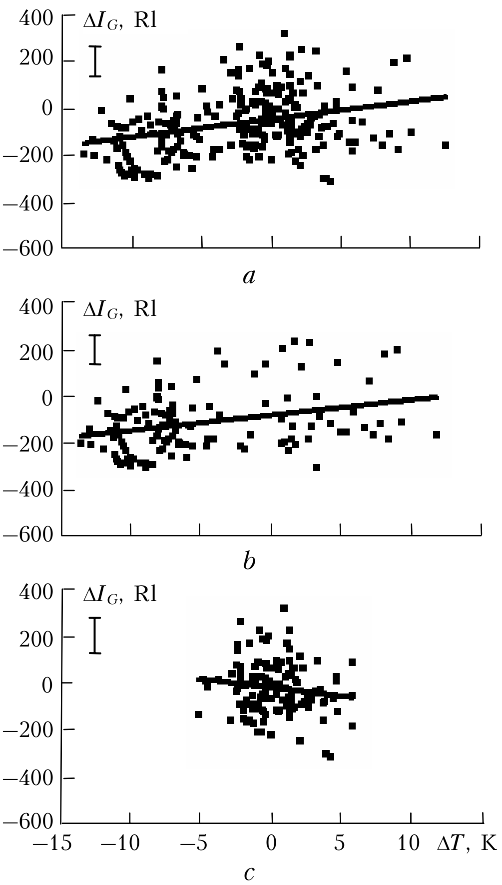

Fig. 3. Deviations of the 557.7 nm airglow intensity ΔI_G as functions of temperature deviations ΔT (signs) and regression lines for a height of 30 km: (*a*) the entire studied period; (*b*) winter period; (*c*) summer period; variances of experimental points from regression lines are shown.

Variations of the 557.7 nm airglow intensity in this case can be considered as an indicator of a disturbance propagating in the atmosphere. This disturbance causes temperature variations in the stratosphere and propagates higher into the mesosphere and lower thermosphere, that is, up to heights of occurrence of the 557.7 nm airglow emission. In the winter period during stratospheric warming events, strong variations of the dynamic regime are observed in the middle atmosphere.[15] In addition, generation and upward propagation of wave disturbances of different scale intensify, and this can lead to significant variations of the 557.7 nm airglow intensity. In summer, when the vertical temperature distribution is quite stable and there are no favorable conditions for the upward vertical propagation of disturbances, no significant regression correlation was found between I_G and the temperature at a height of 30 km (see Fig. 3*c*).

Conclusions

The regression analysis of the night-averaged data on the 557.7 nm airglow intensity from the experimental data obtained at the Geophysical Observatory of ISTP (52°N, 103°E) and the atmospheric temperature at a height of 95 km has revealed their positive correlation, which does not correspond to the temperature dependence of reaction (1) responsible for occurrence of this emission. The observed positive regression correlation may be the result of correlated variations of the major atmospheric constituents and the temperature near mesopause.

The analysis of night-averaged values of the 557.7 nm airglow intensity and stratospheric temperature at a height of 30 km has allowed us to determine the positive regression correlation in the winter period, which can be interpreted by the well-known effect of winter instability of the mesosphere–lower thermosphere caused by intensification of the atmospheric wave activity and possible formation of favorable conditions for the vertical propagation of disturbances. In summer period, no significant regression correlation was revealed between I_G and the stratospheric temperature at a height of 30 km.

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