Seasonal behavior of emission at 558-nm atomic oxygen line in the upper atmosphere

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Observations of airglow in the upper atmosphere are used to study the seasonal behavior of emission from the upper atmosphere at the 558-nm line of atomic oxygen [OI] in Eastern Siberia (52°N, 103°E). It is noted that seasonal variations of 558-nm emission agree qualitatively with the data obtained in previous decades at other midlatitude stations and with model approximations. Some features peculiar for Eastern Siberia, namely, more pronounced autumn peak and high winter (December–January) values are considered. Analysis of factors forming the seasonal behavior of the 558-nm emission and comparison with the wind dynamics in the upper mesosphere – lower thermosphere, as well as stratospheric warming events in Eastern Siberia suggest the existence of regional (longitudinal) peculiarities in the seasonal behavior of the 558-nm emission.

Introduction

The 558-nm green line of atomic oxygen [OI] is the brightest line of discrete emission in the visible spectral region in the nighttime airglow of the midlatitude upper atmosphere. One of the important characteristics of this emission is the pronounced seasonal behavior, which reflects regular dynamic processes in the upper atmosphere and, in particular, variations of the temperature distribution and composition of the mesosphere and lower thermosphere. The seasonal behavior of the 558-nm emission in midlatitudes has been studied experimentally rather well already by the 1960–1970s (Ref. 1). The experimental data obtained allowed the construction of empirical models describing variation of this emission to be attempted.[2,3]

At the same time, numerous papers published in recent years (see, for example, Refs. 4 and 5) evidence many-year variations of the temperature and density of the thermosphere, thermal conditions (in particular, increase in the amplitudes of annual and semiannual temperature variations in the mesosphere[4]), and other characteristics[6] of the upper atmosphere in recent decades. Many-year variations were also observed in the mean annual values of the analyzed emission at 558 nm, which is characterized by the positive linear trend within 0.08–0.6% a year.[2] Therefore, we can assume existence of possible variations in other characteristics of this and other emissions of the upper atmosphere, which call for additional investigations.

In this paper we present the results of investigation of the seasonal behavior of 558-nm emission obtained from observations of airglow of the upper atmosphere in the Geophysical Observatory of the Institute of Solar-Terrestrial Physics SB RAS (52°N, 103°E, Eastern Siberia) in 1991–1993 and in 1997–2001. It should be noted that before this time no regular investigations of airglow in the upper atmosphere were conducted in Eastern Siberia, therefore our investigation is of particular interest, especially, in view of possible features peculiar for this region.[7]

Measurement technique and instrumentation

In 1991–1993 optical airglow in the upper atmosphere was measured with separation of atomic oxygen [OI] lines at 558 and 630 nm by a dual-channel zenith photometer with tilted interference filters ($\Delta\lambda_{1/2} \sim 1$–2 nm). In 1997–2001, besides measurement of radiation in the 558 and 630-nm lines, radiation in the near infrared (720–830 nm) and ultraviolet (360–410 nm) spectral regions was measured in some periods. Measurements in the period of 1997–2001 were conducted with a four-channel zenith photometer connected to an IBM PC with time averaging ~12 s. The photometer angular fields of view were 4–5°. Absolute calibration of the measurement equipment was performed in some periods against reference stars and then controlled using reference light sources. Observations were usually conducted on moonless nights for 1–2 weeks a month mostly in the autumn–winter–spring period.

Results of observations and discussion

The Table presents the statistics on the number of days, in which the 558-nm emission was observed. The total number of observation days used to study the seasonal behavior of the 558-nm emission was 397.

Figure 1 shows the data on the mean nighttime intensity of the 558-nm emission in zenith (dots) depending on a day for the periods of 1991–1993 and 1997–2001 as observed at the Geophysical Observatory ISTPh SB RAS. It also depicts the curve of the seasonal behavior of the 558-nm emission obtained by monthly averaging of the mean nighttime values of the 558-nm emission in the periods studied.

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Year distribution of the number of days, in which the 558-nm emission was observed

Year	1991	1992	1993	1997	1998	1999	2000	2001
Number of observation days	24	28	11	16	54	68	120	76

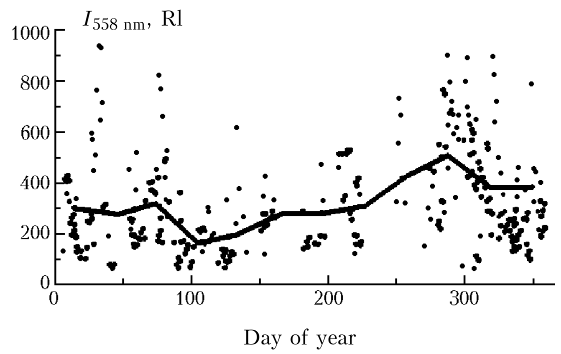

Fig. 1. Mean nighttime intensities I of the 558-nm emission.

As known,[1,8] the intensity of the 558-nm emission in midlatitudes is characterized by the seasonal behavior including peaks in the equinox periods in February–March and October and in summer in June with the highest amplitude in October. This seasonal behavior is characteristic of the majority of midlatitude stations in the region of 35–50°E. The differences consist in the mean annual intensities and in the peak heights of the 558-nm emission. This allows us to speak about the qualitative coincidence of the obtained seasonal behavior of the 558-nm emission with the measurement data for other regions. To reveal possible peculiarities in the seasonal behavior of the 558-nm emission in the region under study, it is worth comparing it with the existing models of the seasonal behavior. In Fig. 2, the monthly mean intensities of the 558-nm emission, as observed in the Geophysical Observatory, are compared with the empirical model of the 558-nm emission based on the data from Ref. 2 and with the approximation of the seasonal behavior according to Ref. 3.

In the calculations by the empirical models, we took into account the corrections for the Irkutsk latitude, many-year trends, and solar activity in the mean annual intensities of the 558-nm emission. Calculations were performed for each year of measurements at different levels of the solar activity and the many-year trend. Figure 2 shows the averaged plots of model calculations for 1991–1993 and 1997–2001.

According to the experimental data of the Geophysical Observatory, the intensity of the 558-nm emission averaged over the entire observation period was 336 Rl (Rayleighs), while its values calculated by the empirical model from Refs. 2 and 3 were 277 and 280 Rl, respectively.

Comparison of the curves in Fig. 2 demonstrates the qualitative agreement between the analyzed observations and model calculations. At the same time, we can notice some quantitative differences in the seasonal behavior of the 558-nm emission obtained from the data of the Geophysical Observatory. These differences are more pronounced autumn and spring peaks (only with respect to calculations by the model from Ref. 2), as well as the higher mean values of the emission intensity in the winter months (December–January). In our opinion, the seasonal behavior of the 558-nm emission obtained from the data of the Geophysical Observatory more closely corresponds to the model approximations of this behavior given in Ref. 3. This is likely connected with the fact that these approximations, in contrast to Ref. 2, account for latitudinal corrections for amplitudes of the main harmonics approximating the seasonal behavior, as well as the phase of the annual harmonic.

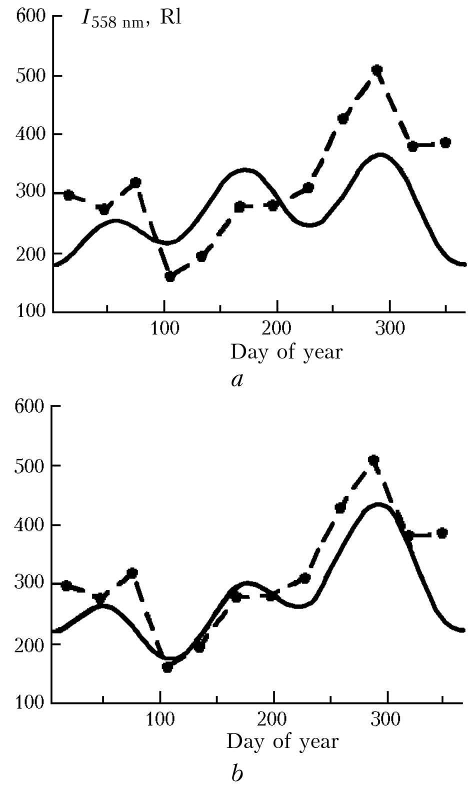

Fig. 2. Seasonal behavior of the 558-nm emission according to data of the Geophysical Observatory (dashed curves) and empirical model approximations (solid curves) from Refs. 2 (*a*) and 3 (*b*).

Interpretation of the above differences in the seasonal behavior requires detailed understanding of the processes and phenomena in the upper atmosphere that determine the intensity of the 558-nm emission. In our opinion, this understanding is still lacking. The spectral analysis of the seasonal behavior of the 558-nm emission allows some its time harmonics to be separated out. The intensity of the 558-nm emission experiences, during a year, oscillations with the period equal to one year and half-year oscillations with a comparable amplitude, as well as marked oscillations with the 4-month period.[1–3,8]

At the same time, it is known that many parameters of the upper atmosphere, including the temperature and density of atmospheric components, experience annual and semiannual variations, which are connected with seasonal spatiotemporal variations in the state of the mesosphere and lower thermosphere.

Different factors causing peculiarities in the seasonal behavior of the 558-nm emission include the following: semiannual variations of the atmospheric density[9,10] and prevailing winds at the altitudes of 85–105 km (Ref. 11), variations of dissipation of diurnal tides and gravitational waves,[12] meridional oxygen transport,[13,14] meridional circulation, vertical winds and diffusion,[15] zonal wind reversal,[16] seasonal variations of the temperature in the mesosphere and lower troposphere, and others.

In this paper, we will consider only two types of the factors possibly leading to the noticed peculiarities in the 558-nm emission. The first factor is connected with the wind conditions of the upper mesosphere–lower thermosphere, whose altitude range coincides with the altitudes of the 558-nm emission. In Ref. 17, a bulky statistical material is used to study the seasonal behavior of the monthly mean values of horizontal winds over two geographic sites with different longitude (52°N, 102°E and 52°N, 15°E), one of which almost coincides with the site of optical observations (52°N, 103°E). The measurements were performed by the method of separated reception of signals from longwave radio stations (D1 method) and cover the 20-year period from 1975 to 1995. Reference 17 analyzes the prevailing zonal and meridional winds and the velocities of semidiurnal zonal and meridional tides for nighttime, when optical observations of airglow are performed.

According to Ref. 17, the wind conditions in the upper mesosphere–lower thermosphere are characterized by the seasonal alternation of the zonal and meridional circulation. Along with the seasonal behavior of the 558-nm emission calculated from the experimental data of the Geophysical Observatory (Fig. 3*c*), Fig. 3 shows the data on the seasonal behavior of the monthly mean velocity of the semidiurnal zonal tide (Fig. 3*a*) and the prevailing meridional wind (Fig. 3*b*). Comparison of the curves in Fig. 3 demonstrates that the periods of spring and autumn alternation of the wind conditions and peaks in the seasonal behavior of 558-nm emission coincide in time.

The highest correlation coefficient (~ 0.73) for the seasonal behavior of the 558-nm emission was obtained for the prevailing meridional wind. This, as mentioned in Refs. 11 to 16, suggests that the seasonal behavior of the 558-nm emission can be connected with the dynamic wind conditions in this region. One more result obtained in Ref. 17 is interesting for us in this relation. It was obtained for two sites located at the same geographic latitude and different longitudes: in Russia (52°N, 102°E) and in Germany (52°N, 15°E). Longitudinal (regional) differences in the wind parameters were revealed for these sites. In particular, the autumn minimum in the zonal wind velocity occurs earlier in Siberia than in Europe, and the spring circulation alternation with wind reversal is observed only in Europe. With the allowance for the above-said, this can lead to existence of longitudinal (or regional) differences in the seasonal behavior of the 558-nm emission that are ignored in the model approximations of Refs. 2 and 3 and can cause a more pronounced autumn peak in the seasonal behavior of the 558-nm emission that is presented in this paper.

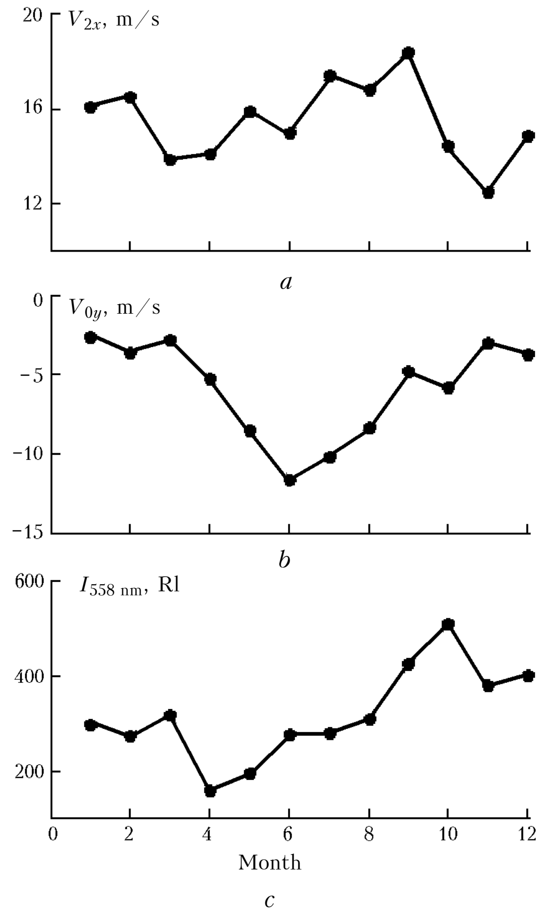

Fig. 3. Seasonal behavior of the monthly mean velocity of the semidiurnal zonal tide (*a*), prevailing meridional wind[17] (*b*), and 558-nm emission (*c*).

It should be noted that the autumn peak in the seasonal behavior of the 558-nm emission is formed mostly by the main annual and semiannual harmonics.[1–3] Reference 4 presents the experimental evidences of significant, up to twofold, increase in the amplitude of annual and semiannual temperature oscillations in the mesosphere during the last decade as compared with the 1970s, when most data on variations of the 558-nm emission used to construct the empirical models in Refs. 2 and 3, were obtained. According to Ref. 8, the temperature at the mesospheric altitudes, in its turn, determines the rates of the excitation and relaxation reactions of atomic oxygen in the ^1S state that is responsible for the 558-nm emission line. If the results of Ref. 4 are valid and will find further confirmation, then it will be needed to estimate the contribution of temperature variations at the altitudes of the 558-nm emission to its intensity and, whenever necessary, to take them into account in the empirical models of variations of the 558-nm emission.

According to Ref. 18 and other papers, one of the factors leading to disturbance of regular variations of nighttime airglow in the upper atmosphere may be a stratospheric warming event. Winter stratospheric warming events are characterized by strong sudden disturbances of the zonal and meridional circulations in the winter stratosphere. As a result, the stratosphere warms up and the vertical circulation activates. At strong stratospheric warming, disturbances cover a wide range of atmospheric altitudes from the Earth's surface to the upper mesosphere–lower thermosphere and ionospheric *F*-region. Now there are no generally accepted models that would quantitatively connect the stratospheric warming characteristics with the level of disturbance of the airglow intensity in the upper atmosphere in these periods. Usually it is mentioned that the intensities of twilight and nighttime airglow of the upper atmosphere experience fluctuations with the amplitude up to 40–70% in twilight and 20% at night during stratospheric warming events. In some cases, the observed increase in the intensity of atomic oxygen emission at 558 nm reached 100%, and this increase was associated with strong stratospheric warming.

In Ref. 7, we have already mentioned the abnormally high values of the 558-nm emission intensity in the period of appearance and development of stratospheric warming in Eastern Siberia in January 1998.

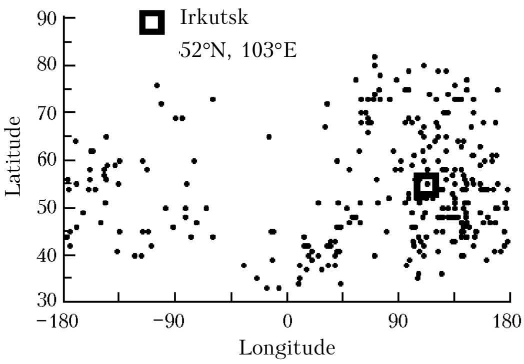

Fig. 4. Spatial distribution of stratospheric warming events, winter 1999/2000.

The increased values of the 558-nm emission in January and December of 1991–1993 and 1997–2001 measured in the Geophysical Laboratory mostly fell on the periods of appearance and development of stratospheric warming in Eastern Siberia. As is known, stratospheric warming events are observed every winter mostly in the Northern Hemisphere and characterized by geographically irregular distribution. As an example, Fig. 4 shows the distribution of daily data on localization of stratospheric warming sites (coordinates of maximum temperatures) for winter of 1999/2000 (December–March). It is clearly seen that their concentration is high in the Asian region and, in particular, near the Geophysical Observatory (shown by the square in Fig. 4). Frequent stratospheric warming events in Eastern Siberia can likely lead to the increase in monthly mean intensity of the 558-nm emission in winter months as compared to the intensities characteristic of other midlatitude stations.

Conclusion

The seasonal behavior of emission at the 558-nm atomic oxygen line in the upper atmosphere obtained from observations in Eastern Siberia in 1991–1993 and 1997–2001 agree qualitatively with the seasonal variations of the 558-nm emission obtained in the previous decades at other midlatitude stations and with model approximations.

The quantitative differences in the seasonal behavior of the 558-nm emission obtained for Eastern Siberia consist in a more pronounced autumn peak and higher values of the monthly mean intensity of the 558-nm emission in winter months (December–January).

Analysis of the factors forming the seasonal behavior of the 558-nm emission and comparison with the dynamics of the wind conditions in the upper mesosphere–lower thermosphere, as well as with the stratospheric warming events in Eastern Siberia suggest the existence of regional (longitudinal) features in the seasonal behavior of the 558-nm emission. Long-period trends or trends connected with change in the thermal conditions of the mesosphere in the last decade may manifest themselves in the seasonal behavior of the 558-nm emission.

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