Simultaneous observations of intensification of the 557.7 nm airglow in the upper atmosphere and occurrence of sporadic layers during temperature disturbances in the strato-mesosphere

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Received July 10, 2007

The event of simultaneous intensification of the 557.7 nm airglow and occurrence of the sporadic E_s layer in middle latitudes during temperature disturbances at heights of the stratosphere and mesosphere in December 2006 is analyzed. Ionospheric data were obtained with a DPS-4 ionosonde located directly in Irkutsk (52.5°N, 104.3°E). Airglow measurements were conducted with a 4-channel zenith photometer and an all-sky CCD imager at the ISTP Geophysical Observatory located 130 km southwest of Irkutsk. In addition, we analyze the vertical profiles of atmospheric temperature measured by a Microwave Limb Sounder (MLS) aboard the EOS Aura spacecraft. In some cases, correlated diurnal variations of the 557.7 nm airglow intensity and the E_s characteristics were observed. The fact that this correlation was observed not always can be explained by different spatial localization of the E_s layer and the emitting layer, as well as by some features of their dynamics. During the maximal intensification of the 557.7 nm airglow, its pronounced spatial inhomogeneity was observed by the CCD imager in continuum. The possible contribution of the mechanism of $O(^1S)$ level excitation due to collisions with electrons of the sporadic E_s layer to intensification of the 557.7 nm airglow during stratospheric warming periods is discussed.

Introduction

Airglow at 557.7 nm in the middle latitudes under undisturbed conditions is excited in a chain of photochemical reactions with participation of neutral atmospheric components. Heights of the 557.7 nm emitting layer lay within 85–115 km [Ref. 1]. It is well-known that airglow at 557.7 nm is intensified during sudden winter warming events,[2] which are connected with planetary waves disturbing the atmospheric circulation and intensifying the vertical transfer. In the same height range in the middle latitudes, occur sporadic E_s layers, which are most probable in summer months.[3] Some papers mention a correlation between characteristics of airglow at 557.7 nm and the sporadic E_s layers. For example, in Ref. 4 the intensification of the 557.7 nm airglow was attributed to the increase in the electron concentration of the sporadic E_s layer.

Disturbances in variations of the 557.7 nm airglow caused by stratospheric warming events and formation of sporadic layers are usually observed and studied independently, possibly, due to significant differences in their seasonal behavior.

This paper reports observation of disturbances in the upper-atmosphere airglow at the 557.7 nm atomic oxygen line with simultaneous occurrence of the sporadic E_s layer and temperature disturbances at stratospheric and mesospheric heights. The observations correspond to the period of winter solstice in December 2006.

1. Instrumentation and observational data

Optical measurements

Optical observations were conducted at the Geophysical Observatory of the Institute of Solar-Terrestrial Physics (ISTP) SB RAS (Eastern Siberia, Tunkinskaya Valley, 52°N, 103°E). The natural optical airglow of the upper atmosphere was measured with the aid of a 4-channel zenith photometer with separation of atomic oxygen [OI] lines at 557.7 and 630 nm, as well as the UV (360–410 nm) and near-IR (720–830 nm) spectral regions. The emission lines at 557.7 and 630 nm were separated by sweep interference filters ($\Delta\lambda_{1/2} \sim 1$–2 nm), while the spectral ranges 360–410 and 720–830 nm were separated by absorption filters. The angular fields of view of the photometer channels were 4–5°.

The absolute calibration of the instrumentation measurement channels was carried out in individual periods against reference stars and then controlled using reference light sources. The photometer software allowed us to record the data of photometric channels with ~12 s averaging. Spatial inhomogeneities and waves in airglow were recorded by an all-sky CCD imager based on Nikon Coolpix 5400 with the color CCD array operating in the RGB color mode. The imager control unit ensured its automated start with an interval of ~10 min during the whole night observation period. We used the signal accumulation mode with an exposure time of 5 min and subtraction of the array noise with a similar noise exposure time of 5 min. The angular field of view of the CCD imager was ~65° vertical × 50° horizontal. The imager was oriented to the north and covered zenith distances of ~10–75°.

Radiophysical measurements

Characteristics of the ionospheric sporadic E_s layer were obtained using a DPS-4 vertical-sounding digital ionosonde[5] installed in Irkutsk in December 2002. The following characteristics of the E_s layer were used: f_0E_s is the critical frequency of the layer determining the maximal electron concentration in the layer $N_mE_s(\text{cm}^{-3}) = [f_0E_s(\text{MHz})]^2/8.06$; E_s is the layer height; PE_s is the occurrence of the night E_s layer, that is, the ratio of the number of the sporadic layer recordings to the total number of observations during a night.

Data on vertical temperature profiles

These data were obtained with the aid of an MLS scanning microwave limb sounder set aboard the Aura space vehicle (http://disc.sci.gsfc.nasa.gov/Aura/MLS/index.shtml). The Aura MLS data are used to reconstruct the profile of the chemical composition, relative humidity, and temperature for atmospheric regions from the troposphere and stratosphere to the upper mesosphere. The Aura satellite has a polar orbit at an altitude of 705 km and nearly global spatial coverage (from –82° to +82° in latitude). The vertical resolution of the measurements is about 3 km. Every vertical profile is measured with an interval of 1.5° (~165 km) along the orbital trajectory. About 15 flights usually take place diurnally.

2. Results and discussion

Interdiurnal variations

A heavy warming zone with a maximal temperature of about 300 K recorded on December 14 (point $T_{SW\,\max}$ in Fig. 1*b*) was observed in December 12–16 of 2006 at the stratospheric level (~40 km).

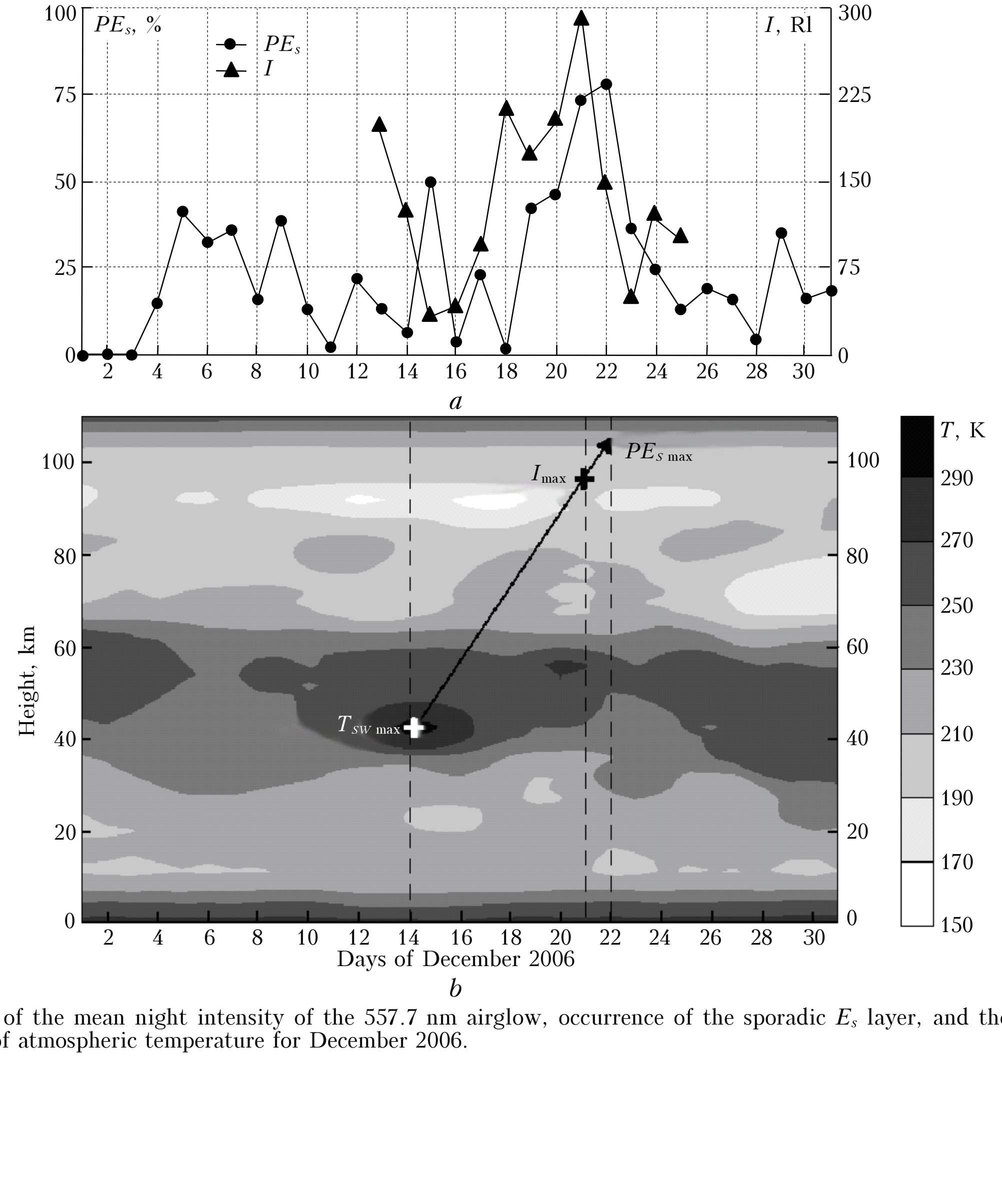

Fig. 1. Variations of the mean night intensity of the 557.7 nm airglow, occurrence of the sporadic E_s layer, and the height–time distribution of atmospheric temperature for December 2006.

According to the data of optical observations, a significant increase in the intensity of airglow at 557.7 nm was observed in December 18–21 at a peak value of 290 Rl for the mean night airglow on December 21 (Fig. 1*a*).

The period of December 18–22 was characterized by the far more often occurrence of the night sporadic E_s layer (see Fig. 1*a*). The most occurrence equal to 78% (at the monthly average value 25%) falls on December 22.

The version is put forward in this paper that the stratospheric warming, intensification of the 557.7 nm airglow, and more often occurrence of the sporadic E_s layer are consequences of the same atmospheric process, which spreads from the bottom upwards from the stratosphere to the lower thermosphere and, possibly, higher. The comparison (in Fig. 1*b*) of disturbances at stratospheric heights ~40 km (point $T_{SW\,\max}$) and at heights of the E_s layer ~107 km ($PE_{s_{\max}}$, %) shows that the delay between the processes is 7–8 days, which roughly corresponds to vertical speed of disturbance motion of 8.5–9.5 km/day. Figure 1*b* shows temperature isolines and the direction of motion of supposed temperature disturbances from stratospheric heights with a speed of ~9 km/day.

Based on the fact that the delay between the more often occurrence of the sporadic layer (point $PE_{s_{\max}}$) and the higher intensity of the 557.7 nm airglow (point $I_{\max}$) is about a day, the estimation of the height range of the 557.7 nm airglow gives the range 97.5–98.5 km. The values obtained differ somewhat from the seasonal height of the maximum of this airglow layer for late December, which is ~93.5 km according to the empirical model[6] for the latitude 52°.

The intensification of the 557.7 nm airglow observed several days after the formation of a stable warming zone at stratospheric heights in the region under study is in a good agreement with the typical behavior of this airglow in stratospheric warming periods.[1] It is usually believed that the decrease of the height of the 557.7 nm airglow layer (that is, the height of the most efficient excitation) is accompanied by the increase of the airglow intensity. In the case considered, the obtained estimate of the airglow height may indicate the mechanism of increase of the 557.7 nm airglow intensity during stratospheric warming events, which is connected with occurrence of the most efficient excitation at other heights (relative to undisturbed conditions).

The efficiency of excitation in this case can be caused both by the increase in the concentration of atmospheric components (causing the population of the ^1S level of atomic oxygen, for example O and O_2) and the thickness of the emitting layer and by the decrease in the concentration of atmospheric components deactivating the population of the ^1S atomic oxygen level (that is, the change in the ratio between atmospheric components taking part in the excitation and quenching of the ^1S level). The estimated height of the 557.7 nm layer, the statistics of observation of which during stratospheric warming events is nearly absent, can be used in empirical models describing variations of characteristics of this airglow.[6]

In Ref. 7, it was noted that sporadic ionization in the ionospheric E layer is a sensitive indicator of ionospheric disturbances. At the same time, it was stated that stratospheric warming results in the decrease of the wind shear, which, in its turn, should result in the decrease in occurrence of the sporadic layer. In our case, the opposite phenomenon is observed, namely, the increase in occurrence of the E_s layer, that is, the increase of the wind shear. This contradiction is likely connected with the fact that we analyze the characteristics of the E_s layer in 6 to 10 days after stratospheric warming, rather than during the warming event. In the general case, both the intensification of the 557.7 nm airglow and the increased occurrence of the E_s layer may be caused by planetary waves observed in this period at the level of the stratosphere and mesosphere (http://strat-www.met.fu-berlin.de/).

Diurnal variations

Figure 2 shows the diurnal variations of the intensity I of the 557.7 nm airglow, the values of f_0E_s, and the height of the sporadic E_s layer for two days: December 20 and 21 of 2006.

It is believed that the 557.7 nm airglow in the winter months most often has the diurnal behavior with a smooth peak near local midnight, which is interpreted by the S_4^2 mode of the solar thermal semidiurnal tide. Shorter-period variations, which are usually attributed to internal gravity waves (IGWs),[1] are quite often superimposed on the regular nighttime behavior of the 557.7 nm airglow. In the analyzed nights of December of 2006, the classical nighttime behavior was not observed for the 557.7 nm airglow, although in some nights the peaks could be seen (see Fig. 2) near local midnight (17 UT). In most cases, the nighttime behavior of the 557.7 nm airglow included oscillations with periods of about 6–8 h and irregular variations of shorter periods imposed on them. This is indicative of the presence of rather strong disturbances of atmospheric parameters at the heights of the 557.7 nm airglow.

The CCD imager observations of airglow in the upper atmosphere also indicate the presence of strong small-scale spatial inhomogeneities.

Figure 3 shows two consecutive frames (with an interval of 10 min) of airglow in the G color channel of the CCD imager for December 21, 2006.

The images underwent the identical procedure of processing of brightness channels to separate inhomogeneities. It should be noted that no spatial inhomogeneities of airglow with similar characteristics were observed earlier (observations by the CCD imager were carried out for 1–2 weeks every month in the new-moon periods since the fall 2005).

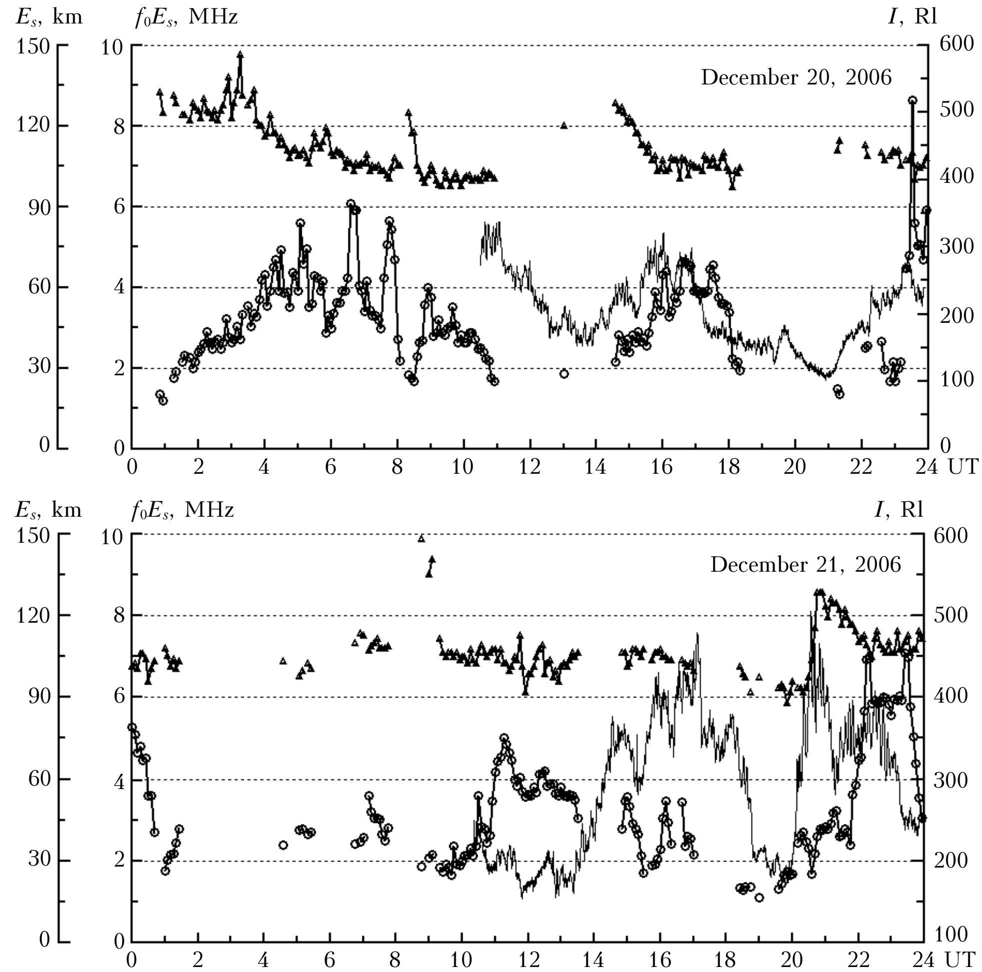

Fig. 2. Variations of the intensity I of the 557.7 nm airglow (solid curves), f_0E_s values (circles), and the height of the sporadic layer E_s (triangles) for December 20 and 21 of 2006.

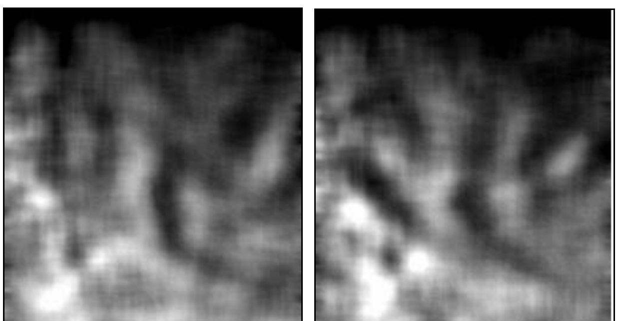

Fig. 3. Two consecutive frames of airglow in the G color channel of the CCD imager for December 21, 2006.

The tentative analysis of the CCD imager data has shown that in contrast to wave disturbances recorded earlier in some cases, for which it was possible to determine the direction and speed of their motion, the spatial inhomogeneities of airglow on December 21, 2006, were, to a larger extent, permanently existing inhomogeneities varying from one frame to another. The characteristic scale of these inhomogeneities remained the same and equal to ~10–15°.

The radiation recorded in the R–G–B color channels of the CCD imager is mostly caused by the continuum airglow of the upper atmosphere, since at long spectral recording intervals (~100–150 nm) the continuum becomes the main component in the airglow of the night atmosphere.[1] The maximum height of the continuum airglow is about 90 km, which allows us to estimate the characteristic spatial scale of inhomogeneities as ~18–24 km. Spatial inhomogeneities in the airglow at the mesosphere height with the similar spatial scales are typical and can be attributed to small-scale IGWs (see, for example, Ref. 8).

The characteristic periods of several hours can also be found in the parameters of the E_s layer. In the most cases, the variations of the 557.7 nm airglow intensity and the parameters of the E_s layer are not in-phase (see Fig. 2). If we assume that the variations with the periods of several hours are caused by the IGW propagation at the studied heights, then this can be indicative of the different heights of the 557.7 nm emitting layer and the occurrence of the E_s layer. It is believed that IGWs mostly come from the lower lying atmospheric layers. From the available data, it is impossible to separate the predominant direction. Nevertheless, we can estimate the characteristic speed of disturbance propagation from the obtained difference between the mean height of the E_s layer and the height of the emitting layer (~5–10 km) and from the characteristic time shifts of ~3–7 h between maxima in variations of the 557.7 nm airglow intensity and f_0 values of the sporadic E_s layer. The estimates give the speed of propagation of short-period disturbances equal to ~0.7–3 km/h. In this connection, of interest are the results of Ref. 9, which studied the relation between variations of the height of the E_s layer and the intensity of the nighttime 557.7 nm airglow and estimated the vertical speed of disturbances. The vertical disturbance speeds obtained in Ref. 9 range within 1–6 km/h, while disturbances of the analyzed parameters are interpreted by IGW propagation.

It is also important to note the possible contribution from occurrence of the sporadic E_s layer to the increase of the 557.7 nm airglow intensity according to the reaction $O + e \rightarrow O(^1S) + e$ [Ref. 9]. In particular, the increase of the electron concentration in the sporadic E_s layer was attributed to increase of the 557.7 nm airglow intensity.[4] For the geophysical conditions considered, in the absence of in-phase variations in the characteristics of the sporadic E_s layer and the 557.7 nm airglow intensity, there are no grounds to believe that this reaction contributes significantly to increase of the 557.7 nm airglow intensity. Nevertheless, the question on the quantitative contribution of this process to the total intensity of the 557.7 nm airglow in a particular geophysical situation remains open and likely calls for separate consideration.

Thus, the tentative analysis of the temperature conditions of the strato- and mesosphere, ionospheric data, and data on airglow of the upper atmosphere in the 557.7 nm airglow indicates the manifestation of the well-known effect of the increased winter variability of mesospheric parameters[10] in the considered period. This effect shows itself in the 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, intensification of vertical transport and turbulent processes, disturbance of atmospheric circulation, etc. Some of these phenomena manifest themselves in the form of spatial, latitudinal-longitudinal inhomogeneities (see, for example, Ref. 11). It seems important to estimate the height of the disturbed 557.7 nm emitting layer during stratospheric warming. This height may be indicative of the possible mechanism of increase of the 557.7 nm airglow intensity during the development of stratospheric temperature disturbances.

Conclusions

1. In the winter solstice period in December 2006, the simultaneous increase of the nighttime airglow of the upper atmosphere in the 557.7 nm atomic oxygen line and the occurrence of the sporadic E_s layer in mid-latitudes during the temperature disturbance at stratospheric heights attributed to intensification of the wave activity (planetary waves, IGWs) in the atmosphere in this period was observed in Eastern Siberia.

2. The comparative analysis of variations in diurnal values of the characteristics of the 557.7 nm airglow layer, the sporadic E_s layer, and the dynamics of vertical temperature profiles of the atmosphere has allowed us to estimate the height of the 557.7 nm airglow layer during stratospheric warming.

3. The tentative analysis of variations in the characteristics of the 557.7 nm emitting layer and the sporadic E_s layer gives no grounds to attribute the diurnal disturbances of the 557.7 nm airglow intensity to the occurrence of the sporadic E_s layer under the considered geophysical conditions and leaves the question on the contribution of the electron concentration of the sporadic E_s layer to the total intensity of the 557.7 nm airglow open.

Acknowledgements

This work was supported in part by the Presidium of RAS (Program No. 16, Part 3).

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