Manifestation of solar activity in variations of atmospheric emissions at 557.7 and 630 nm in the 23rd solar cycle

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Received April 10, 2007

We present the preliminary analysis of experimental data of nightglow observation of the atomic oxygen 557.7 nm (emitting layer heights are 85–115 km) and 630 nm (180–250 km) lines emissions in the current 23rd solar cycle. The experimental data were obtained at ISTP Geophysical observatory near Irkutsk (52°N, 103°E). The obtained data are compared with atmospheric, solar, and geophysical parameters. Generally, the 630 nm emission intensity in the 23rd solar cycle varied in phase with the solar cycle, increasing from the low to high solar activity periods. As for 557.7 nm emission, the difference in coefficients of correlation between its intensity and $F_{10.7}$ solar activity index in different phases of solar cycle was noted. A negative correlation between monthly average 557.7 nm emission intensity and $F_{10.7}$ was revealed in the phases of solar activity increase and maximum, which then changed into a positive correlation in the decay phase. The perturbation in the phase synchronism of 557.7 nm emission and $F_{10.7}$ behavior during the phases of solar activity increase and maximum is preliminary explained by a high sensitivity of atmospheric parameters, determining the 557.7 nm emission intensity, to atmospheric dynamics and various disturbances (including the effects from below) at the emitting layer heights.

Introduction

First investigations of inter-annual and long-term variations of mid-latitude atmospheric emissions in the upper atmosphere were carried out in 1920th–1930th.[1] The fullest data on long-term variations of atmospheric emissions were obtained in the second half of 20th century[2]; they cover about five solar cycles (from 18th to 22nd). By now, the dependence of long-term variations of atmospheric emissions in 557.7 nm (emitting layer heights are 85–115 km) and 630 nm (180–250 km) atomic oxygen lines on the level of solar activity can be considered as an established fact. Note, that the degree of solar activity effect in the above atmospheric emissions can differ in different solar cycles.[3]

At 557.7-nm emitting layer heights, both effects of dynamics and different perturbations of underlying atmospheric layers and external effect of solar activity manifest themselves. Identification and separation of these effects is a complicated and still unresolved problem. Probably, just this causes a difference in results, obtained by different authors at different stations and observation periods, and points to different degrees of dependence of 557.7 nm emission intensity on the level of solar activity – from very high[2] to moderate[4] and weak, or its absence.[5]

Atmospheric emission at 630 nm is more “sensitive” to the solar activity effect due to a higher emitting layer height (F is the ionospheric region) and forming mechanisms. This emission in mid-latitudes is formed due to the processes of dissociative recombination, photodissociation, and collisions with photoelectrons. The ratio of contributions of these mechanisms in the total intensity of 630 nm emission depends on the latitude, longitude, local time, and season.[6] Hence, in general, the dependence of 630 nm emission intensity on the level of solar activity can be complicated and have some peculiarities in different latitudinal-longitudinal zones.

A relatively small number of solar cycles, for which airglow observation data are available, the difference in solar cycles, and some quantitative difference in manifestation of solar activity effects in atmospheric emission variations cause an interest to the study of airglow behavior in the 23rd solar cycle in order to determine climate characteristics and trends,[3] as well as for the use in empirical models of variations of the parameters of upper atmosphere.[6]

In this work, we present the preanalysis of long-term variations of atmospheric emissions in the atomic oxygen 557.7 and 630 nm lines depending on solar activity in the 23rd solar cycle for Asian mid-latitudes, based on experimental data obtained at ISTP Geophysical observatory near Irkutsk (52°N, 103°E) during 1997–2006.

Equipment and observation data

Optical radiation of the upper atmosphere was measured using zenith photometers with interferential

0235-6880/08/05 369-06 $02.00

oscillating light filters ($\Delta\lambda_{1/2} \sim$ 1–2 nm) in 557.7 and 630 nm radiation lines. The near IR (720–830 mn) and UV (360–410 nm) radiation was also recorded. Spectral ranges 360–410 and 720–830 nm were separated by means of absorption light filters. Angular fields of view of the photometer channels were 4–5°. Absolute calibration of measurement channels of the equipment was carried out by reference stars and controlled with the help of reference light sources in evening and morning observation hours. Photometer software allowed recording about 12-s-averaged data of photometric channels.

The following data were used in this work:

– experimental observation data of atomic oxygen atmospheric emissions at 557.7 nm for the period from 1997 to April of 2006 and at 630 nm – from 1999 to April of 2006, obtained at the Geophysical observatory of ISTP SB RAS;

– NOAA/SEC data (Boulder, USA) on the solar radio radiation flux at a 10.7 cm wavelength ($F_{10.7}$) and planetary A_p-index;

– TOMS satellite data on total ozone (http://jwocky.gsfc.nasa.gov);

– data on zonal temperature anomalies in the middle atmosphere (http://www.cpc.ncep.noaa.gov/products/stratosphere/strat-trop/).

Observation results and discussion

Figure 1 presents variations of monthly mean intensities of 557.7 nm (green, I_G) and 630 nm (red, I_R) emissions of atomic oxygen, solar radio radiation index $F_{10.7}$ (the level of solar activity), and planetary A_p-index (the level of geomagnetic disturbance) for the period under study. Intensities of 557.7 nm and 630 nm emissions in 1999–2006 were measured simultaneously and processed by a common technique. The r.m.s. deviations from monthly mean values for I_G emission are also shown in Fig. 1. The period under study includes the phases of increase, maximum, and decay in the 23rd solar cycle.

630 nm emission

It is seen in Fig. 1 that the 630 nm emission intensity in the 23rd solar cycle generally varies in phase with the solar cycle, increasing from low to high solar activity periods.

Maximal monthly mean I_R (~82 R) was observed in July, 2000 and can be attributed to the first maximum of $F_{10.7}$. Minimal monthly mean I_R for the period under study was observed in March, 2006. The stronger second maximum of $F_{10.7}$ at the end of 2001 – beginning of 2002 did not give similar increased monthly mean I_R. This can well be due to the seasonal variability of 630 nm emission,[7] according to which I_R is maximal in July–August. Higher values of I_R in summer in comparison with winter could provide for higher absolute values of I_R in July, 2000 in comparison with a period from the end of 2001 – beginning of 2002 at comparable disturbance levels.

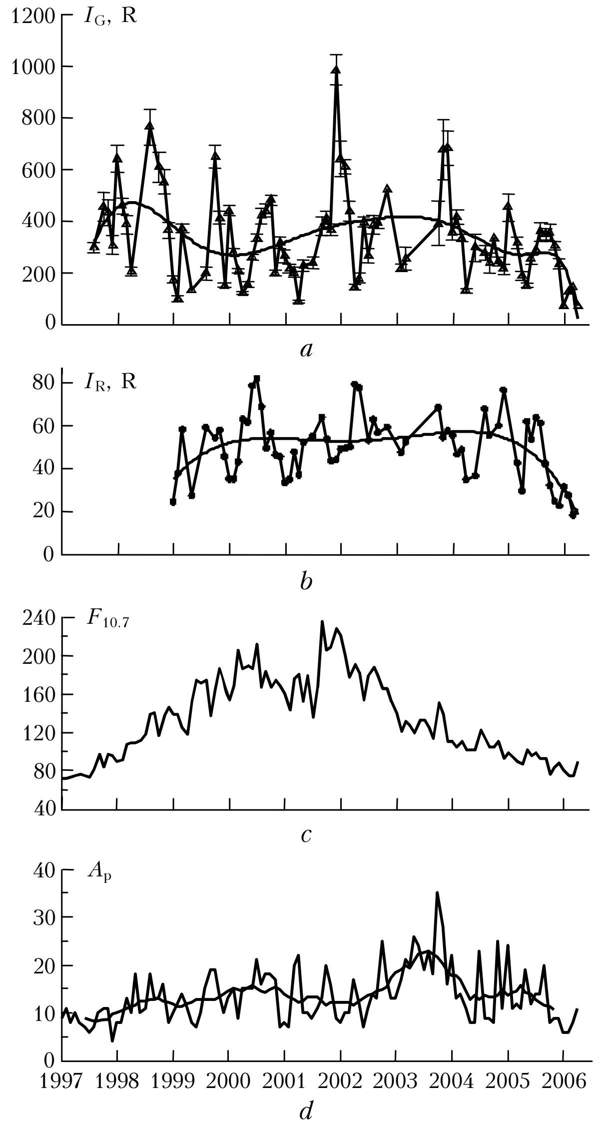

Fig. 1. Variations of monthly mean intensities of the atomic oxygen green emission I_G, 1997–2006 (*a*) and red one I_R, 1999–2006 (*b*), solar radio radiation index $F_{10.7}$, 1997–2006 (*c*), and planetary A_p-index, 1997–2006 (*d*).

To estimate long-term variations of atmospheric emissions quantitatively, annual mean values of corresponding emissions are often used. Because of a lack for comprehensive data for 2006, which, according to forecasts, corresponds to solar activity minimum, mean values of I_R for the first four months of every year were used as estimates of long-term I_R variations, which allowed partial separation of solar and geomagnetic activities. The latter is a quite complicated problem for 630 nm emission,[6] since the frequency of geomagnetic storms increases with the increase of solar activity. According to Ref. 8, the majority of magnetic storms are observed in fall (September–November).

Mean I_R and $F_{10.7}$ values for the first four months (January–April) of 1999–2006 are shown in Fig. 2.

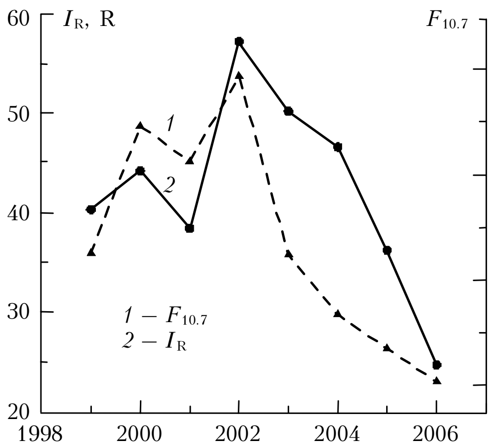

Fig. 2. Mean I_R and $F_{10.7}$ values for the first four months (January–April) of 1999–2006.

The curves for I_R and $F_{10.7}$ (Fig. 2) show their quite good correlation (the correlation coefficient is 0.68); both variables reached their maxima in 2002. The correlation of I_R and A_p, obtained similarly, is worse for these months (the coefficient of correlation is about 0.5). The use of mean values for fall months (September–November) as estimates of long-term variations of 630 nm emission, on the contrary, gives higher coefficients of correlation between I_R and A_p (0.64) than between I_R and $F_{10.7}$ (about 0.43)

The obtained estimate of the coefficient of long-term variations of 630 nm emission in the 23rd solar cycle from the maximum to minimum of solar activity over the first four months of the year is about 2.3. This value is in sufficiently good agreement with coefficients of 630 nm emission variations, obtained for mid-latitude stations of the Upper Provence (about 2) [Ref. 9] and Zvenigorod (about 2.5 at $F_{10.7}$ variation from 95 to 190),[10] as well as with estimates obtained by the empirical model of atomic oxygen 630 nm emission variations[6] for annual mean (about 1.4) and midnight (about 1.85) values of I_R, if $F_{10.7}$ are the actual values for the first four months (January–April) of 2002 ($F_{10.7} \sim 197$, maximal four-month I_R values) and 2006 ($F_{10.7} \sim 81$, minimal four-month I_R values).

At the same time, according to the data from Ref. 11 for the low-latitude station (22°N, 45°W), the intensity variation of 630 nm emission from the maximum to minimum of solar activity in the 21st solar cycle was about 7. The authors[11] connect this fact with a higher variation of the electron concentration N_e relative to other atmospheric parameters, influencing the intensity of 630 nm emission (O, O_2, N_2), when changing from high to low solar activity in the region of equatorial ionospheric anomaly.

Especially note the data[3] of long-term measurements of annual-mean I_R values, significantly differing in the 21st and 22nd solar cycles at comparable variations of the solar activity according to the $F_{10.7}$ index (from low to high). This can well point to different character of variations of atmospheric parameters, forming 630 nm emission, or different contributions of different effects (e.g., geomagnetic activity) in different solar cycles.

Cyclic aperiodic variations of 630 nm, caused by solar activity, with an approximate period of 2–3 years are indicated in Ref. 6. We made an attempt to isolate variations with such periods in the period under study (January, 1999 – April, 2006). The monthly mean I_R values with sliding mean averaging over seven months for the above observation period are shown in Fig. 3.

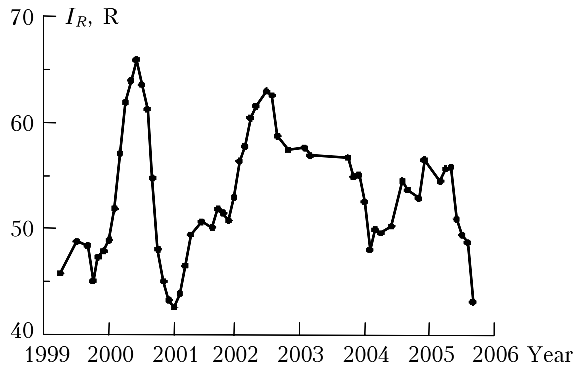

Fig. 3. Monthly mean I_R values with sliding mean averaging over seven months.

A preliminary analysis of the curve in Fig. 3 actually allows 2–3 summer variations of 630 nm emission to be isolated. Note that the second maximum of the curve (Fig. 3) can be related to the maximum of the 23rd solar cycle, while the first and third maxima – to phases of increase and decay of solar activity, when an increase of geomagnetic activity is usually notable. In this case, an appearance of variations with a 2–3-year period (Fig. 3) can result from a superposition of out-of-phase variations of solar and geomagnetic activities.

557.7 nm emission

Many authors, studying the dependence of I_G on the solar activity, usually point to its positive correlation with the index $F_{10.7}$ [Refs. 2–4]. Only several authors noted a negative correlation of these parameters for some observation periods. Thus, the coefficients of correlation between I_G and $F_{10.7}$ for 1984 and 1985 were –0.46 and –0.09, respectively.[5] Asynchronism in the behavior of these parameters was noted in long-term variations of 557.7 emission intensity.[3]

Various character of the dependence of I_G on the level of solar activity ($F_{10.7}$) for the period under study follows from I_G variations (Fig. 1). A decrease of I_G and corresponding negative correlation between I_G and $F_{10.7}$ (the coefficient of correlation is −0.33) are observed for the phase of the solar activity increase in 1997–2000. Beginning from the second maximum of the solar activity according to $F_{10.7}$ (the end of 2001 – beginning of 2002), a decrease of both $F_{10.7}$ and I_G and, hence, a positive correlation between these parameters (the coefficient of correlation is 0.38) are observed. Sometimes (e.g., the end of 2003), short-term variations of $F_{10.7}$ answer the corresponding variations of I_G.

Within the thermosphere at altitudes of more than 100 km, the atmospheric parameters are more exposed to the direct solar radiation and can reflect solar activity variations.[11] This is confirmed by the behavior of monthly mean values of atomic oxygen 630 nm emission (Fig. 1), at the *F*-region emitting layer heights (about 180–250 km). At 557.7-nm emitting layer heights, atmospheric dynamics (including stratosphere) can be a deterministic factor for variation of the emission along with the solar activity.[2] To find probable reasons of I_G behavior in 1997–2000, available parameters of lower atmosphere (total ozone content (TOC) and anomalies of zonal temperature at the level of lower mesosphere) have been considered.

Mean I_G values for October and November of every year are shown in Fig. 4, as well as annual mean I_G and $F_{10.7}$, zonal temperature anomalies for 60–90°N latitudes, and TOC.

The TOC can reflects both long-term and inter-annual and quasi-biannual variations of the global atmospheric dynamics in stratosphere and mesosphere.[12] An additional argument for the use of TOC is the results from Ref. 5, where high negative coefficients of correlation between TOC and I_G have been obtained. To study TOC variation, the TOMS satellite data (http://jwocky.gsfc.nasa.gov) were used. Daily values of TOC for the coordinates nearest to the Geophysical Observatory were also used and then averaged over months and years.

As for the correlation between stratosphere and mesosphere temperature and I_G, it can be said the following. The effect of I_G increase during stratosphere warming in the winter–spring season is known.[13] It is necessary to note, that the contribution of the effect in monthly mean I_G values for Eastern Siberia, where the Geophysical observatory of ISTP is located, can be more significant in comparison with other mid-latitude stations. In addition, we have noticed that the periods of I_G increase at the Geophysical Observatory during stratosphere warming events[15] well correlate with the periods of zonal temperature anomalies for the 60–90°N latitudes (http://www.cpc.ncep.noaa. gov/products/stratosphere/strat-trop). The dependence of I_G on the mesospheric temperature was noted in many works (see, e.g., Ref. 16).

Long-term data on zone temperature anomalies in the middle atmosphere in 1979–2005 were used for the analysis (http://www.cpc.ncep.noaa.gov/products/stratosphere/strattrop/); here the data are presented as color images with color resolution, corresponding to a temperature of 4°C for every year. Therefore, the quantitative data could be obtained with a 4°C increment. We used the data for summer months at the upper altitudes of the range of measurements (about 50 km, lower mesosphere) since daily variations of the mesosphere temperature in summer are minimal.

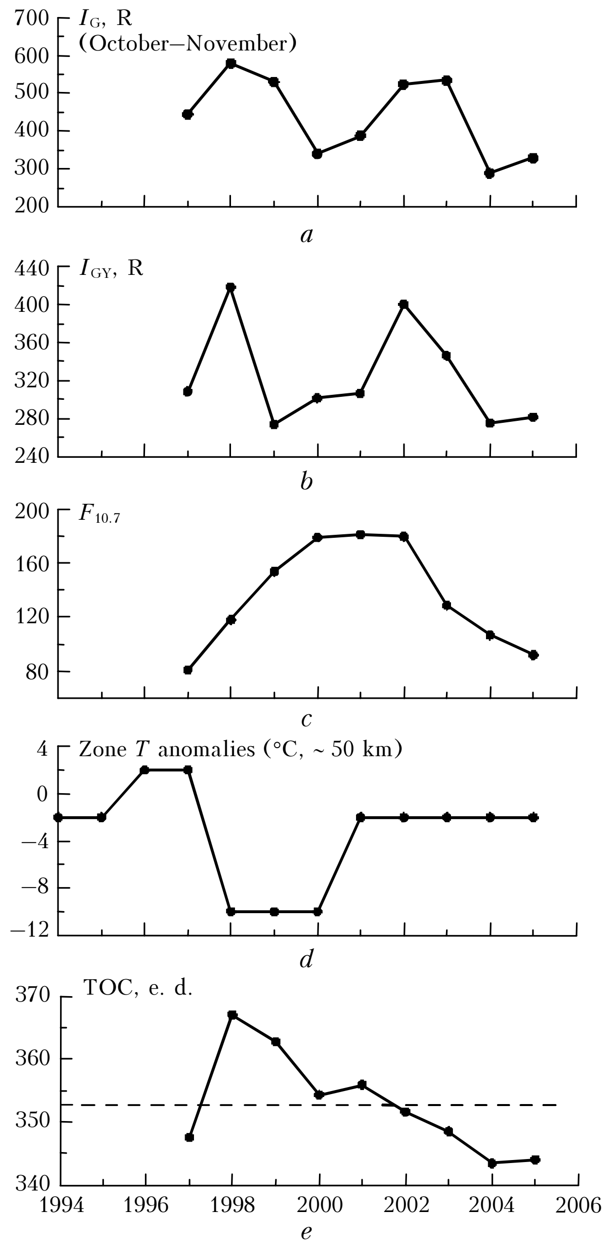

Fig. 4. Variations of mean I_G for October and November of every year (*a*), annual mean I_{GY} (*b*) and $F_{10.7}$ (*c*), zonal temperature anomalies for 60–90°N latitudes (*d*), and annual mean TOC for the region under study (*e*).

Annual mean intensities of 557.7 nm emission I_{GY} were obtained by averaging monthly mean I_G for every year.

Mean I_G values for October and November were also analyzed. The seasonal maximum of the emission is noted in these months. As it has been noted in Ref. 17, the solar activity manifests itself in variations of 557.7 nm emission depending on the season. Maximal correlation between monthly mean 557.7 nm emission intensities and the level of solar activity, always remaining positive, is observed in March – April, sharply decreases in summer, and again increases to the autumnal equinox. However, it again decreases in the period of fall intensity maximum (October–November). The 557.7-nm emitting layer height[17] is minimal (94–100 km) in the periods of summer correlation minimum and October seasonal maximum. In this case, emission variations in the period of fall maximum can be essentially influenced by the dynamics of lower atmosphere in the region of mesosphere and stratosphere.

The comparison of annual mean I_{GY} values and index $F_{10.7}$, shown in Fig. 4, allows the conclusion on a positive correlation between I_{G} and $F_{10.7}$ during solar activity decay (2002–2006) to be confirmed. There is no correlation between these parameters in the phase of solar activity increase, including its maximum.

The behavior of I_{G} and I_{GY} in Fig. 4 can be explained by the superposition of an irregular perturbation of 2–3 years in duration onto the main harmonics of I_{G}, connected with the solar activity (about 11 years). The curves in Figs. 4*d* and *e*, corresponding to the behavior of mesosphere temperature and TOC, witness the existence of 2–3 year perturbations of atmospheric parameters in stratosphere. In these conditions, the one-year delay in perturbations of the temperature, TOC, and I_{G} is to be explained. Possibly, this can well be due to the procedure of annual averaging of the compared parameters.

As for the 11-year fluctuations of 557.7 nm emission, it can be noted the following. Usually, 11-year (~20–30%), 5.5-year (~5%), and quasi-biannual (~10%) fluctuations are present in long-term I_G emission variations in mid-latitudes.[18] In equatorial latitudes, the quasi-biannual harmonics is the basic.[13] Variations of I_G, shown in Fig. 4, can be explained by variations close to the 5.5-year variations with an amplitude of about 20% (~ ± 70 R) of the mean value (~340 R). In this case, the harmonic of 5.5-year fluctuations of I_G variations is the basic. This can be resulted from enhancement of the influence of lower atmosphere in this frequency range in the period under study. The about 5.5-year period is quite well notable on the curve of zonal temperature anomalies (Fig. 4*d*). It is necessary to note, that the zonal temperature anomalies in 1998–2000, shown in the Figure, are the greatest for the entire 35-year observation period (1979–2006). It can be supposed that the disturbance of the temperature conditions of the middle atmosphere in 1998–2000 propagated to higher altitudes as well, reaching the altitudes of 557.7-nm emitting layer. El-Nino phenomenon and maxima of global temperature anomalies were also observed in these years (http://www.globalwarmingart.com/wiki/Image: Short_Instrumental_Temperature_Record_png). El-Nino phenomenon is considered as the reason of the disturbance in the global circulation of the atmosphere.

Fluctuations with about 5.5-year periods were noted for the 557.7 nm emission in other works as well.[7] The conclusions of Ref. 19, based on long-term nightglow observations are of interest in this connection. According to this work, the main components of twilight airglow fluctuate with periods of 4.5–6 and 11 years at the 40–300 km altitudes. The fluctuations with 5–6-year periods prevail below 100 km and higher –with 11-year periods. The amplitude of 5–6-year fluctuations increases with the increase of altitude.

Thus, temperature anomalies in the lower mesosphere in 1998–2000, TOC behavior in stratosphere in 1998–1999, signs of sufficiently effective influence of thermodynamic stratospheric conditions on 557.7 nm emission variations in periods of temperature perturbations, and the behavior of other atmospheric parameters at the emitting layer height allow a preliminary interpretation of the 557.7 nm emission as conditioned by the dynamic processes in the lower atmosphere.

Conclusion

Thus, the performed analysis of variations of night intensities of atomic oxygen 557.7 and 630 nm emissions allowed the following preliminary conclusions.

1. In general, according to the observation data at the Geophysical Observatory of ISTP SB RAS, the intensity of 630 nm emission in the 23rd solar cycle varies in phase with the solar cycle, increasing from the low to high solar activity periods. The ratio of the intensity values in the solar activity maximum and minimum is about 2.3. Probably, the ratio can vary in different solar cycles due to peculiarities of particular solar cycles.

2. Two–three-year periods are notable in variations of monthly mean values of 630 nm emission, which are probably connected with a superposition of out-of-phase variations of solar and geomagnetic activities.

3. During the 23rd solar cycle, a correlation between 557.7 nm emission intensity and the solar activity ($F_{10.7}$) differ qualitatively in different cycle phases. In the phases of solar activity increase and maximum, a negative correlation between monthly average intensities of 557.7 nm emission and the index $F_{10.7}$ is observed, which changes into a positive correlation in the decay phase.

4. The disturbance in correlation between the month average intensities of 557.7 nm emission and the index $F_{10.7}$ in the phase of solar activity increase in the 23rd solar cycle is connected with anomalous thermodynamic conditions of the middle atmosphere in 1998–2000.

Acknowledgements

This work was supported by the Presidium RAS (Program No. 16, Part 3) and the joint Russian-Bulgarian Project "Atmos."

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