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Changes in molecular oxygen and hydroxyl airglow of the mesosphere and lower thermosphere as observed at Zvenigorod in 2000-2019

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ABSTRACT

According to the ground-based spectral observations of airglow emissions in the near infrared at Zvenigorod in 2000-2019, multi-year changes in the intensity of $O_2A(0-1)$ band at 865 nm and OH(6-2) band at 840 nm are studied. It was shown that the intensities of both the emissions had a significant negative long-term time trend and a positive response to the change of solar activity in the 11-year cycle. In the spectrum of their interannual harmonic variations, statistically significant quasi-decade and quasi-two-decade oscillations were found.

Keywords: mesosphere, lower thermosphere, airglow, emission intensity, multi-year changes

1. INTRODUCTION

At present time, changes in the characteristics of the mesosphere and lower thermosphere (MLT), which reflect its gas composition and temperature regime, are the subject of many studies of the upper atmosphere. The reasons for changes in the MLT can be both heliogeophysical factors of influence – solar radiation and climatological variations in the lower atmosphere, and anthropogenic changes in the atmosphere.

One of the most effective methods of studying changes in the MLT is observations of its intrinsic radiation – airglow. Among airglow emissions, the most powerful and observable from the Earth's surface are molecular oxygen and hydroxyl ones[1]. Molecular oxygen emissions arise at heights from 40 to 110 km in daytime and at 85-105 km, with a peak at 94-96 km, in nighttime[2]. Hydroxyl emissions arise in the region from 80 to 100 km with a peak intensity at ~87 km[3]. In nighttime the O_2 and OH emissions, due to their nature of occurrence, are an indicator of the content of atomic oxygen in the MLT region[4].

The airglow emissions experience significant spatial and temporal variations, which are regular and irregular. Among the time variations, the strongest changes are diurnal, day-to-day and seasonal ones[1]. They are mainly caused by the propagation of internal gravity, tidal and planetary waves, as well as seasonal changes in a wind circulation in the atmosphere at MLT altitudes[5]. Lesser studied are long-term changes in the airglow due to limited time series of observations.

In the present work, we analyze multi-year series of the airglow emissions in order to estimate their long-term changes including linear trends and multi-year variations. With this aim, the 20-year (2000-2019) observations of the 865 nm $O_2A(0-1)$ and 840 nm OH(6-2) band intensities at the Zvenigorod station (56° N, 37° E), Russia, are used.

2. OBSERVATIONS

Data on the molecular oxygen and hydroxyl emissions, intensities of their bands, were derived from the spectrographic observations with digital recording of the infrared part of the spectrum within the 800-1000 nm range. The specification of spectral instrument, SP-50 spectrograph used for the observations, is given by Khomich et al.[1] The spectral

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measurements at the Zvenigorod station are mainly conducted at zenith angle of 53° and azimuth of 23° (counted from North to West) during cloud-free nights. In order to obtain a good signal/noise ratio, the signal integration time for one spectrum measurement is 10 minutes. The obtained intensities are reduced to the zenithal conditions and are calibrated in units of Rayleigh (R, 10^6 photons cm^{-2} s^{-1}). The measurement error of the O_2A(0-1) and OH(6-2) band intensities is 5-6 R. A more detailed description of the observational conditions and procedure of the determination of the investigated intensities can be found in the paper by Pertsev and Perminov[4].

3. ANALYSIS AND RESULTS

In the present work, we took emission band intensities averaged from 21 h to 22 h UT, i.e. around local midnight. This allowed us to analyze the most complete data series, each of which consists of 1663 values. Figure 1 shows the analyzed series. As one can see, the emissions have significant changes over the entire multi-year period of observations: from three tens to a thousand rayleighs in the case of O_2A(0-1) and from two hundred to two thousand rayleighs in the case of OH(6-2). Among them, regular seasonal variations and long-term changes stand out. The mean intensities of O_2A(0-1) and OH(6-2) are ~265 R and ~710 R, respectively.

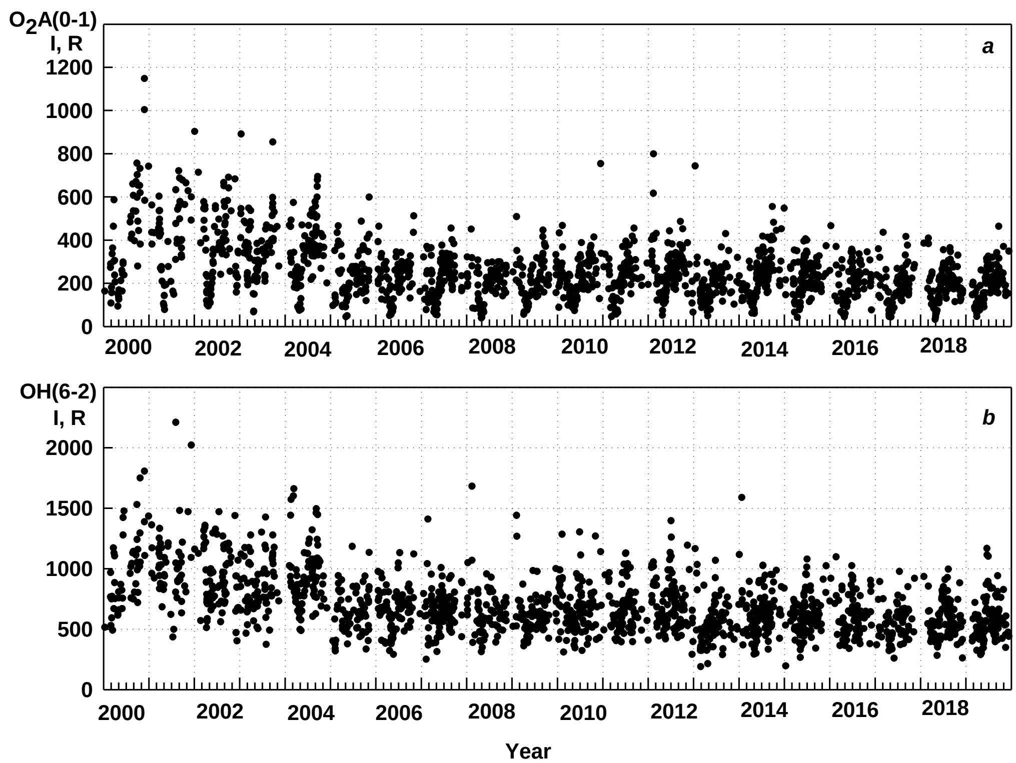

Figure 1. Multi-year series of the midnight 1-hour intensities (I) of O_2A(0-1) (a) and OH(6-2) (b) from observations at the Zvenigorod station.

Interannual changes in emission intensities are considered in more detail using their mean annual values I_{ma}. To better investigate the interannual behavior of the emission intensities, their midnight values were averaged for the periods from January 1 to December 31 and from July 1 of one year to June 30 of a following year. The obtained series are shown in Figures 2a, c. They show a non-linear type of intensity changes: a strong decline from 2000 to 2008 and a further slow decline in the case of OH(6-2) or the absence of any significant trend in the O_2A(0-1) emission. The calculated LS-periodograms[6,7] of variations for these series show statistically significant 11-year oscillations (most likely due to the 11-year cycle of solar activity) and highly significant long-term changes (oscillations with periods of several decades and/or a linear trend) (see Figures 2b, d). An estimation of the relationship between emission intensities I_{ma} and solar activity as well as their linear trend for 2000-2019 was carried out by a multiple regression analysis (MRA) using the following model representation:

$$I_{ma} = I_0 + A_{tr}(t - 2000) + A_{sol}(Ly\alpha - 4.5), \qquad (1)$$

where I_0 is the mean intensity for 2000, reduced to the conditions of average solar activity; t is the time (in years), $Ly\alpha$ is the solar Lyman-alpha flux (photons cm^{-2} s^{-1}), taken as an indicator of solar activity; A_{tr} is the linear trend (R/year); A_{sol} is the response to changes in the Lyman-alpha flux (R/10^{11} photons cm^{-2} s^{-1}). The results of this estimation are presented in Table 1. Both emissions are characterized by a statistically significant negative linear trend and a positive response to changes in solar activity.

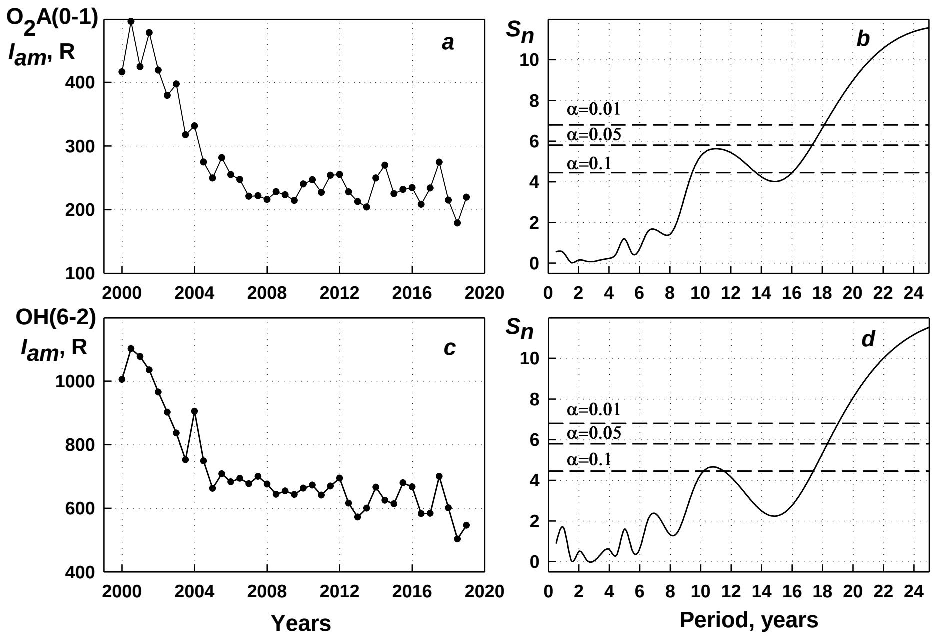

Figure 2. Multi-year changes in mean annual intensities (I_{am}) of $O_2A(0\text{-}1)$ (a) and OH(6-2) (c). LS -periodograms of harmonic variations of $O_2A(0\text{-}1)$ (b) and OH(6-2) (d). S_n is the normalized power of harmonic signal in data series. α is the significance level (dash line).

Table 1. Results of the multiple regression analysis by using the model (1). Regression coefficients are given with an error equal to one standard deviation (1σ).

Emission	I_0, R	A_{tr}, R/year	A_{sol}, R/10^{11} photon cm^{-2} s^{-1}
$O_2A(0\text{-}1)$	357.2±12.3	-6.6±1.3	73.5±11.8
OH(6-2)	893.0±21.7	-15.4±2.2	106.4±20.9

The values of the given characteristics of emission changes are in good agreement with the recently published results of studies of seasonal features of the long-term trend and response to solar activity[8]. However, the trend in hydroxyl airglow, determined from earlier observations (before 2000s)[1,9,10,11], has a non-linear character, increasing to the 1980's and then slowly growing in the next decades. Currently (2000-2019), we observe a decrease in the intensity of hydroxyl airglow, which is most likely associated with corresponding changes in the content of atomic oxygen in the MLT. A number of works[4,12,13,14,15] give us some representation of the 11-year solar cycle effect in the MLT airglow emission. According to them as in the present work, the airglow emissions positively correlate with solar radiation.

At the next stage, we investigated the variations in the series of residual emission intensities ΔI_{ma} (Figures 3a, c). These intensities are the difference between the initial data series (Fig. 2a, c) and their approximation (1), calculated with the numerical parameters shown in Table 1. Figures 3b, d demonstrate LS-periodograms of variations for the residual intensity series of the corresponding emissions. As one can see, variations with periods of about 8 years (quasi-decadal oscillation) and 21 years (quasi-two-decadal oscillation) are statistically significant. The parameters of these oscillations are estimated by approximating the residual intensities of emissions with the expression (2) using the MRA method:

$$\Delta I_{ma} = A_0 + A_{qdo}\cos\left(\frac{2\pi}{T_{qdo}}\left(t - f_{qdo}\right)\right) + A_{q2do}\cos\left(\frac{2\pi}{T_{q2do}}\left(t - f_{q2do}\right)\right), \quad (2)$$

where A_0 is the constant, T_{kdo}, T_{k2do}, A_{kdo}, A_{k2do}, f_{kdo} and f_{k2do} are the periods, amplitudes and phases of the quasi-decadal (*qdo*) and quasi-two-decadal (*q2do*) oscillations. The periods correspond to the peaks on the LS-priodograms (see Figures 3b, d). The results of the multiple regression analysis are given in Table 2.

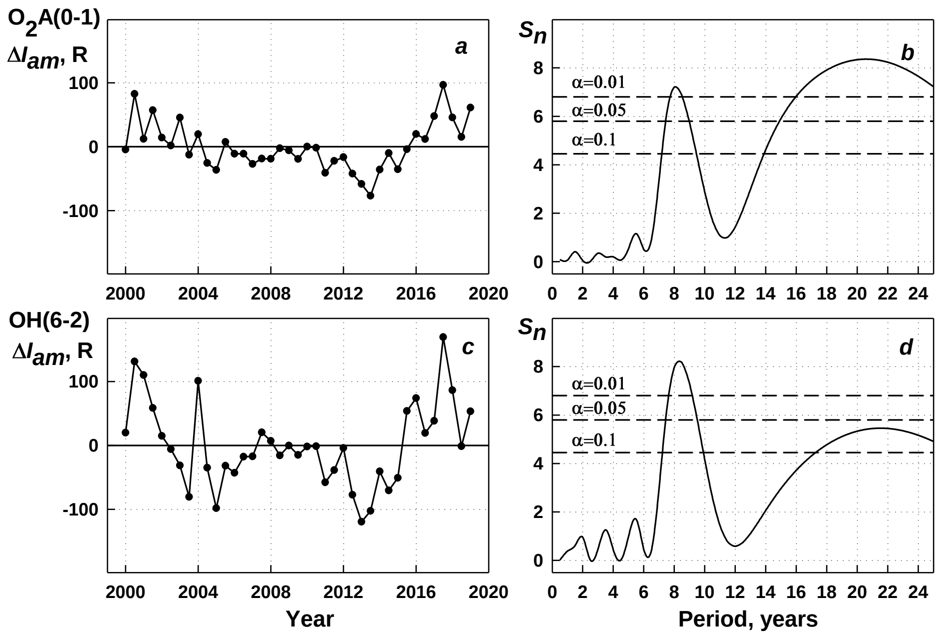

Figure 3. Same as Figure 2, but for multi-year changes in residual annual intensities (ΔI_{am}).

Table 2. Results of the multiple regression analysis by using the model (2). Oscillation phases correspond to the first maxima. Regression coefficients are given with an error equal to one standard deviation (1σ).

Emission	Quasi-decadal oscillation			Quasi-2-decadal oscillation		
	T_{qdo}, years	A_{qdo}, R	f_{qdo}, year	T_{k2do}, years	A_{q2do}, R	f_{q2do}, year
$O_2A(0-1)$	8.2	23.7±5.6	2001.2±0.3	20.5	27.5±5.7	2000.1±0.6
OH(6-2)	8.3	50.3±10.6	2000.6±0.3	21.5	36.8±11.4	1999.3±0.9

The quasi-decadal and quasi-two-decadal oscillations are poorly studied. Only Reid et al.[12] note the multi-year oscillation with a period of near 3000 days (~8.2 years) in the OH airglow intensity. The quasi-two-decadal oscillation in the MLT has already been extracted from summer mesopause temperature[16]. The nature of this oscillation is supposed to associate with the solar 22-year cycle of the polar magnetic field reversal.

4. CONCLUSIONS

We have analyzed midnight measurements of hydroxyl and molecular oxygen airglow intensities as observed at the Zvenigorod station for 2000-2019. As a result, we can conclude the following:

1. The long-term linear trends in the observed emission intensities are negative and statistically significant.

2. Both emission intensities demonstrate a statistically significant positive correlation with solar activity.
3. It is found that these intensities experience quasi-decadal and quasi-two-decadal oscillations, the amplitudes of which are from 5 to 10 % of the mean emission intensities.
It seems that all the observed changes in the airglow emissions are due to atomic oxygen dynamics in the MLT region.

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