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Variations in Mesopause Region Characteristics: Space-Factor Effects[1]

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Abstract—Some important data on both lunar tidal and solar effects on mesopause region characteristics, which were obtained by scientists of the Obukhov Institute of Atmospheric Physics in cooperation with colleagues from other organizations, are discussed. The present-day evidence that supports the hypothesis proposed by A.I. Semenov and N.N. Shefov about the existence of oscillations (with periods of the lunar synodic month and its half) in the mesopause region characteristics is considered. The oscillation amplitudes are estimated based on a statistical analysis of measurement data, possible mechanisms for generating these oscillations are indicated. Statistical data on the effect of solar activity on the mesopause region are discussed. It is shown that the effects of solar activity on some atmospheric characteristics on interannual and intraseasonal time scales have opposite signs, which suggests that there are different physical mechanisms of solar-terrestrial relations within these frequency ranges.

Keywords: lunar tides, semidiurnal tide, diurnal tide, synodic month, mesopause region, solar-terrestrial relations

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1. INTRODUCTION

Humans have taken an interest in space effects on the Earth's different shells since ancient times. However, from the natural-scientific point of view, any serious progress in their studies could be achieved only when long-term measurement data series became available. This also applies to the study of the mesopause region in the Earth's atmosphere (heights of 80–95 km). The most important scientific results on both lunar and solar effects on mesopause region characteristics, which were obtained by scientists of the Obukhov Institute of Atmospheric Physics (OIAP) in cooperation with colleagues from other organizations, are discussed in this work. Deep interest in this topic arose at the OIAP mainly due to the works by N.N. Shefov and A.I. Semenov who obtained the first interesting results and continued to develop this theme throughout their lives [1].

Studying space effects on the mesopause region chronologically began at the OIAP [2], as well as in the world practice [3], with a search for a lunar rather than a solar effect. This was associated with rather short data series at the first stage of measurements of mesopause region characteristics, which did not allow one to reliably keep track of variations due to the most powerful and rather long (~11-year) solar activity cycles. At the same time, the available time series covered a large number of lunar months. The objective of this work is not to list all lunar and solar periodic or quasiperiodic harmonics selected from the time series of measured mesopause region characteristics, but to show the most interesting results regarding their scientific perspectives. Section 2 considers the discovery of a synodic lunar monthly oscillation and its second harmonic in the mesopause region characteristics and its subsequent confirmations in detail; in addition, possible mechanisms of their generation, some of which are indicated for the first time, are listed in this section. Section 3 briefly considers the history of the inclusion of solar cycles into the practice of empirical models of mesopause region characteristics with emphasis on the recently discovered multidirectional effect of solar activity variations on the mesopause region characteristics on different time scales.

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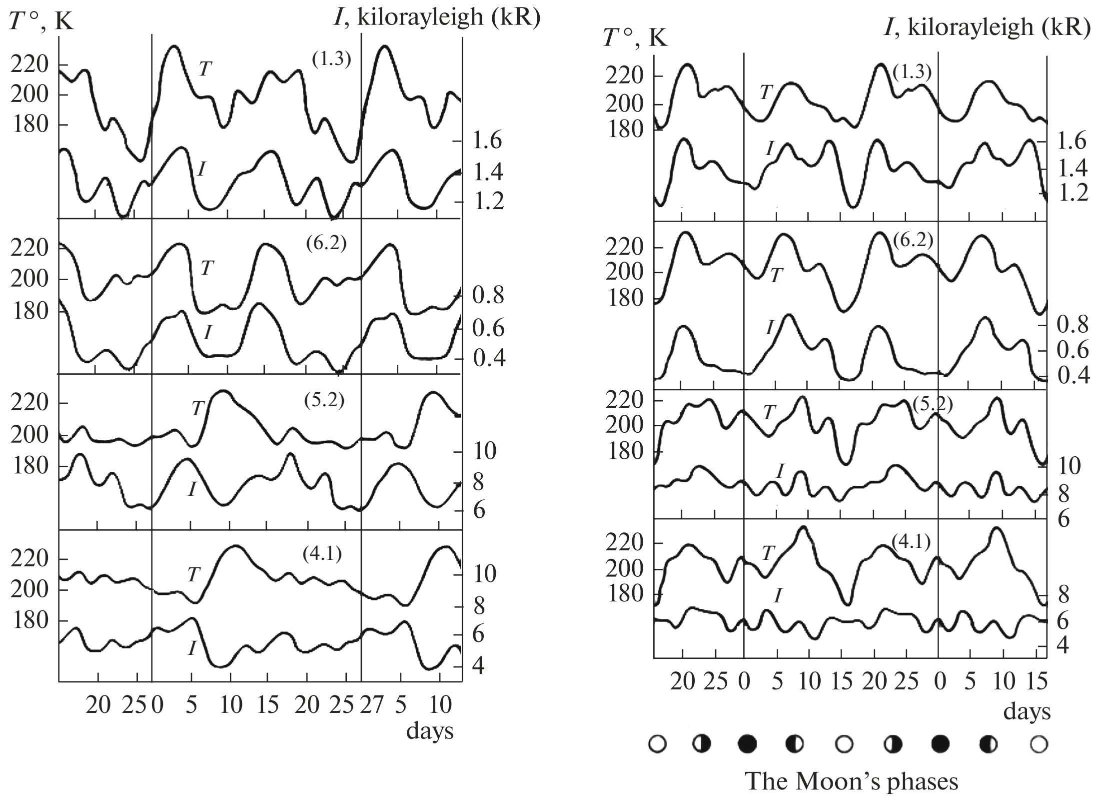

Fig. 1. The first estimates of lunar OH-layer perturbations [2]. Average variations in the intensities (*I*) and rotational temperatures (*T*) of the OH (4–1), (5–2), (6–2), and (7–3) bands with a period of 27 days (on the left) and with respect to the Moon's phase (on the right).

2. FINDING PERTURBATIONS WITH PERIODS OF A LUNAR SYNODIC MONTH AND ITS HALF

Long-term measurement data on upper-atmospheric night airglow components, including rotational temperature and the intensity of different hydroxyl bands (the hydroxyl emission layer is localized within the mesopause region with maximum emissions at a height of ~87 km), had been accumulated at the OIAP by the mid-1960s. The corresponding data series based on measurements at the OIAP Zvenigorod Scientific Station were analyzed by Shefov [2] to find lunar effects. The initial time series were averaged using the superposed epoch method with specified periodicities of 27 days (which is close to a lunar sidereal month and a synodic solar rotation period) and 29.5 days (a synodic lunar month). Figure 1 shows the result of averaging [2]. Attention is drawn to the unrealistically large oscillation amplitude exceeding 20 K for the hydroxyl layer temperature. Apparently, it was the result of short samples. At that time, confidence intervals and statistical significance estimates were not used as a necessary tool in analyzing geophysical data. Later, the oscillation amplitudes calculated using longer samples were significantly reduced [4].

It should be noted that Shefov regarded critically his results [2] and the similar data obtained by foreign colleagues [5–7] on atomic oxygen emission 558 nm. The results on the lunar effect were formulated as a hypothesis rather than a final conclusion. Nevertheless, these early results provided inspiration to continue studying the lunar effect on different mesopause region characteristics. In the 1970s, lunar tidal effects were found in the wind-velocity components measured using the meteor method [8], the vibrational temperature of hydroxyl emissions [9, 10], and in the frequency of occurrence of noctilucent clouds [11].

The chief drawback of the above-indicated works published in the 1960s–1970s was apparently a polling interval of 24 h for the variables under study (reference of measurements to the astronomical midnight). In this case, the Moon's phases prove to be strictly referred to the lunar time, and any N-th harmonic of a lunar day (lasting, on average, 24 h 51 min) for such a special sample becomes indistinguishable from the N-th harmonic of a synodic lunar month lasting, on average, 29.53 days. Taking the fact into account that the results may be interpreted in two ways, the data in the form of oscillation graphs are given in [9, 10] using two time scales. However, as a rule, the results were perceived as oscillations with

Table 1. The amplitudes (calculated in [15]) of different lunar tidal oscillations in data on polar mesospheric summer echoes

Period of oscillations under consideration	Variables under analysis		
	Logarithm of the reflection coefficient	Zonal wind velocity component, m/s	Meridional wind velocity component, m/s
Lunar synodic month	0.053 ± 0.016	0.4 ± 0.5	1.3 ± 0.6
Half the lunar synodic month	0.039 ± 0.016	0.4 ± 0.5	0.3 ± 0.5
Lunar day	0.023 ± 0.016	0.7 ± 0.5	1.0 ± 0.5
Half the lunar day	0.021 ± 0.016	1.1 ± 0.5	0.5 ± 0.5

Errors are given for a probability of 95%.

periods equal to a lunar day and their second and higher harmonics, because they are present in the linear model of lunar gravitational perturbations in the atmosphere [12].

The theme of an alternative interpretation of both old and new results was further developed by Semenov and Shefov in [4]. The authors of this work not only repeated the analysis made by Shefov in [2, 9] on the basis of longer observations but also compared these observational data with the results found for both lunar diurnal and semidiurnal tides in the temperature and intensity of hydroxyl emissions, which were obtained from both temperature and intensity graphs (for 15 nights) based on measurements at 32° S latitude [13]. During this analysis, attention was given to the fact that the temperature and intensity amplitudes in the case of the superposition of both synodic monthly and lunar-diurnal oscillations and the superposition of synodic semimonthly and lunar semidiurnal oscillations, which were obtained based on Zvenigorod measurement data, were several times larger than the amplitudes of purely lunar diurnal and lunar semidiurnal oscillations, as determined from data given in [13].

The first statistically validated separation of a lunar semidiurnal tide and a lunar synodic semimonthly oscillation on the basis of the same long-term observational data on winter hydroxyl temperatures (with a data averaging interval of 1 h) was performed in [14]. This supported the validity of the Shefov and Semenov hypothesis for the existence of hydroxyl temperature oscillations with a period of half a lunar synodic month. The subordination between the amplitudes was also supported: for semimonthly oscillations, the amplitude was 2.5 ± 0.8 K (the error is given for a probability of 90%) and, for lunar semidiurnal oscillations, the amplitude was smaller and statistically insignificant.

It is impossible to obtain reliable data on lunar diurnal tides on the basis of hydroxyl temperatures, because the duration of night measurements even in winter does not exceed or only slightly exceeds half a day. Therefore, to simultaneously find oscillations with periods of a lunar day and a lunar synodic month and with half the periods, other data obtained for approximately the same heights, at which the hydroxyl layer is located, were used in [15]. These other data on polar mesospheric summer echoes were obtained from round-the-clock measurements using the ESRAD radar located in northern Sweden, Kiruna (a data averaging interval of 1 h). The logarithm of the coefficient of reflection of sounding radiowaves and the wind-velocity components at the reflection height were taken as the variables under analysis. Table 1 gives the results obtained in [15] for the amplitudes of the oscillations under study in the corresponding long-term time series. It follows from Table 1 that the amplitudes of the four oscillations under study are of the same order of magnitude; in addition, for the reflection coefficient logarithm, the amplitudes of both monthly and semimonthly oscillations exceed those of lunar diurnal and lunar semidiurnal ones.

In [15], the amplitudes were calculated using the method of multiple regression analysis. In this case, special measures were taken against possible interferences due to basic tidal harmonics. Thus, for example, due to the statistical relationship between the lunar synodic month phases and the Moon's declination that is responsible for a zonal tide with a period of 13.66 days (see [14]), one may suggest the isolation of fictive oscillations (with a period of half a synodic month) induced by zonal tides. To exclude such interferences, all possible tide components that could be their generators were simultaneously calculated and isolated.

Thus, for a period of 29.53 days and its second harmonic, the Shefov and Semenov hypothesis for the existence of a lunar synodic oscillation was also confirmed.

As was noted above, the linear theory of lunar gravitational tides in the atmosphere does not predict the existence of these two components in the spectrum. At present, one can only outline possible mechanisms of their generation. For lunar synodic semimonthly tides, two mechanisms of their generation were already considered in [14]: the ineffective mechanism based on the modulation of distances to the Moon in a synodic semimonthly cycle and the nonlinear mechanism of quadratic demodulation based on the multiplication of two superpositions of oscillations with periods of both solar and lunar semidiurnal tides. The quadratic components of hydrodynamic equations demodulate beats between both solar and lunar semidiurnal tides and generate two new sinusoids with the sum and difference of frequencies. Another version of nonlinear generation (proposed here, apparently, for the first time), that is, the multiplication of two superpositions of oscillations with periods of 13.66 days (a very noticeable lunar zonal tide) and 182.625 days (a semiannual tide), may be one more efficient mechanism for generating semimonthly synodic oscillations.

Similar mechanisms may also be considered for the generation of a monthly synodic tide but with doubling of all valid periods. However, for the first mechanism, the modulation of distances to the Moon by synodic monthly oscillations becomes negligible. In the third mechanism, one should consider, instead of a very noticeable tide with a period of 13.66 days, a much weaker (in the linear theory [12]) tide with doubled period. Only the second mechanism, that is, the multiplication of two superpositions of oscillations with periods of both solar and lunar diurnal tides, allows one to hope for the efficient generation of a lunar synodic monthly tide. Despite the fact that, in the linear theory, the lunar diurnal tide with a period of 24 h 51 min is significantly weaker than the lunar semidiurnal tide, the analysis of data on polar mesospheric summer echoes [15] shows that their observed amplitudes are of the same order, which, on the one hand, requires independent investigation and, on the other hand, may provide the nonlinear generation of lunar synodic oscillations with a period of 29.53 days.

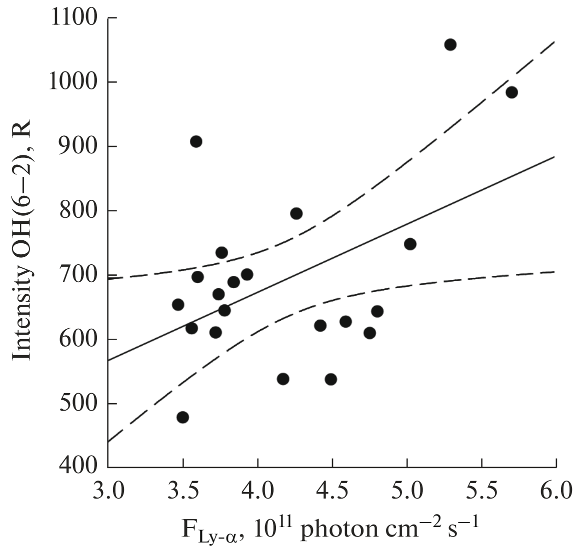

Fig. 2. A comparison between the intensities of the OH(6–2) band and the solar radiation flux in the Lyman-alpha line ($F_{Ly\text{-}\alpha}$). The values are taken as averages over intervals from October 1 to March 31, 2000 and 2001 after smoothing with the superposition of the four annual harmonics (i.e., higher harmonics are excluded). The straight line corresponds to the linear regression (with coefficient 106 ± 102 R/(10^{11} photon cm^{-2} s^{-1})). The value of the Lyman-alpha flux measured in units of 10^{11} photon cm^{-2} s^{-1} and reduced to a distance of 1 AU from the Sun is used as a measure of its intensity. The intensity of hydroxyl emissions is measured in Rayleigh (R), 1 R = 10^6 photon cm^{-2} s^{-1}. The dashed lines correspond to the 95% probability level limits.

3. SOLAR ACTIVITY MANIFESTATIONS ON DIFFERENT TIME SCALES

During the 20th century, the understanding of the effect of solar activity on the mesopause region was transformed from the first assumptions of the existence of such an effect to its quantitative consideration in models. An 11-year cyclicity in the properties of meteor trails was found in 1904 [16]. The first evidence for variations in the characteristics of infrared emissions from the mesopause region within the solar activity cycle appeared in the middle of the 20th century [17]. Then, 10–11-year peaks were obtained in the spectrum of the number of nights with the occurrence of mesospheric clouds [18]. The ~11-year solar activity cycles were first quantitatively taken into account in the models of the characteristics of mesopause region emissions in [19]. As a result of Shefov and Semenov's efforts directed towards developing models of basic emissions of the mesopause region, such empirical models had been created by the beginning of the 21st century [1]. These models took into account solar activity variations within the ~11-year cycle with the aid of the solar radio emission index $F_{10.7}$ averaged over several months. Later, when studying the effect of solar activity on mesospheric clouds [20] and infrared emissions of the mesopause region, it made more sense to use (instead of this index) the flux of solar radiation in the Lyman-alpha line (122 nm) [21] as a factor affecting directly the medium under study through photochemical reactions.

Later, it turned out that both interannual and interdiurnal variations in the Lyman-alpha flux affect the mesopause region characteristics. This was demonstrated using a model [22] and an analysis of measurement data [23]. In studying interdiurnal solar activity manifestations with both correlation and regression methods, it becomes necessary to preliminarily filter the most powerful signal of the slow component of the time series (for example, through data averaging by a sliding 35-day time window [24]). The most powerful ~27-day oscillation associated with the Sun's rotation period is pronounced in the spectrum of interdiurnal oscillations in solar activity indices and mesopause region characteristics [24, 25].

To understand the mechanisms of the effect of solar activity on the mesopause region, it is important to determine whether they differ on both interannual and intraseasonal time scales. The corresponding verification was carried out based on 22-year time series of the intensities of infrared emissions of molecular oxygen ($O_2A(0–1)$ band) and hydroxyl (OH(6–2) band), OH rotational temperatures, and variables characterizing the activity of mesospheric clouds (number

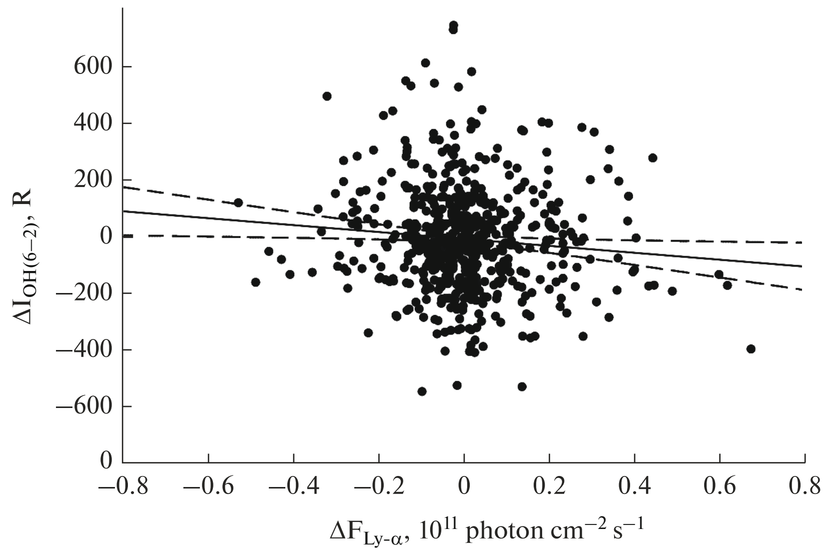

Fig. 3. Comparison of deviations $\Delta I_{OH(6-2)}$ in the intensity of the OH(6–2) band and the solar flux in the Lyman-alpha line from their smoothed values for time intervals from October 1 to March 31, 2000 and 2001. The straight line corresponds to the linear regression (with coefficient -121 ± 106 Rl/(10^{11} photon cm^{-2} s^{-1})). Explanations to the measurement units are given in the caption to Fig. 2. The dashed lines correspond to the 95% probability level limits.

of their occurrences, brightness) [24, 26, 27]. It turned out that the response of some of these parameters to variations in the Lyman-alpha flux on intraseasonal and interannual time scales may have even opposite signs. Thus, in winter, the intensity of the hydroxyl band has a positive response to interannual variations in the Lyman-alpha flux (Fig. 2). If one excludes slow variations in both parameters under comparison from time series and leaves only their intraseasonal variations, then a negative response to intraseasonal variations in the Lyman-alpha flux is noted (Fig. 3). Both dependences are statistically significant with a probability of no less than 95%.

It should be noted that for discontinuous series of observations (discontinuities were caused by unfavorable weather conditions in measuring the night-sky airglow) the separation of the series into the fast and slow components is ambiguous. Figure 3 shows the result corresponding to the excluded smoothed values calculated using the superpositions of the zero and first four annual harmonics for each winter season. A similar regression dependence may be obtained in excluding the slow component calculated through smoothing the primary series by a 34-day time window after the interpolatory data gap filling. The result we obtained suggests that on both slow interannual and fast (with characteristic periods of less than 35 days) time scales, solar activity may affect the middle atmosphere through different mechanisms. Thus, within the 11-year solar cycle, the basic mechanism is the direct effect of solar ultraviolet (UV) radiation on the structure of the gas composition of the mesopause region. Due to the intensified dissociation of molecular oxygen with an increase in UV radiation, the content of atomic oxygen, whose recombination product is the hydroxyl emission, increases [1]. Thus, as a result of photochemical processes, a direct relationship between solar UV radiation and the intensity of hydroxyl emissions occurs. In the case of 27-day variations, the most probable mechanism is dynamic changes in the mesosphere and lower thermosphere [28].

4. CONCLUSIONS

(1) The Shefov and Semenov hypothesis for the existence of oscillations in the mesopause region with periods of a synodic lunar month and its half has been verified based on the time series of different mesopause region characteristics. The validity of the hypothesis has been confirmed.

(2) Possible mechanisms that generate these oscillations have been considered, some of them have been discussed for the first time.

(3) On the basis of data obtained for the winter period, it is shown that the response of some measured characteristics of the mesopause region to variations in solar activity on both intraseasonal and interannual time scales is statistically significant and has opposite signs. This suggests that the physical mechanisms through which solar activity affects the mesopause region on these two scales are different.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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