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On the Geomagnetic Variations Observed on the Earth's Surface in the Period Range of Planetary Waves

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Abstract—The spectra of geomagnetic variations calculated in the period range close to planetary waves—5, 10, and 16 days—are analyzed. The records of the geomagnetic field at the Geophysical Observatory "Mikhnevo" of the Institute of Geosphere Dynamics of Russian Academy of Sciences are used. Spectral estimation based on parametric approach is carried out for the winter and summer periods of 2009 (low solar activity) and 2015 (high solar activity). For the first time, it is established that the harmonics directly related to the manifestation of the atmospheric planetary waves in the entire period range from 4 to 17 days are only observed in winter and, irrespective of solar activity; the changes in the atmospheric pressure are about a month ahead of the changes in the geomagnetic field. In the spectra of geomagnetic variations in the period range of 4–17 days, the harmonics of the 27-day geomagnetic periodicity and the harmonics associated with their modulation by the 11-year solar cycle, annual and semiannual variations are revealed. In the spectra for the period range from 12 to 17 days, harmonics with periods close to tidal waves M_f and M_{sf} are identified.

Keywords: planetary waves, variations in the Earth's magnetic field, modulation, lunar–solar tide

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INTRODUCTION

Geomagnetic variations observed on the Earth's surface are recorded in a fairly wide period range: from secular variations with a duration of tens to hundreds of years to the variations lasting several minutes to fractions of seconds. In particular, it is believed that the latter type of the variations (the so-called ultra-low-frequency (ULF) variations in the frequency range 0.01–30 Hz) is generated by geomagnetic pulsations Pc1/Pi1, Schumann resonances, ionospheric Alfvén resonator, noise signal which has an increased amplitude in the vicinity of the thunderstorm fronts, and quasi-periodic signals after sprites, the passage of the internal atmospheric waves through the ionosphere (Troitskaya and Guglielmi, 1969; Belyaev et al., 1990; Fraser-Smith, 1993; Fullekrug et al., 1998; Shalimov and Bosinger, 2006; Kunitsyn and Shalimov, 2011). In all the cited studies, it is believed that the source of the magnetic signals is the magnetosphere, ionosphere, or atmosphere.

Tidal harmonics have the highest intensity in the geomagnetic variations. The tidal harmonics manifest themselves in all geospheres—from the inner core to the ionosphere (Riabova and Spivak, 2019). The tidal impact in the outer geospheres (atmosphere and ionosphere) is mainly associated with thermal tides, i.e. with the action on the outer geospheres exerted by the Sun) (Shalimov, 2018). The analysis shows, however, that quite frequently, the origin of the intense spectral peaks can barely be attributed to the harmonics of the tides. Moreover, these peaks prove to be fairly close to the periods of 5, 10 and 16 days. In turn, these periods correspond to the so-called planetary waves or Rossby waves in the Earth's atmosphere, which mediate the interrelation between different outer shells.

The most developed theoretical approach for describing planetary waves in the atmosphere is based on finding the solutions of the homogeneous linearized equations for a stationary isothermal atmosphere on a rotating sphere (these solutions are sometimes called Rossby normal modes). Each mode is represented by an ordered pair of integers $(m, n - m)$, where m is the zonal wavenumber, n is the meridional index of the structure (which is associated with the index of the Hough function). The meridional structure for perturbations of the geopotential is symmetric about the equator for odd $n - m$ and antisymmetric for even $n - m$. Perturbations of the atmospheric parameters are typically recorded in the period ranges $T \approx 4.5$–6.2, ~7.5–12, and ~11–21 days. In accordance with the theoretical approach, these perturbations are commonly called quasi-5-day, quasi-10-day, and quasi-16-day waves and denoted (1,1), (1,2), and (1,3). The quasi-16-day waves are most intense in the spectrum.

Atmospheric planetary waves have a nonzero vertical velocity (Hirota and Hirooka, 1984) which, however, is rather low (2–10 km/day). As a result, the expected correlation of these waves with the ionosphere, depending on the propagation conditions of passage, may either be absent or observed with a substantial delay.

If the energy of atmospheric planetary waves penetrated to the heights of the ionosphere, the consequence would have been either direct detection of the variations in the ionospheric parameters in the range of periods of these waves, or the ground-based recording of the variations in the geomagnetic field in this range. In the latter case, the variations would have been due to the influence of planetary waves on the ionospheric currents flowing in the lower ionosphere at the heights of the *E*-layer. The cause of this influence is the collision of neutral and charged particles in the weakly ionized ionospheric plasma.

The typical periods of the atmospheric planetary waves were first detected in the variations of the ionospheric absorption of radio waves (in the *D*-region), and these periods were thought associated with the simultaneous 5-day waves in the stratosphere (Frazer, 1977). Later, the ground-based observations recorded quasi-16-day oscillations of the horizontal magnetic field component and pressure oscillations at stratospheric heights with a lead time of one month relative to the corresponding geomagnetic oscillations (Kohsiek et al., 1995).

In this work, the results of geomagnetic monitoring at the Geophysical Observatory "Mikhnevo" and spectral analysis methods, are used to study the spectral harmonics of geomagnetic variations in the period range from 4 to 17 days.

DATA AND METHODS

The study is based on the analysis of the spectra of geomagnetic variations recorded at Geophysical Observatory "Mikhnevo" of the Institute of Geosphere Dynamics of Russian Academy of Sciences (IDG RAS). Geomagnetic variations at the observatory are recorded with 1-s sampling interval by a digital three-component fluxgate magnetometer LEMI-018 installed in a specially equipped room. The LEMI-018 magnetometer has high resolution (10 pT) and low noise level at 1 Hz (<10 pT rms) which allows reliable recording of even weak changes in the Earth's magnetic field.

The spectral estimation in this work is conducted with the use of parametric approach which implies creating a mathematical model for approximating the generating process of the time series under study. In this approach, the power spectral density (PSD) is a function of the parameters of this model (Goldenberg et al., 1985). The application of the parametric methods does not require creating the windows suppressing spectral leakage and, therefore, increases the resolution. The estimation quality is determined by the adequacy of the selected model to the studied process (Bychkov et al., 2017).

The spectra of geomagnetic variations are calculated using the autoregressive (AR) model which is an equation that predicts the *k*th term of the sequence from *p* previous terms (Rabiner and Gould, 1978):

$$x(k) = -\sum_{n=1}^{p} a_n x(k-n) + \varepsilon(k),$$

where a_n are the autoregression coefficients; $\varepsilon(k)$ is the remainder term of the regression; and p is the order of the model.

PSD is determined based on the following formula (Marple, 1990):

$$S = \frac{1}{2\pi\left|1 + \sum_{1}^{p} a_n e^{-i\omega n}\right|}.$$

The coefficients in the constructed AR-model are determined based on the system of Yule–Walker equations (Sergienko, 2011). The system is solved with the use of the recurrent procedure—the Levinson–Durbin method (Durbin, 1960; Levinson, 1946).

DATA ANALYSIS

Let us focus in more detail on the analysis of the spectra of geomagnetic variations in the period range close to the 5-day planetary wave. Figure 1 shows the spectra for the periods of time from December 2008 to February 2009 (winter, low solar activity), from June 2009 to August 2009 (summer, low solar activity), from December 2014 to February 2015 (winter, high solar activity), and from June 2015 to August 2015 (summer, high solar activity). The analysis of the spectra shown in Fig. 1 indicates that all of them contain a spectral component that can be identified with one harmonics of the 27-day geomagnetic variation (approximately 6 days). We recall that the 27-day variations are associated with the rotation period of the visible solar surface as seen from the Earth (the periodicity is due to the nonuniform distribution of active regions on the Sun). Besides, a number of spectral harmonics associated with the so-called modulating effect of the long-period variations on the shorter-period variations (Riabova and Spivak, 2019) can be identified in the spectra. That is, the spectra contain harmonics with frequencies ω_0 (fundamental harmonic), $\omega_0 + \Omega$ (upper sideband harmonic) and $\omega_0 - \Omega$ (lower sideband harmonic), where ω_0 is the angular frequency of the non-modulated carrier oscil-

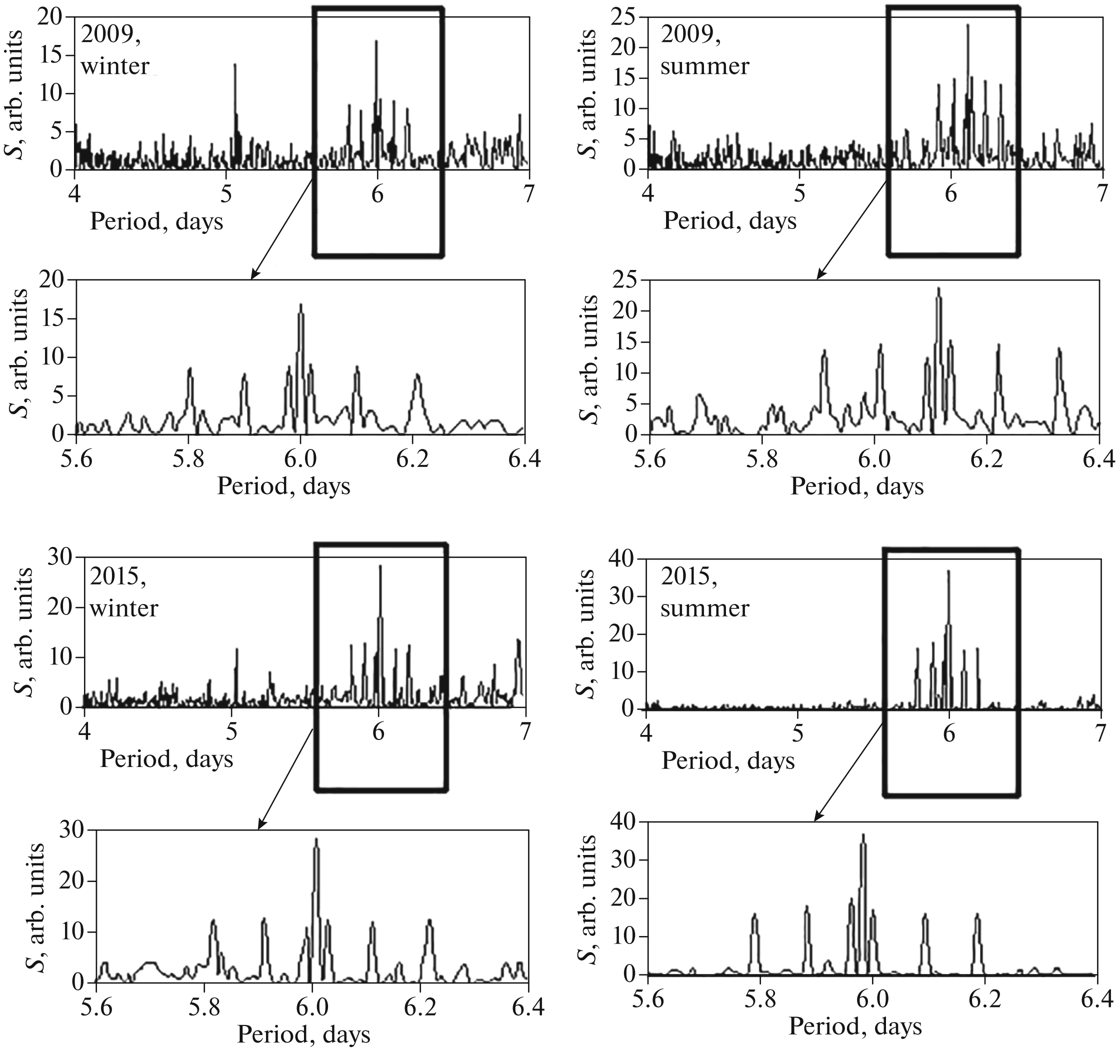

Fig. 1. Spectra of geomagnetic variations in period range from 4 to 7 days (time interval of data used for calculations is indicated in figure).

lation, and Ω is the frequency of amplitude modulation of carrier oscillation (Andreev, 1982). For example, in the spectrum for winter 2009, the peak with a period of 6 days is the harmonic of the 27-day periodicity; the peaks with the periods of ~5.98 and ~6.02 days correspond to the modulation of this harmonic by the 11-year cycle; the peaks with the periods of ~5.9 and ~6.1 days reflect the modulation impact on this harmonic from the annual variation; and the peaks with periods of 5.81 and 6.21 days are associated with the modulating effect of semi-annual variation on this harmonic. As seen from Fig. 1, the same peaks are clearly identified in the spectrum for other time intervals. However, these peaks are generally more pronounced during the periods of high solar activity.

For studying the manifestations of planetary waves in geomagnetic variations, the main interest is in the presence of spectral harmonics with a period close to five days. The analysis of the calculated spectra shows (Fig. 1) that this harmonic is clearly identified only in the winter period. At the same time, it is established that, in contrast to the modulation-related harmonics, the intensity of the harmonic with a period close to the 5-day planetary wave only slightly depends on solar activity while the position of the intensity peak of the quasi-5-day wave is fairly stable under the transition from the low to high solar activity.

The analysis of the spectra of geomagnetic variations in the range close to the period of the 10-day planetary wave (Fig. 2), in the same way, demonstrates the presence of spectral harmonics. Some of them, as in the case of spectra in the range of periods from 4 to 7 days, can be explained by modulation effects: an 11-year cycle, annual and semiannual variations. In this range, the same dependence of the spectral composition on the season and solar activity is found: the

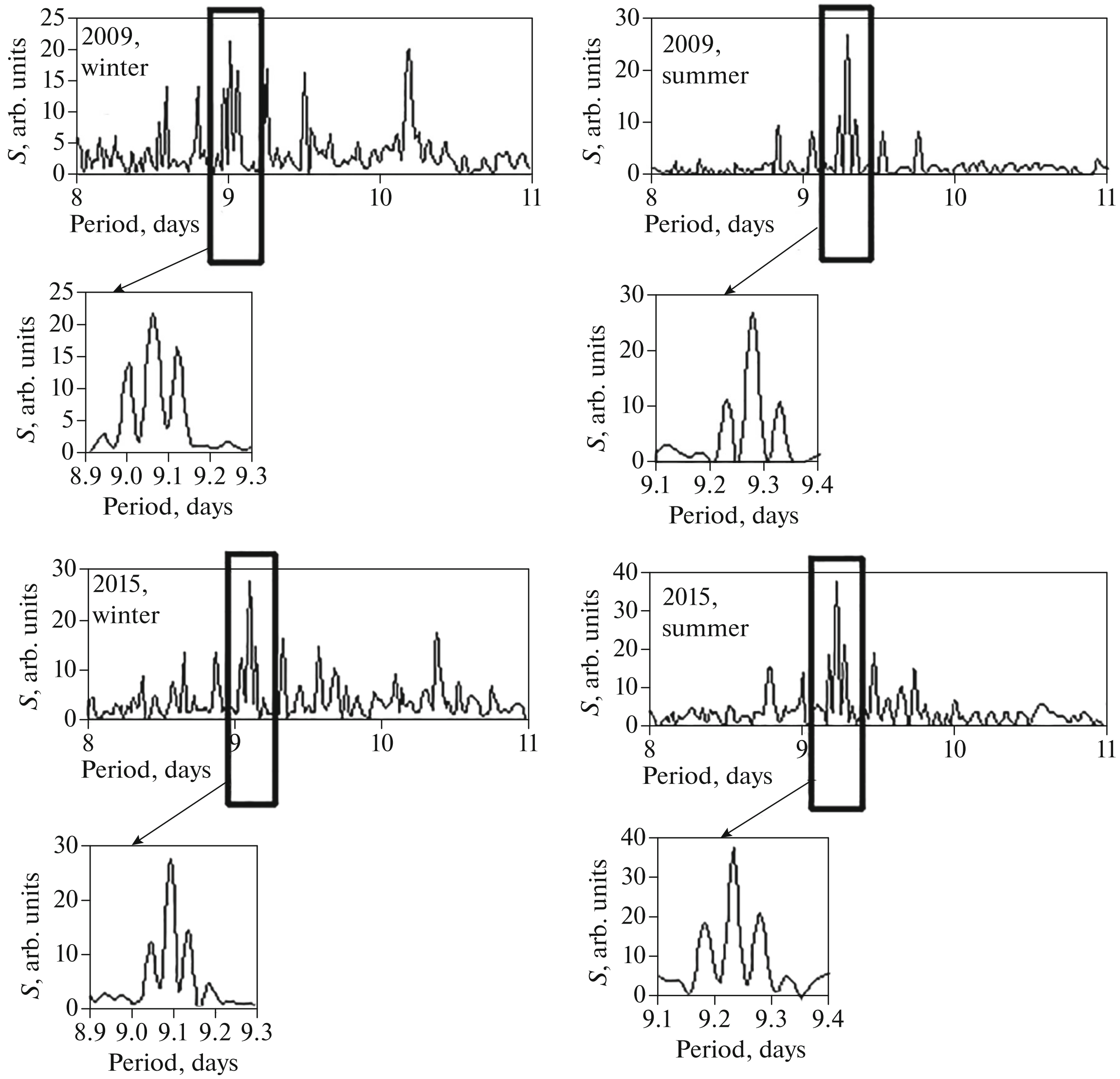

Fig. 2. Spectra of geomagnetic variations in period range from 8 to 11 days (time interval of data used for calculations is indicated in figure).

presence of a 10-day planetary wave in the spectrum only in the case of the winter period of time (with approximately the same intensity regardless of the level of solar activity); an increase in the intensity of harmonics due to amplitude-modulated exposure during the period of strong solar activity. It is also possible to note a slight shift in the peak of the quasi-10-day wave to the long-period region during the transition from low to high solar activity.

Besides, we have analyzed the spectra of geomagnetic variations in the two-week period range (the 16-day planetary wave). From Fig. 3 it can be seen that the spectrum contains a two-week harmonic of the 27-day periodicity and the peaks associated with the modulation effect of the 11-year cycle, annual, and semiannual variations. The intensity of the variations increases during phases of high solar activity.

We note that several harmonics are identified in the spectra. The presence of the spectral peaks with periods of ~13.66 and ~14.76 days both during the winter and summer seasons and both during the high and low solar activity can be attributed to the effect of lunar-solar tide (Adushkin et al., 2017; Sheremet'eva, 2011) considering the closeness of the periods of these harmonics to tidal waves M_f and M_{sf} (Riabova, 2018). These harmonics are more manifest during low solar activity.

The detailed analysis of the spectra in the two-week period range revealed the quasi-16-day harmonics in the winter spectra of the geomagnetic field, which can be interpreted as a manifestation of the atmospheric planetary 16-day wave. In the summer period, this harmonic is not identified. We note also a slight shift of the spectral peak of the quasi-16-day wave towards

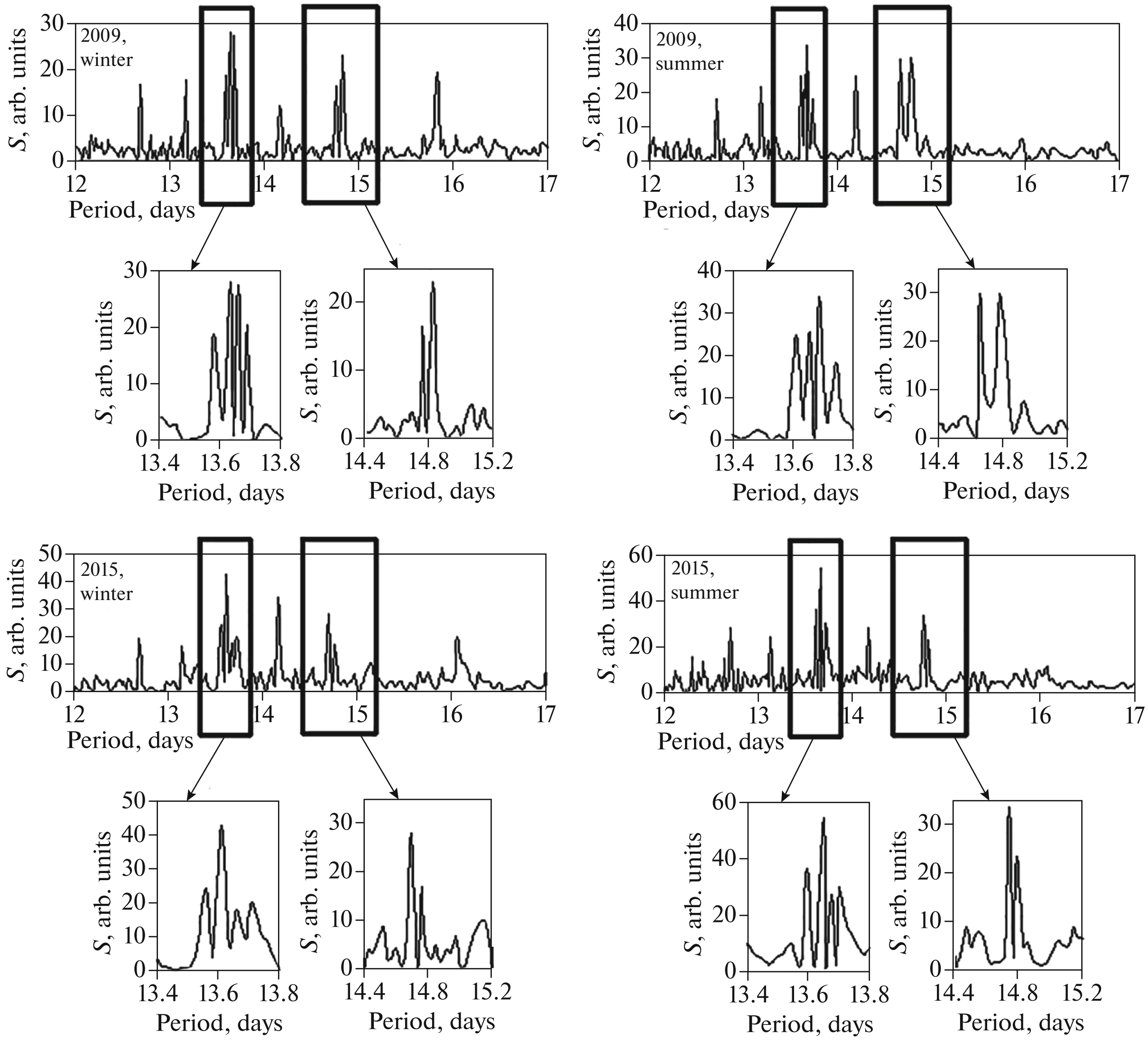

Fig. 3. Spectra of geomagnetic variations in period range from 12 to 17 days (time interval of data used for calculations is indicated in figure).

the long-period region at the transition from the low to high solar activity and the independence of the intensity of the variation on the level of solar activity.

The entre set of the results obtained in this study is summarized in Tables 1–3. As can be seen from the data presented in the tables, the study of the spectra in the period ranges close to the planetary waves (5, 10 and 16 days) suggests the following conclusions.

Most of the spectral peaks are associated with the harmonics of the 27-day geomagnetic variation and their modulation by the 11-year cycle, annual, and semiannual variations. In the two-week period range, the spectrum contains the harmonics close to the periods of tidal waves M_f and M_{sf}. Meanwhile, the spectral peaks which can be directly ascribed to the manifestation of the atmospheric planetary waves are only observed in the winter period. We note that the intensities of all these spectral peaks are comparable.

Based on the atmospheric pressure data recorded by the automated weather station Davis Vantage Pro2, we have analyzed the cross-correlation between variations in the magnetic field and in the atmospheric pressure in the surface layer of the atmosphere. In the calculation of the cross-correlogram, the digital time series were filtered in the period bands close to the planetary waves: from 4 to 5.5 days, from 10 to 11 days, and from 15.5 to 17 days. As an example, Fig. 4 shows the cross-correlogram between variations in the geomagnetic field and atmospheric pressure recorded from December 2008 to February 2009 (digital time series are pre-filtered in the period range from 15.5 to 17 days). As seen from Fig. 4, the maximum correlation coefficient (0.82) is observed at a lag of ~30 days

Table 1. Spectral harmonics identified in the spectrum of geomagnetic variations in the range of periods from 4 to 7 days

Probable explanation	Spectral components			
	December 2008 to February 2009	June 2009 to August 2009	December 2014 to February 2015	June 2015 to August 2015
Planetary wave	5.07 days	–	5.03 days	–
Modulating effect from semiannual variation	5.81 days	5.91 days	5.81 days	5.79 days
Modulating effect from annual variation	5.9 days	6.01 days	5.91 days	5.88 days
Modulating effect from 11-year cycle	5.98 days	6.09 days	5.99 days	5.96 days
A harmonic of 27-day periodicity of magnetic field	6 days	6.11 days	6.01 days	5.98 days
Modulating effect from 11-year cycle	6.02 days	6.13 days	6.03 days	6 days
Modulating effect from annual variation	6.1 days	6.22 days	6.11 days	6.09 days
Modulating effect from semiannual variation	6.21 days	6.33 days	6.22 days	6.19 days

Table 2. Spectral harmonics identified in the spectrum of geomagnetic variations in the range of periods from 8 to 11 days

Probable explanation	Spectral components			
	December 2008 to February 2009	June 2009 to August 2009	December 2014 to February 2015	June 2015 to August 2015
Modulating effect from semiannual variation	8.59 days	8.82 days	8.66 days	8.78 days
Modulating effect from annual variation	8.8 days	9.05 days	8.87 days	9 days
Modulating effect from 11-year cycle	8.96 days	9.23 days	9.05 days	9.18 days
A harmonic of 27-day periodicity of magnetic field	9.02 days	9.27 days	9.09 days	9.23 days
Modulating effect from 11-year cycle	9.07 days	9.33 days	9.14 days	9.28 days
Modulating effect from annual variation	9.25 days	9.52 days	9.33 days	9.48 days
Modulating effect from semiannual variation	9.49 days	9.76 days	9.58 days	9.73 days
Planetary wave	10.2 days	–	10.38 days	–

Table 3. Spectral harmonics identified in the spectrum of geomagnetic variations in the range of periods from 12 to 17 days

Probable explanation	Spectral components			
	December 2008 to February 2009	June 2009 to August 2009	December 2014 to February 2015	June 2015 to August 2015
Modulating effect from semiannual variation	12.67 days	12.72 days	12.67 days	12.69 days
Modulating effect from annual variation	13.16 days	13.19 days	13.14 days	13.13 days
Modulating effect from 11-year cycle	13.58 days	13.61 days	13.56 days	13.6 days
A harmonic of 27-day periodicity of magnetic field	13.63 days	13.69 days	13.61 days	13.65 days
Declination wave M_f	13.66 days	13.66 days	13.66 days	13.67 days
Modulating effect from 11-year cycle	13.69 days	13.74 days	13.71 days	13.7 days
Modulating effect from annual variation	14.14 days	14.20 days	14.14 days	14.16 days
Modulating effect from semiannual variation	14.72 days	14.81 days	14.69 days	14.73 days
Tidal wave M_{sf}	14.78 days	14.75 days	14.75 days	14.8 days
Planetary wave	15.82 days	–	16.07 days	–

indicating that the changes in atmospheric pressure are about a month ahead of the changes in the geomagnetic field. The similar results were obtained in the calculations of cross-correlograms based on the winter data filtered in other period ranges (Table 4). We note that in the summer period, the correlation coefficient is at most 0.2 at any time lag. Thus, considering the obtained results, we can state that, irrespective of solar activity, the changes in the atmospheric pressure in the studied period range in winter are

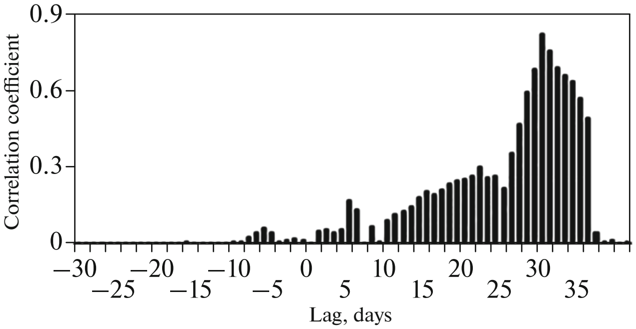

Fig. 4. Cross-correlogram between variations in geomagnetic field and atmospheric pressure (December 2008 to February 2009).

about a month ahead of the changes in the geomagnetic field.

DISCUSSION AND CONCLUSIONS

The analysis of the spectra of geomagnetic variations in the period ranges close to planetary waves (5, 10, and 16 days) has shown that, in addition to the periods of planetary waves, this range also contains harmonics of the 27-day variations and their modulation by the 11-year cycle, annual, and semiannual variations. In the spectra in the period range from 12 to 17 days, the harmonics close to the periods of tidal waves M_{f} and M_{sf} are detected. Besides these most intense harmonics, there are also peaks of lower intensities associated with the probable wave interactions; however, their identification requires additional research.

As established in this work, the direct manifestation of the periods of planetary waves in the geomagnetic variations has the following features: (1) the harmonics of the atmospheric planetary waves in the geomagnetic variations (5, 10 and 16 days) are only observed in winter; (2) irrespective of solar activity, in the atmospheric pressure for variations these periods are about a month ahead of the variations in the geomagnetic field.

It is known that the vertically propagating planetary waves obey the Charney–Drazin criterion (Charney and Drazin, 1960), according to which these waves cannot penetrate through the summer systems of easterly winds. The waves cannot also propagate through the strong winter westerly winds. This criterion gives a clue to why the planetary waves can reach the ionosphere (and, therefore, can excite geomagnetic variations) only in winter.

It should be noted, however, that there are observations (Shalimov et al., 2006) indicating that variations in the ionospheric parameters in the period range of planetary waves (in particular, with quasi periods of 2 and 7 days) also exist in the summer period. These variations will be analyzed in a separate work.

Based on the results of this study (Table 4 and Fig. 4), it is possible to estimate the vertical velocity of planetary waves. Assuming that the source of the waves is located in the troposphere, we obtain that a wave that reaches the lower ionosphere in 30 days propagates at a vertical velocity of approximately 3 km/day.

Thus, the ground-based measurements of geomagnetic variations at mid-latitudes and the spectral analysis of these variations show that the impact on the ionosphere (that leads to the observed geomagnetic variations) comes both from the Sun and from the atmosphere (through planetary waves). The geomagnetic variations excited by this impact have quite comparable spectral intensities. However, the atmospheric waves in the studied period range of 4–17 days reach the ionospheric heights in winter. Previously, this conclusion has been reliably known only for the quasi 16-day wave (Kohsiek et al., 1995). As believed, it is this wave that is responsible for violation of symmetry

Table 4. The results of cross-correlogram calculation: lag with maximum correlation coefficient (lag) and value of maximum correlation coefficient (*R*)

Parameter	Period of time			
	December 2008 to February 2009	June 2009 to August 2009	December 2014 to February 2015	June 2015 to August 2015
Data filtered in period range from 4 to 5.5 days				
lag	29 days	–	28 days	–
R	0.85	–	0.9	–
Data filtered in period range from 10 to 11 days				
lag	27 days	–	31 days	–
R	0.76	–	0.86	–
Data filtered in period range from 15.5 to 17 days				
lag	30 days	–	32 days	–
R	0.82	–	0.82	–

of the polar vortex and for sudden stratospheric warming in the winter hemisphere (Shalimov, 2018). The results of this work suggest that atmospheric waves with zonal numbers $m = 1$ in the entire range of periods 4–17 days can contribute to the development of the stratospheric warmings.

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