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TIDAL WAVES AND PRESSURE VARIATIONS IN THE EARTH'S ATMOSPHERE

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Abstract. The results of instrumental observations carried out at the geophysical observatory "Mikhnevo" and in the Center of geophysical monitoring, Institute of Geosphere Dynamics, RAS, Moscow during 2008–2015 are analyzed. The purpose of observations was to investigate the influence of the lunar-solar tide on the atmospheric pressure variations.

Atmospheric pressure variations were recorded at the frequency range of 10^{-4}–10^{2} Hz. Their spectral characteristics were estimated on the basis of the parametric autoregression method. The narrowband adaptive band-stop filters were applied for more qualitative separation of tidal waves with close periods. As a result of data processing, the basic tidal waves with diurnal and semi-diurnal periods were distinguished.

Diurnal and semi-diurnal harmonics of atmospheric pressure variations are accompanied by side equidistant spectrum lines, which directly confirm the modulation of these spectral components. The modulation periods of corresponding tidal waves are about 13.6 and 27.5 days, as well as 1/3, 1/2, and 1 year. The modulation depth of the tidal wave S_1 by the annual harmonic is about 0.9 and by the semi-annual is about 0.2. For the tidal waves S_2, K_2, R_2, T_2, and λ_2, it can be estimated as ~0.5 and ~0.15 accordingly.

Keywords: instrumental observations, atmospheric pressure, lunar-solar tide, tidal waves in atmosphere.

Introduction

Tide as a result of gravitational interaction, mainly in the system of three celestial bodies – the Earth, the Moon and the Sun – plays a very important role in geophysical phenomena and processes in the near-surface zone of the Earth [*Avsuk,* 1996; *Melchior,* 1968; *Rzhonsnitskii,* 1979; *Covey et al.,* 2014]. According to various estimates (see, for example, [*Sidorenkov,* 2002; *Kaula,* 1971]) power of tidal influence in the solid geosphere amounts from $\sim 3\cdot 10^{19}$ to 10^{20} J/year. An influence that the tidal deformation of the Earth exerts on almost all known physical processes and fields is also known [*Avsuk,* 1996; *Garetskiy, Dobrolubov,* 2006; *Adushkin, Spivak,* 2012, 2014].

Along with flow and tide in the solid Earth, we got interested in the atmospheric tide that plays a significant role in formation of average characteristics of air mass movement, both in global and local scale [*Adushkin, Spivak, Kharlamov,* 2016; *Golitsyn,* 2004; *Sidorenkov,* 2002, 2015; *Chapman, Lindzen,* 1972; *Zurbenko, Portzeva,* 2009]. Unlike the tidal effect in the Earth's crust and lithosphere, the atmospheric tide is a result of three factors: gravitational interaction from the Moon and the Sun (gravitational component of the atmospheric tide), rotation of the Earth and warming of the atmosphere on the daylight side of the Earth. At the same time, the intensity of the atmosphere warming is determined by absorption of solar energy, and characteristic period of the process is 1day, coinciding with the period of gravitational tidal wave S_1 (thermal component of atmospheric tide).

Study of atmospheric tide is of special interest and, first of all, to specify and determine new morphological features of global distributions of tidal variations of atmospheric pressure and atmospheric vector characteristics (wind movements of air masses), in particular, when operating aircraft. Dynamics of atmospheric tide plays a significant role among factors influencing variations of the Earth's rotation speed and its nutation [*Sidorenkov,* 2002]. Here, we should emphasize the importance of studying the atmospheric tide also for clarifying the model of the Earth's internal structure, in particular, interaction processes on the core – mantle boundary.

Indeed, since the frequency and amplitude of the diurnal nutation of the Earth is largely determined by its internal structure, deviation analysis of observed and theoretically predicted amplitudes of the nutational harmonics provides good opportunities for improvement of the Earth's model.

Study of atmospheric tide on the basis of analysis of the change in the absolute value of atmospheric pressure has well-known difficulties that are determined by strong baric perturbations of the atmosphere – cyclones and anticyclones. Even with the use of long series of atmospheric pressure records, only some tidal waves can be distinguished [*Zurbenko, Potrzeva,* 2009].

In the present work, extraction of periods coinciding with periods of lunar-solar tides was performed on the basis of analysis of envelope of atmospheric pressure variations in the frequency range of 0.0001–10 Hz. Such formulation of the problem is an analogue of a problem of high-frequency seismic noise modulation by tidal perturbtions of the Earth's crust [*Gordeev et al.,* 1995; *Rykunov, Khavroshkin, Tsyplakov,* 1980; *Spivak, Kishkina,* 2004].

The guaranteed data representativeness was ensured by the use of long series of digital records for the analysis explaining the studied phenomenon, and the high repeatability of processing results, also for the fragments, provided reliability and validity of final results.

Initial data

As initial data were used series of instrumental observations of atmospheric pressure carried out in 2008–2015 at the Geophysical Observatory "Mikhnevo" (54.9595 °N, 37.7664 °E) and at the Moscow Geophysical Monitoring Center[1] (55.7052 °N, 37.5707 °E) of the Institute of Geosphere Dynamics RAS [*Adushkin*, *Spivak, Kharlamov,* 2016; *Adushkin et al.,* 2016; *Spivak et al.,* 2015]. Simultaneously with atmospheric pressure P_0 were recorded its variations $P(t)$ in the frequency band 10^{-4}–10^2 Hz (digitalization frequency is 20 Hz). For this purpose, was used a small-pressure barometer MB-03, equipped with wind suppressing spatial filters [*Rybnov, Kharlamov, Evmenov,* 2005; *Spivak et al.,* 2015]. Small-pressure barometer was put into a well with the depth of 2 m to reduce the temperature drift.

Registration results in the form of digital series $P(t)$ were gathered on hard carriers and uploaded on the web-site IGD RAS (data of the Observatory "Mikhnevo" in graphical form at http://idg.chph.ras.ru/~mikhnevo/ , in digital form at http://idg.chph.ras.ru/~mikhnevo/data /; data of the Monitoring Center in graphical and digital form: http://idg-comp.chph.ras.ru/~idg/ Data/).

Applied methods of data processing and analysis

For the analysis were formed digital data series with a discreteness of 1 min. Thus, were processed series consisting of more than $4.2 \cdot 10^6$ values of the atmospheric pressure P_0. Spectrum of P_0 variations was estimated by parametric autoregression method [*Kanasevich,* 1985; *Marple,* 1990]. Autoregressive model of order p represented an equation predicting k-th sequence term by p previous:

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

where a_n is autoregression coefficient and $\psi(k)$ is a white noise.

[1] Further, for short will be used names the Observatory "Mikhnevo" and the Monitoring Center.

Parameters of $AR(p)$-model were estimated using the Levinson-Durbin method, implementing the solution of Yule-Walker equations. The spectrum of the process was estimated according to the calculated values of model parameter

$$S(\omega) = \frac{1}{2\pi\left|1 + \sum_1^p a_n e^{-i\omega n}\right|}.$$

Parameter p was chosen equal to the length of the analyzed data series, in order to achieve the maximum resolution of components of tidal waves. Besides, the frequency sampling interval was $\Delta f = 1.426 \cdot 10^{-5}$ 1/h.

The narrowband adaptive band-stop filters were applied for more qualitative separation of tidal waves with close periods in addition to parametric spectral analysis [*Widrow, Glover, Makul,* 1975; *Widrow, Stearns,* 1989]. Advantage of these filters is the simplicity of bandwidth tuning and almost unlimited suppression of close harmonics with accurate tracking of the frequency. For this purpose, the total atmospheric pressure was represented as a superposition of several (N) independent components $P_i(t)$, i=1, 2, 3, …, N, as a result, series $P(t)$ obtained after measurements were presented in the form of vector convolution ratio:

$$P(t) = \sum_{i=1}^{N} g_i * P_i(t), \quad (1)$$

where $g_i(t)$ is an impulse response characteristic determined by solving the integral convolution equation (1) [*Tihonov, Arsenin,* 1979].

Amplitude of the extracted harmonic with the given frequency ω is determined by:

$$P_i = C\sqrt{W_{1,i}^2 + W_{2,i}^2},$$

where C is amplitude of fluctuations (variations); $W_{1,i}$ and $W_{2,i}$ are coefficients of adaptive filter calculated according to expressions

$$W_{1,i+1} = W_{1,i} + 2\mu\varepsilon_i P_{1i},$$

$$W_{2,i+1} = W_{2,i} + 2\mu\varepsilon_i P_{2i}.$$

In these expressions μ is a parameter characterizing the convergence rate of the adaptation algorithm of filter coefficients; ε_i is difference between the original $P(t)$ and synthesized $P_i(t,\omega)$ signals; in this case

$$P_{si} = P_{1i}W_{1,i} + P_{2i}W_{2i}.$$

Quadrature components P_{1i} and P_{2i} with frequencies ω_i of separated signals are determined by dependences

$$P_{1i} = C\cos(\omega_i \Delta t + \varphi),$$

$$P_{2i} = C\sin(\omega_i \Delta t + \varphi),$$

where Δt is sampling interval equal to 1 h.

The Q factor of such filter is determined by parameters μ and C according to formula

$$Q = \omega\Delta t/2/\mu/C^2.$$

With the selected μ=0.02 and C=0.02 the value of Q is $1\cdot10^4$–$2\cdot10^4$, that provides a frequency resolution of $DF=2\mu C^2 = 8\cdot10^{-6}$ 1/h or time resolution of 0.0046 h. Such resolution allows distinguishing even the closest waves S_1 and P_1, which periods differ by 0.0648 h.

Values of ω_i were chosen equal to frequencies of the tidal potential. Algorithm of calculations gave the possibility to simultaneously summarize several synthesized signals with different ω_i.

Analysis of the atmospheric pressure variations

Fig. 1 represents amplitude spectra of atmospheric pressure variations P_0 calculated for the entire recording period at the Observatory "Mikhnevo" and in the Monitoring Center. The ranges of periods T with different-scale turbulence are clearly demonstrated. One maximum in the vicinity of a 12h period is clearly manifested and can be identified as tidal wave S_2.

In Fig. 2 on a larger scale is given an example of spectrum in the vicinity of (*a*) 12 h and (*b*) 24 h periods, where appear (though not quite clearly) spectral components of tidal waves K_1 with the period of 24.064 h and P_1 with the period of 23.935 h.

Data in Fig. 1 and 2 indicate that the use of even sufficiently long data series obtained by measuring the atmospheric pressure P_0, do not allow to register and allocate the entire spectrum of tidal waves. That is most likely due to the strong impact of cyclonic processes occurring in middle latitudes.

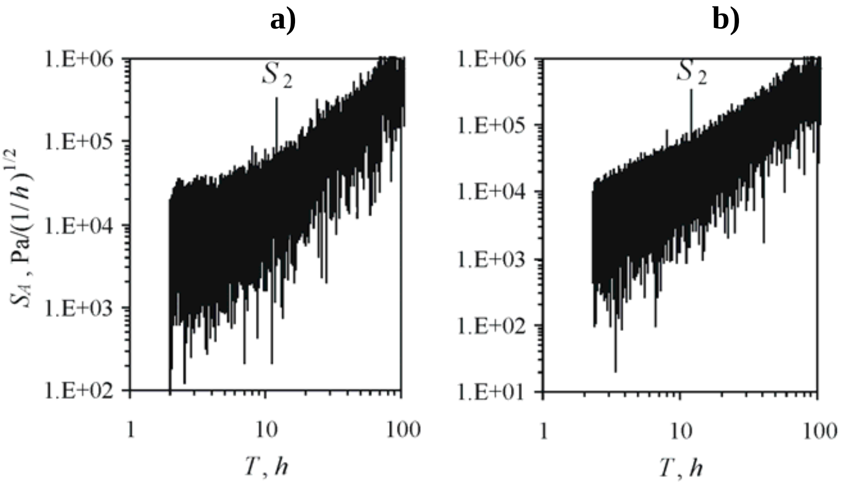

Fig. 1. Spectral amplitude of atmospheric pressure variations S_A (*a*) at the Geophysical Observatory "Mikhnevo" and (*b*) in the Moscow Geophysical Monitoring Center; S_2 is the peak frequency corresponding to the main solar tidal wave

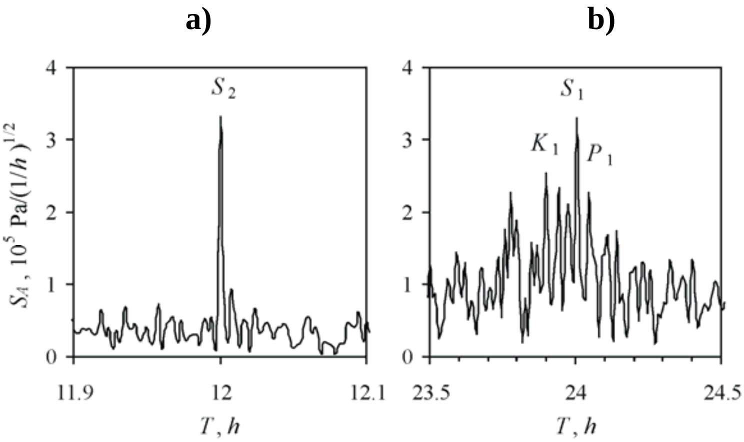

Fig. 2. The Geophysical Observatory "Mikhnevo". (*a*) Semi-diurnal and (*b*) diurnal spectrum regions of atmospheric pressure variations. Here and below, symbols of tidal waves are given.

A significant effect associated with the selection of tidal waves can be achieved by analyzing the atmospheric pressure variations $P(t)$, not its absolute value P_0. Indeed, as it is seen from the processing of the observation results, almost all known tidal waves are clearly distinguished on $P(t)$ spectra. As an example in Fig. 3 are given spectra of atmospheric pressure variations in vicinity of semi-diurnal and diurnal periods in Moscow.

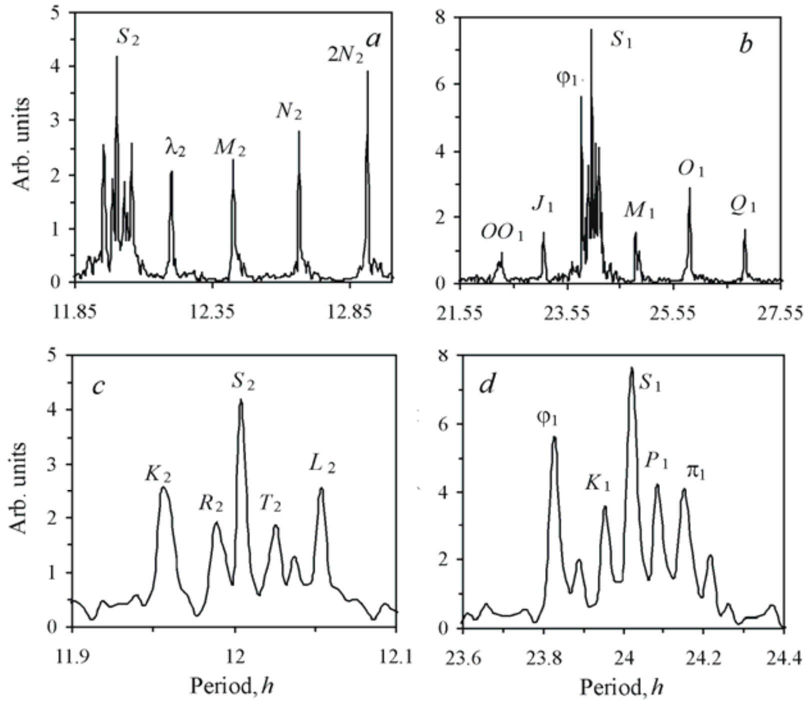

Fig. 3. Moscow Geophysical Monitoring Center. (*a*, *c*) Semi-diurnal and (*b*, *d*) diurnal spectrum regions of the atmospheric pressure variations.

Approach based on the application of adaptive band-stop filters also allows distinguishing close periods of tidal waves. As an example in Fig. 4 are given parts of spectrum of atmospheric pressure variations near (*a*) semi-diurnal and (*b*) diurnal periods at the Observatory "Mikhnevo". Alongside with solar tidal waves S_1 and S_2, tidal waves P_1, K_1 (see Fig. 4, *b*) and L_2, K_2 (see Fig. 4, *a*) with close periods are clearly distinguished.

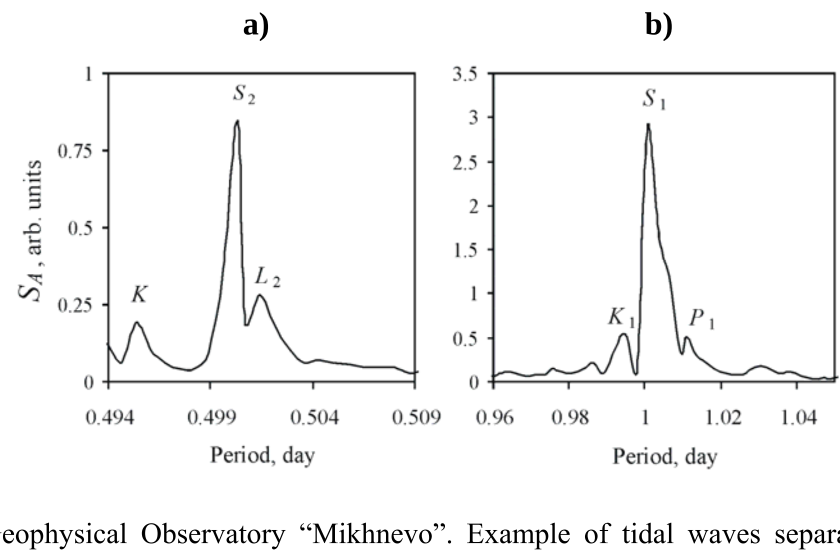

Fig. 4. The Geophysical Observatory "Mikhnevo". Example of tidal waves separation with close periods. Sections of variations' spectrum for the period from April to September 2011 in the range of (*a*) semi-diurnal and (*b*) diurnal periods.

Obtained data indicate that considering the uncertainty of spectral estimates, periods of selected quasi-harmonic components correspond to the periods of main tidal waves (Table), and phases of selected tidal waves and tidal signal almost coincide.

Main characteristics of tidal waves

Wave	Period of tidal signal (T_0)	Period, calculated by spectrum (T_S)	$(T_0 - T_S)/T_0$, %
Q_1	26.868	26.831	0.138
O_1	25.819	25.811	0.031
M_1	24.833	24.809	0.096
π_1	24.132	24.151	–0.079
P_1	24.066	24.085	–0.079
S_1	24.00	24.020	–0.083
K_1	23.934	23.954	–0.083
Φ_1	23.804	23.825	–0.088
J_1	23.098	23.118	–0.086
OO_1	22.306	22.319	–0.058
$2N_2$	12.904	12.899	0.039
N_2	12.658	12.653	0.039
M_2	12.420	12.415	0.040
λ_2	12.220	12.192	0.229
L_2	12.191	12.043	1.216
T_2	12.017	12.015	0.013
S_2	12.00	11.993	0.058
R_2	11.984	11.977	0.058
K_2	11.967	11.945	0.184

Unlike the earth tides, the spectral amplitudes of solar tides in general exceed the amplitude of lunar tides. This known fact is associated with the additional influence of terminator – the thermal solar tide [*Chapman, Lindzen,* 1972].

Here it is appropriate to note that formation of tidal waves in the atmosphere is a significantly more complicated process compared to formation of a tide in the solid Earth. This is due not only to the warming of the atmosphere on the daylight side of the Earth, but also due to strong variations of the atmospheric pressure as a result of cyclonic activity and significant multidirectional spatial transfers of air masses. Features of the atmospheric tide have not been yet fully studied instrumentally. This concerns, in particular, relation between amplitudes of different tidal waves. For example, if in the case of a tide in the solid Earth the amplitude of the tidal wave M_2 in middle latitudes is almost 35 times larger than the amplitude of the wave L_2, then in the atmosphere these amplitudes are comparable (see Fig. 3)

Analysis of the obtained data indicates that amplitudes of the tidal waves A vary considerably in time. As an example in Fig. 5 are given variations of relative spectral amplitudes of the main tidal waves, calculated from the data of the present work. Periodicities in the changes of considered values are clearly pronounced. For example, amplitude of the tidal wave K_2 changes over time with the period ~4.8 month. However, a greater interest provokes behavior of the amplitude of solar elliptic wave S_1. Its amplitude first occasionally reaches maximum values, comparable, and sometimes even exceeding, amplitude of such stably registered waves as K_2, L_2, M_2, etc., then it is so small that it cannot be distinguished by methods of this paper.

Since the wave S_1 is one of the main waves when considering thermal component of the atmospheric tide, it can be assumed that the growth and fall of its amplitude is determined by the degree of atmosphere warming, i.e. magnitude of temperature variations. Results of the analysis indicate that the really maximum amplitude values of the solar tidal wave S_1 are observed during the periods of increased relative values of air temperature T.

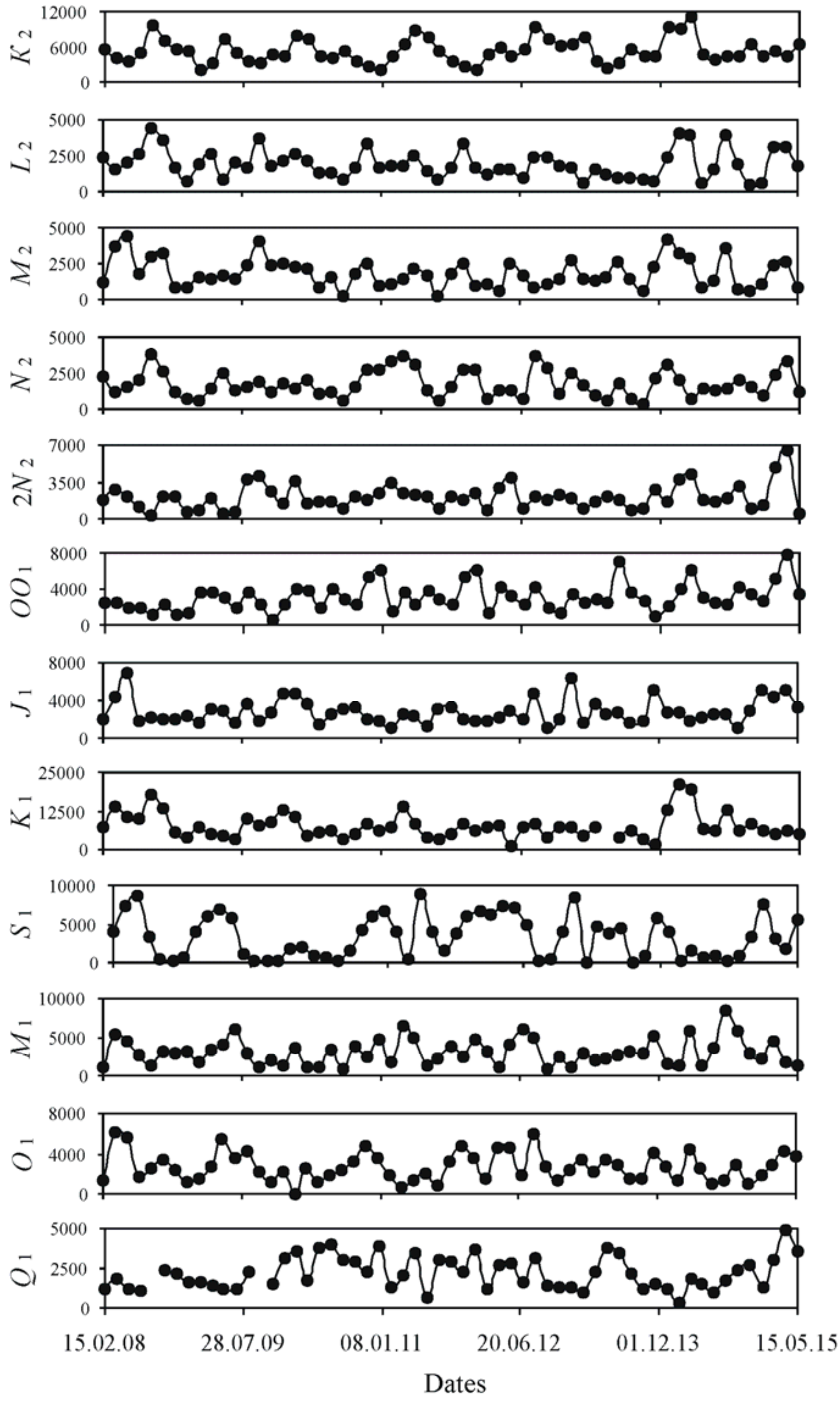

Fig. 5. The Geophysical Observatory 'Mikhnevo". Amplitude variations of the main tidal waves during the period from February 2008 to May 2015. On ordinate axes A, rel. units; near axes are notations of corresponding tidal waves

Modulation of atmospheric pressure variations by tidal waves

Due to nonlinearity of processes occurring in the atmosphere, superposition of long-period and short-period variations of atmospheric pressure P results in the appearance of additional periods on spectra of P variations. Since the duration of meteorological year changes slightly (not more than for a few percent), it can be expected that at least diurnal pressure variations are modulated by annual ones.

Amplitude-modulated oscillation is written in the form of the following model [*Zernov, Karpov,* 1972; *Sidorenkov*, 2008]:

$$P = V\cos(\omega t + \varphi) + \sum_{i=1}^{N} 0.5Vm_i \cos\left[(\omega + \Omega_i)t + \Phi_i\right] + \sum_{i=1}^{N} 0.5Vm_i \cos\left[(\omega - \Omega_i)t + \varphi + \Phi_i\right],$$

where V, ω and φ are an amplitude, angular frequency and initial phase of carrying oscillation, correspondingly; m is depth of modulation; Ω and Φ are frequency and modulation phase of carrying oscillation, respectively; t is the time; i is a harmonic number. This expression reflects the character of amplitude-modulated oscillation that includes the carrying oscillation (the first term), harmonic components with frequencies $\omega + \Omega_i$ (upper side frequency) and $\omega - \Omega_i$ (lower side frequency). Besides, amplitudes of lateral components are determined by the value $0.5Vm_i$.

As an example, we will analyze the spectrum of diurnal variations of atmospheric pressure micropulsation calculated with the use of adaptive band-stop filters, registered at the Monitoring Center and at the Observatory “Mikhnevo” (Fig. 6). It should be noted that modulation of these micropulsations is more correctly considered in the example of spectra.

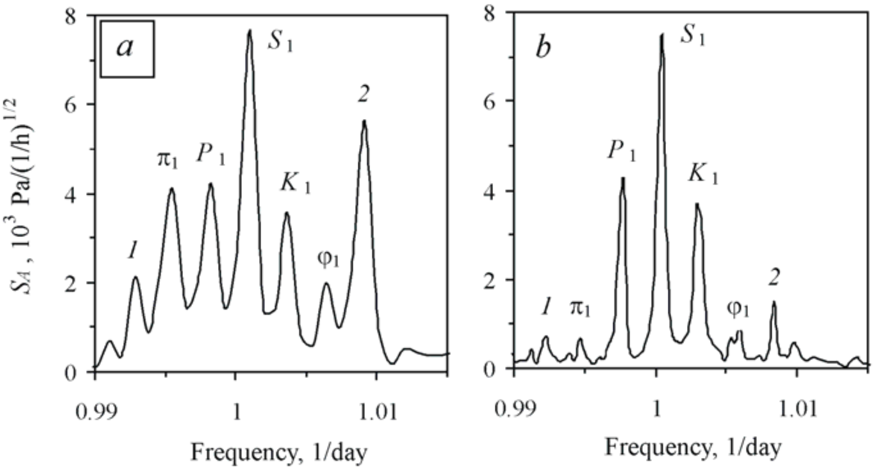

Fig. 6. Separation of the central and lateral oscillations in case of amplitude modulation of the tidal wave S_1, in conditions of (*a*) Moscow and (*b*) the Geophysical Observatory “Mikhnevo”. Comments to wave notations see in the text

Peaks with frequencies of ~0.997 and ~1.027 1/day, separated in the spectrum of atmospheric pressure micropulsations, are identified with the main solar tidal wave P_1 (period 1.0027 days) and lunar-solar declination wave K_1 (period 0.997 days), and are equidistant from the peak of diurnal wave of thermal tide S_1 at ~0.0027 1/day. Superposition of central and two lateral oscillations characterizes the modulation of amplitude of diurnal oscillations with the period of about 1 year.

At the same time, there are peaks with frequencies of ~0.994 1/day (period ~1.005 days) and ~1.0054 1/day (period ~0.994 days). These are tidal waves φ_1 and π_1, that occur as a result of modulation of diurnal oscillations of the atmospheric pressure by semiannual period (182 days). There are also peaks with frequencies of ~0.9918 1/day (peak *1* in Fig. 6) and ~1.0082 1/day (peak *2* in Fig. 6) that occurred as a result of modulation of diurnal oscillations of the atmospheric pressure by third-annual period and that are equidistant from the wave S_1 at 0.0082 1/day, which corresponds to modulation period of 122 days.

Let's analyze spectra of semi-diurnal variations of the atmospheric pressure micropulsations given in Fig.7. There are clearly distinguished five main peaks – central with frequency of 2 1/day (wave S_2 with period of 0.5 day) and two pairs of lateral peaks.

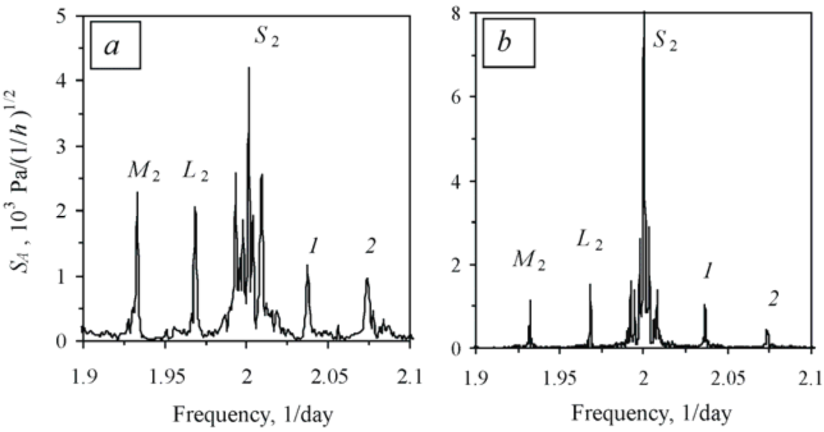

Fig. 7. Separation of the central and lateral oscillations in case of amplitude modulation of tidal wave S_2, in conditions of (*a*) Moscow and (*b*) the Observatory "Mikhnevo"

First pair with frequencies of ~1.968 1/day (corresponds to the wave L_2 with the period of ~0.508 days) and ~2.03 1/day (peak *1* with the period of ~0.492) is equidistant from the central peak S_2 at ~0.03 1/day. Second pair with frequencies of ~1.932 1/day (corresponds to the wave M_2 with the period of ~0.5175 days) and ~2.069 1/day (peak *2* with the period of ~0.482) is approximately equidistant from the central peak at 0.068 1/day. First pair corresponds to modulation with the period of ~27.55 days, second pair with the period of ~13.66 days.

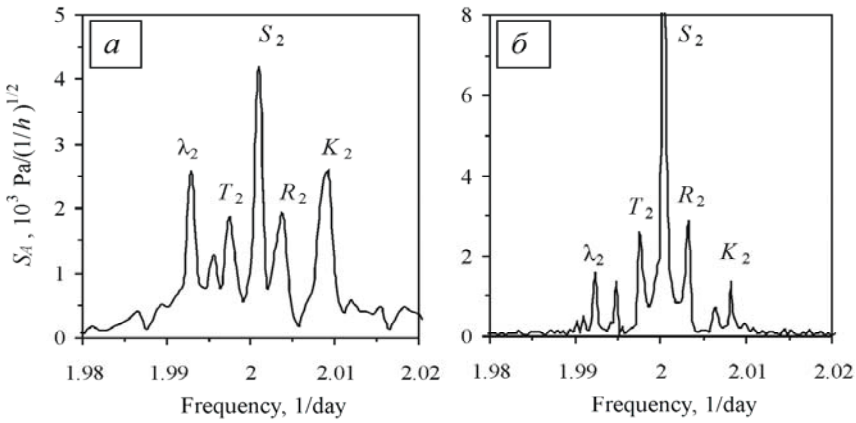

Fig. 8. Separation of the central and lateral oscillations in case of amplitude modulation of the tidal wave S_2 by long-period oscillations according to the data of (*a*) the Monitoring Center and (*b*) the Observatory "Mikhnevo".

Group near the central peak in Fig. 7, includes five main peaks that are clearly seen simultaneously at the Observatory "Mikhnevo" and in Moscow (Fig. 8). The peak corresponding to the tidal wave S_2 is in the center; two pairs of lateral peaks are distant from

S_2 by ~0.0028 1/day (waves R_2 and T_2) and by 0.0055 1/day (waves K_2 and λ_2). It can be assumed that tidal waves R_2 and T_2 are a consequence of S_2 modulation with the period of about 1 year, and tidal waves K_2 and λ_2 correspond to semi-annual period of modulation.

Fig. 9 shows an example of amplitude-modulated oscillation formed by the waves S_1, P_1, K_1, π_1 and φ_1. It follows from the amplitude ratio of the named waves that the depth of S_1 modulation by annual period is m~0.9, and by semi-annual is m~0.2. For the waves S_2 , K_2, R_2, T_2 and λ_2 the corresponding modulation values are estimated as ~0.5 and ~0.15.

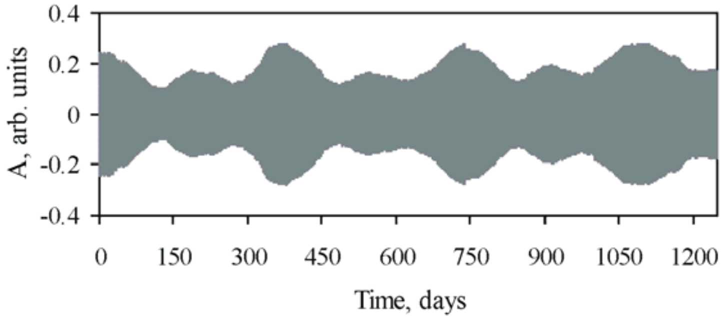

Fig. 9. The Geophysical Observatory "Mikhnevo". Example of amplitude-modulated oscillation formed by the waves S_2, P_1, K_1, π_1 and φ_1

From the point of view of a possible modulation of tidal fluctuations in the atmosphere, it is of interest to consider other groups of spectral peaks. In particular, the analysis of spectrum of diurnal variations indicates the presence of two pairs of lateral peaks. First pair is peaks with the periods of 1.0342 days and 0.9624 days, that are distant from the central peak S_1 by 0.0342 days (wave M_1) and 0.0376 days (wave J_1.), respectively. Second pair is peaks with the periods of 1.0759 days (wave O_1) and 0.9294 days (wave OO_1), distant from the central peak S_1 by 0.0758 and 0.0706 days.

Thus, taking into account the uncertainty of spectra estimation, waves M_1 and J_1 can be considered with the acceptable for the practice accuracy as lateral frequencies of amplitude-modulated oscillation with the modulation period of 27.554 days, and waves O_1 and OO_1 can be considered as lateral frequencies of amplitude-modulated oscillation with the modulation period of 13.66 days.

Analysis of recording results shows that the spectra of atmospheric pressure variations have well-distinguished tidal waves of large periods M_m (T=27.55 days) and M_f (T=13.66 days). Results of spectral estimates for T=10–30 days are given in Fig. 10.

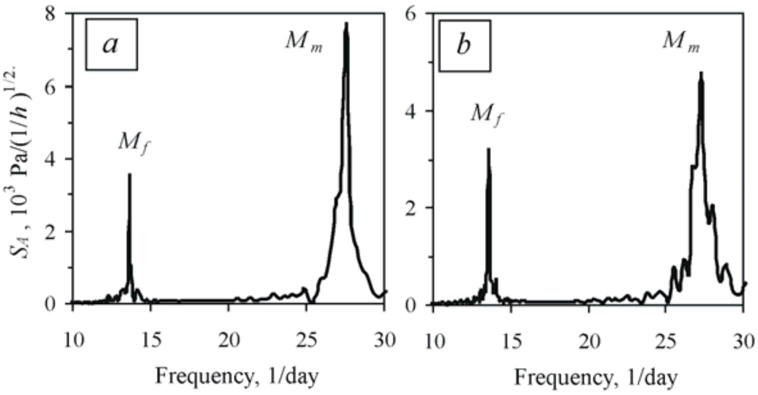

Fig. 10. Periodogram of atmospheric pressure variations in the periods of 13 and 27 days (*a*) at the Observatory "Mikhnevo" and (*b*) in Moscow

Conclusions

The presented data indicate the complexity of full-scale selection of diurnal and semi-diurnal groups of tidal waves in the atmosphere on the basis of analysis of atmospheric pressure variations, despite a rather long observation series.

The proposed approach based on the analysis of atmospheric pressure variations with the use of adaptive band-stop filters allows separating almost all known tidal waves.

Estimation of spectral characteristics of atmospheric pressure variations over a long period of observations using adaptive band-stop filters shows that diurnal and semi-diurnal harmonics of atmosphere pressure variations are accompanied by lateral equidistant spectral lines, which is a direct indication of modulation of these spectral components. Modulation periods of corresponding tidal waves are about 14 days, 27 days, third of a year, six months and year.

Modulation depth of tidal wave S_1 by annual period is about 0.9, semi-annual is ~0.2. For tidal waves S_2 , K_2, R_2, T_2 and λ_2 the corresponding modulation values are estimated as ~0.5 and ~0.15.

Results of this work, in the authors' opinion, can be needed in the construction of general model of the Earth's atmosphere and establishment of main laws of atmospheric movements.

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