Statistical study of seismic and ground pressure oscillations with steady frequencies in the 0.7–5 h period range

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Abstract. Product spectra of ground pressure variation and seismic oscillations have been calculated in the period sub-ranges of 42–90 min and 2.5–5 h, based on synchronous, co-located microbarograph and seismograph measurements at St. Petersburg (60° N, 30° E). The 200 records of 2–3.5 days in length and a combined duration of 525 days have been used. The product spectra have been computed for winter, spring, summer, and autumn, both individually and in combination. The spectra of different seasons are distinct from each other for both microbarograph and seismograph measurements; this can be caused by a seasonal variation in both frequency and amplitude of free oscillations of the atmosphere. There are pressure and seismic oscillations with close frequencies in the spectra for both, for each season and when all seasons are combined. At present, suggestions may only be made regarding the origin of most of these common oscillations. Once again, the penetration of the Earth's free oscillation $_0S_2$ with a period of about 54 min into the atmosphere has been confirmed. A common pressure and seismic oscillation with the 206 min period has been detected and has attracted considerable interest. The 159-min periodicity revealed in pressure variations may be associated with the well-known solar oscillation of the 160.01 min period.

Key words. Meteorology and atmospheric dynamics (middle atmosphere dynamics; waves and tides)

1 Introduction

Quasi-periodic fluctuations of wind, pressure, density, and temperature in the ~ 1–5 h period range are observed ubiquitously in the lower and middle atmosphere. The fluctuations are associated with the propagation of internal gravity waves (IGWs) from different meteorological tropospheric sources (e.g. Gossard and Hooke, 1975). The IGW period depends on source features which vary from one case of IGW gener-

ation to another. There are, therefore, no well-defined IGW periods.

However, microbarograph observations of ground pressure variation have shown atmospheric oscillations with steady frequencies in the $\sim 1-2$ h period range (Garmash et al., 1989; Lin'kov et al., 1989; Shved et al., 2000). These frequencies coincide with those observed in seismic oscillation spectra. Among the above atmospheric oscillations the 54-min periodicity is the only oscillation with a known physical source (Shved et al., 2000). This pressure oscillation is forced by the fundamental spheroidal mode $_0S_2$ of the Earth's free oscillations (Aki and Richards, 1980). As for other oscillations with steady frequencies, those can be caused by both the free atmospheric oscillations (Petrova and Shved, 2000) and tectonic effects (e.g. Petrova, 1994).

Only 13 records of synchronous co-located microbarograph and seismograph observations have been used up to now in Garmash et al. (1989), Lin'kov et al. (1989), Petrova et al. (1996), and Shved et al. (2000) and processed, to derive oscillations common to the atmosphere and the Earth in the $\sim 1-5$ h period range. These records were characterized by a strong visible variability in the signal. We have continued the processing of synchronous, co-located microbarograph and seismograph observations, by using many more records, to improve the statistical significance of the results. We did not exclude from consideration the records characterized by a weak visible variability in the signal. Our purpose in this paper is to find steady frequencies of atmospheric and seismic oscillations individually and to select from these the oscillations common to the atmosphere and the Earth. In order to examine a plausible seasonal change in oscillation appearance, we have subdivided the observational data into four parts − winter, spring, summer, and autumn records. We also discuss conceivable reasons for the oscillations observed.

2 Instrumentation

The ground pressure (p) variations have been measured with a microbarograph, made on the basis of the standard

Table 1. Time periods of synchronous co-located microbarograph and seismograph observations at St. Petersburg (60° N, 30° E), used for determining the oscillation frequencies

Season	Time periods of continuous measurements (combined duration of measurements)	Number of analyzed records
Winter	28 November 1995 – 19 January 1996 20–28 January 1996 29 November – 13 December 1997 15–25 December 1997 26 December 1997 – 30 January 1998 (120 days)	52
Spring	1 March – 29 April 1996 28 February – 7 April 1997 28 February – 15 March 1998 13–27 April 1998 (138 days)	48
Summer	30 May – 19 June 1996 2 June – 8 July 1997 25 July – 4 August 1997 23 June – 2 July 1998 8–27 July 1998 28 July – 3 August 1998 22 June – 28 July 1999 (140 days)	52
Autumn	30 August – 3 November 1996 29 August – 4 November 1997 (127 days)	48
Total	525 days	200

millibarograph M-22 (Kozhevnikova et al., 1980). As far as the seismograph is concerned, we used a Kirnos' vertical pendulum (Savarensky and Kirnos, 1955), protected from the direct effect of variations of the atmospheric pressure and temperature with a special chamber (Lin'kov et al., 1982b). The sensors of both instruments are equipped with converters which contain photodiodes. A set of filters, employed at the output of the converters, has resulted in the detection of oscillations with periods (τ) in the $\sim 0.5 - 5$ h range. For this τ range, the seismograph records vertical acceleration due to a combination of ground displacement and gravitational acceleration perturbations. The microbarograph sensitivity at the converter output was in the $1 - 5$ mWPa^{-1} range, which has enabled us to measure pressure variations as small as a few tenths of a μbar. Amplification of the seismometer channel at $\tau = 1$ h equals about 10.

3 Measurements

We have used synchronous, co-located microbarograph and seismograph measurements at St.Petersburg (60° N, 30° E), examples of which can be seen in Petrova et al. (1996) and Shved et al. (2000). The sampling time of the measurements is 1 min and the measurement periods are shown in Table 1. The observational data are grouped according to seasons, defined as two-month periods around the winter and summer solstices and the spring and autumn equinoxes. Thus, we consider records in December–January, March–April, June–July, and September–October as data for winter, spring, summer, and autumn, respectively. The observations of combined duration not less than 4 months have been used for each season. The total duration of the data analyzed is more than 17 months.

The seismic and ground pressure oscillations considered are transient. Fairly short records are required for spectral analysis so that the oscillation regime can be assumed to be quasi-steady during the records. However, it is desirable that the length T of the record would satisfy two conditions: (1) $T/\tau \geq 10$, and (2) the frequency resolution of the Fourier analysis ($\Delta \nu = 1/T$) must be less than the frequency distance between adjacent free oscillations of the atmosphere (see Sect. 6). Data from Table 1 have been divided into the short records of $2 - 3.5$ days in length. We have checked these records selectively for the steadiness of oscillation regime, in accordance with the technique described by Bendat and Piersol (1971). The testing has justified the use of the quasi-steady oscillation regime assumption. About 50 short records have been used for each season.

4 Analysis procedure

Results of our spectral analysis are represented as product spectra used for revealing the Earth's oscillations (e.g. Smylie, 1992; Smylie et al., 1993; Hinderer et al., 1995). The product spectrum, formed by multiplying many individual power spectra, enhances oscillations with steady frequencies and amplitudes that otherwise may be very small. In other words, a transient oscillation or an oscillation with varying frequency cannot be identified in a product spectrum, even in the case of its large amplitude. Synthetic tests (Petrova, 1982) have shown that the use of product spectra makes it possible to detect a harmonic signal buried in noise. A preliminary processing of the raw records was done to remove a long-term trend and the mean value of the residual signal. Finally, before we computed power spectra for the individual records, we suppressed frequencies outside each subrange with high-and low-frequency Potter filters. Furthermore, the product of the individual power spectra has been computed for each season and the complete data set. The details of a method for assessing the statistical significance of spectral peaks in the case of product spectra are given in Petrova (1982) and briefly reproduced in the Appendix.

Table 2. Frequencies of oscillations in the 42−90-min period subrange, measured by microbarograph (B) and seismomograph (S) at St. Petersburg (60° N, 30° E). Table shows the oscillations which exceed the 10% probability level (see Appendix). Close frequencies observed by both instruments are shown as bold-faced numbers

Season	Instrument	Frequencies (μHz)					Total number of peaks
Winter	B	**207**,*	219,	223,*	243,*	264,*	33
		286,	**308**,	323,*	**357**,	366,	
		377					
	S	**210**,*	231,*	251,*	272,	280,*	35
		308,*	313,	**355**			
Spring	B	**216**,	219,	**223**,*	238,*	243,*	35
		296,*	299,*	328,	346,	368	
	S	198,*	**215**,	**226**,	246,*	269,	39
		273,*	286,	322,*	388		
Summer	B	200,*	202,*	211,	241,*	247,*	34
		278,	**284**,	**289**,	328		
	S	186,*	218,	222,	229,*	250,*	32
		285,	**288**,	300,*	318,	324,*	
		337,	342,	358,	388		
Autumn	B	195,	207,*	218,	**252**,	266, *	30
		271,*	**288**,	**301**,*	314,	**319**,*	
		341,	354				
	S	226,	**252**,*	259,*	268,	276,*	30
		290,	**301**,*	**321**,*	334,	**340**,	
		361,	395				
Complete data set	B	210,	218,	**223**,*	241,*	**284**,	36
		299,*	330,	**357**,	383		
	S	**225**,	**285**,	**301**,*	**321**,*	**323**,*	39
		359					

* The oscillation was also revealed in the product spectrum of Garmash et al. (1989).

5 Results

We have restricted our consideration to two frequency sub-ranges of the ∼1–5 h period range, namely those in the 55.55–110.72 μHz and 185.15–396.5 μHz subranges (2.5–5 h and 42–90 min periods, respectively). The spectral spacings of 0.43 and 1.04 μHz for the above intervals, respectively, were used.

We searched for statistically significant oscillations among the spectral peaks which exceed the 10% probability level (see Appendix). The frequencies of these peaks and the total number of peaks in the product spectra are given in Tables 2 and 3. Figures 1 and 2 show the annual average product spectra for all the available records. Examples of product spectra for individual seasons are represented in Figs. 3 and 4.

The product spectrum of any season is generally unlike that of both any other season and also the annual average spectrum, in spite of a number of revealed coincidences in peak frequencies for different spectra. For the 42−90 min period subrange, both microbarographic and seismographic product spectra of each season and the complete data set show about 10 peaks which exceed the 10% probability level. The 10% of the total number of peaks can be of the "noise"

type, i.e. 3–4 peaks can most likely correspond to false oscillations. As for the 2.5−5 h period subrange, the number of peaks which exceed the 10% probability level varies from several to zero in the summer seismographic and autumn microbarographic spectra. Since 1–2 peaks can be achieved randomly, such a result is not statistically significant; hence, the reality of some oscillations is proved by comparing with other observations (Sect. 6).

6 Discussion

Earlier, product spectra for synchronous co-located microbarographic and seismographic records were estimated by Garmash et al. (1989). In the analysis, they used only 12 records from St. Petersburg. Both microbarographic and seismographic product spectra, in the ∼1−2 h period range, each showed 9 statistically significant peaks. The frequencies of the peaks in the different spectra were found close to each other in pairs. The coherence coefficients of the 0.66−0.85 range have been obtained by Garmash et al. (1989) for the seismic and ground pressure oscillations with close frequencies. In the overlapping range of periods, each
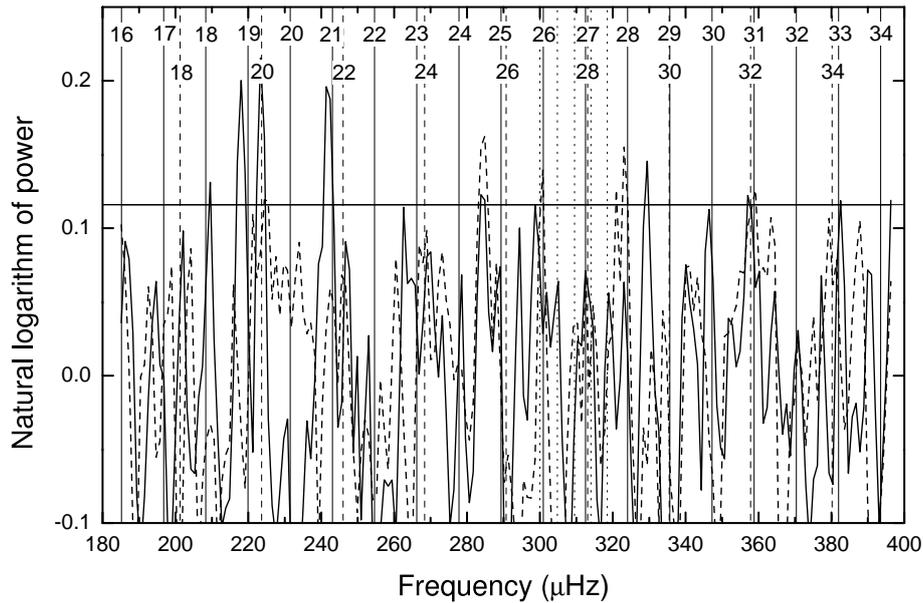
Fig. 1. Product spectra of ground pressure (continuous line) and seismic (dashed line) oscillations in the 42−90-min period subrange, obtained from all the available measurements by microbarograph and seismograph at St. Petersburg (60° N, 30° E). The horizontal line represents the 10% probability level. The vertical lines correspond to the frequencies of harmonics of the solar (solid lines) and lunar (dashed lines) day and of the $_0S_2$ mode components (dotted lines). Numbers at the vertical lines are the harmonics.

oscillation obtained by them is also revealed in one or more of the product spectra obtained here. These coincident oscillation frequencies are noted in Table 2.

Sources of the oscillations can be found in both the atmosphere and the solid Earth. On the one hand, it is common knowledge that seismographs and gravimeters respond to slow meteorological processes (e.g. Hinderer and Crossley, 2000). This is caused by both displacements of the ground due to a surface pressure change and gravity variation due to Newtonian attraction and crustal deformation from changes in the atmosphere. On the other hand, the Earth's free seismic oscillations may be thought of as forcing atmospheric ones by both ground acceleration and gravitational potential perturbation, due to vertical ground displacements and Earth's density variations (Garmash et al., 1989; Petrova et al., 1996; Shved et al., 2000).

Below we discuss plausible sources of the atmospheric and seismic oscillations observed by us. In order to search for the sources, we have analyzed oscillation observations which were made by other researchers for both period subranges. We consider not only atmospheric and seismic oscillations revealed by immediate observations of atmospheric and tectonic processes, but also solar oscillations, geomagnetic disturbances, and intradiurnal irregularities of the Earth's rotation.

There are families of spheroidal and torsional modes of the Earth's free oscillations (e.g. Aki and Richards, 1980), denoted by $_nS_l$ and $_nT_l$, respectively. Here, n is the number of nodes between the surface and the center of the Earth for the radial wave function of a mode. The integer l is the degree of the spherical surface function which describes the horizontal

structure of motions associated with the mode. The lowest frequency modes are the fundamental ($n = 0$) modes, $_0S_2$ and $_0T_2$, centered at periods of about 54 and 43 min, respectively. These modes are the only global oscillations of the solid Earth that fall within the short-period subrange considered; they are multiplets split by rotation, ellipticity, and lateral inhomogeneity into 5 components.

The $_0S_2$ multiplet lies in the range 300.0 to 318.5 μHz (55.6 to 52.3 min) (Buland et al., 1979) and is shown in Fig. 1. Analysis of vertical seismometer records by Lin'kov et al. (1982a, 1989) and that of superconducting gravimeter records by Nawa et al. (1998) have shown that the $_0S_2$ oscillation is observed not only after very large earthquakes, but also on seismically quiet days. The penetration of the $_0S_2$ oscillation into the atmosphere is demonstrated by (i) microbarograph observations of $_0S_2$ multiplet components in the spectra of ground pressure variations (Garmash et al., 1989), (ii) synchronous, co-located microbarograph and seismograph observations of a certain phase relationship for $_0S_2$ components (Shved et al., 2000), and (iii) the observation of all five $_0S_2$ components in the spectrum of the geomagnetic AE-index (Bobova et al., 1990). The latter may be interpreted in terms of the ionospheric wind dynamo (e.g. Kelley, 1989), since the 54-min wind variation in the lower thermosphere generates a corresponding current variation, leading to the 54-min periodicity in electric fields and magnetic perturbations.

For excitation of continuous spheroidal free oscillations, the atmospheric mechanism appears to be most likely (Kobayashi and Nishida, 1998; Nishida and Kobayashi, 1999). The free oscillations can be excited by meso-
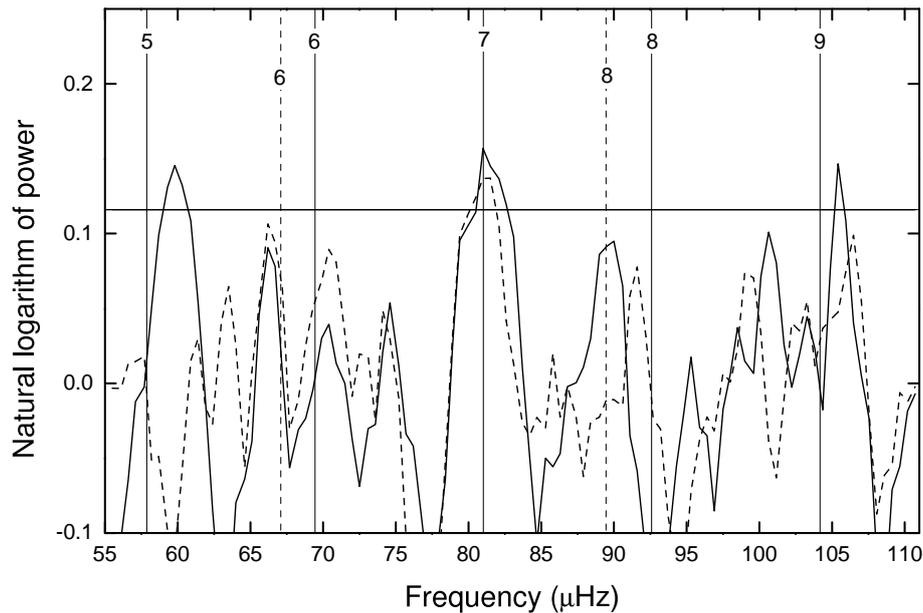
Fig. 2. As for Fig. 1 but for the 2.5−5-h period subrange.

turbulence (and perhaps macro-turbulence) of the atmosphere, which is accompanied by random space-time variation of ground pressure over the whole Earth's surface. In the case of the atmospheric excitation, a seasonal change in the appearance of the $_0S_2$ mode appears to be evident. Although the $_0S_2$ mode has been clearly observed in our product spectra (Table 2), it is not such a prominent peculiarity of the spectra as we might hope for. This is caused by an interference of the $_0S_2$ multiplet components, which are closely spaced in frequency (e.g. Aki and Richards, 1980). As a result, the observed frequencies of the $_0S_2$ components turn out to be dissimilar for different records. This fact results in a decreasing in strength of the $_0S_2$ components in the product spectra. Another result of the use of product spectra is that the $_0S_2$ peaks fall near the edges of the $_0S_2$ multiplet range, excluding the winter spectra.

As for the $_0T_2$ mode, this cannot be revealed in our product spectra with confidence, since this mode lies at the high-frequency boundary of the subrange considered. It is thought that the autumn seismic peak at $395\,\mu$Hz might be associated with the $_0T_2$ mode, despite the fact that the seismograph with vertical pendulum is not able to directly detect torsional oscillations consisting only of a horizontal displacement of the Earth's surface. The contradiction could be resolved if the penetration of a torsional oscillation into the atmosphere, due to entrainment of air by the above displacement, is taken into account. This entrainment is evidenced by observations of geomagnetic disturbances at torsional oscillation periods (Winch et al., 1963), which may be interpreted in terms of the ionospheric wind dynamo, as for the $_0S_2$ mode. The forced atmospheric oscillation must be accompanied by ground pressure variations, resulting in vertical displacements of the Earth's surface, which can be detected by the seismograph.

Theory predicts a translational oscillation of the Earth's solid inner core in the liquid outer core about the center of mass (e.g. Slichter, 1961; Crossley et al., 1992). The Earth's rotation splits the oscillation into three components, labelled as the Slichter triplet. The triplet periods depend on the Earth model, predominantly the radial density jump between the inner and outer cores of the Earth (e.g. Crossley et al., 1992). The periods fall within the $\sim$4−6 h interval for current models (Crossley et al., 1992; 1999). For example, for PREM (Dziewonski and Anderson, 1981), assuming an inviscid core, the periods are approximately 4.77, 5.31, and 5.98 h.

Unlike the seismic spheroidal and torsional modes, the Slichter triplet has never been observed following even a large earthquake. Several reports have made positive claims for triplet detection, but each time there have been objections on either observational or theoretical grounds (Crossley et al., 1999). For example, Smylie (1992) claimed the detection of the Slichter triplet at periods of 3.582, 3.768, and 4.015 h (frequencies of 77.6, 73.7, and 69.2 μHz, respectively), analyzing a product spectrum based on four European superconducting gravimeter (SG) continuous records of the $\sim$2.5−4 year length. Hinderer et al. (1995), however, found these periodicities neither in the cross-spectrum of those same four SG records, which takes into account phase information, nor in the spectra of 2-year high quality continuous records, where the noise level in the frequency band was an order of magnitude lower than in the records used by Smylie.

So, although the interval where the detection of the Slichter triplet is expected overlaps partially with the 2.5−5 h subrange considered, it is unlikely that the oscillations revealed by us are the triplet components. It should be noted that the SG spectrograms show the oscillations of unknown origin in the frequency range of interest. For example, the SG
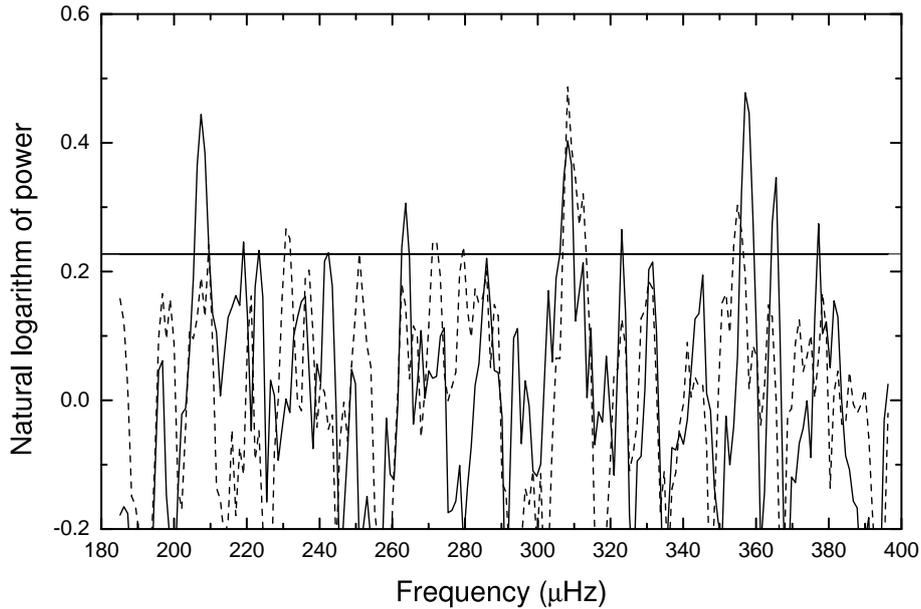
Fig. 3. Product spectra of ground pressure (continuous line) and seismic (dashed line) oscillations in the 42−90-min period subrange, obtained from winter measurements by microbarograph and seismograph at St. Petersburg (60° N, 30° E). The horizontal line represents 10% probability level.

spectrograms of Nawa et al. (1998) for stations in Antarctica, Japan, and Australia show peaks at about 0.25 and 0.35 mHz. These peaks can be correlated with some oscillations in Table 2.

Like the Earth's free oscillations, there is no upper limit for the frequencies of the normal modes of the atmosphere (Dikii, 1965; Longuet-Higgins, 1968). Observational studies of various types have identified with confidence the normal modes of the atmosphere at periods in the ∼2−20 day range (e.g. Lindzen et al., 1984). By measuring the variations of wind, pressure, density, or temperature of the atmosphere, it is difficult to detect the intradiurnal normal modes of interest, due to their small amplitudes. These modes have been detected up to a period of ∼10 h at the ground surface by barometric observations from several tropical stations (Hamilton and Garcia, 1986), up to a period of ∼7 h near the mesopause by meteor radar and optical instruments (e.g. Forbes et al., 1999b), and up to a period of ∼6 h by satellite measurements of thermospheric densities near 200 km (Forbes et al., 1999a).

As for the atmospheric normal modes in the ∼1−5 h period range, there is indirect evidence of their existence, based on the frequency separation between adjacent normal modes that are two-dimensional Lamb waves (modes) propagating only in a horizontal direction (Dikii, 1965). In the "classical" theory of free oscillations of the atmosphere (assumed to be isothermal, dissipationless, and windless), the Lamb modes are solutions of Laplace's tidal equation for an "equivalent depth" of

$$h = \gamma H, \tag{1}$$

where γ is the ratio of specific heat at constant pressure

to that at constant volume and H is the atmospheric scale height. This theory yields an asymptotic formula for the angular frequency of a normal mode,

$$\omega_l = \frac{1}{a}\sqrt{l(l+1)gh}, \tag{2}$$

in the limit of short periods, corresponding to the assumption of the non-rotating Earth (Dikii, 1965; see also Shved et al., 2000). Here, a is the Earth's radius, g is the acceleration of gravity, and l is the degree of the spherical surface function which describes the horizontal structure of motion associated with the mode. According to Eqs. (1) and (2), the frequency separation between adjacent Lamb modes (l changes 1) is about 8 μHz for $\gamma = 7/5$ and $H = 7.5$ km. The frequencies σ_l at $l = 7−13$ and $l \sim 20−50$ fall within the subranges of the 2.5−5 h and 42−90 min periods, respectively. Due to the Earth's rotation, the lth Lamb mode is a multiplet of separation in $2l + 1$ components. In the limit of short periods, the length of the frequency interval occupied by a multiplet can be approximated as:

$$\delta\omega_l = \frac{2\Omega}{l+1}, \tag{3}$$

were Ω is the angular velocity of Earth (Dikii, 1965). Petrova and Shved (2000) have just revealed the mean frequency distance close to 8 μHz between spectral peaks in the 155−290 μHz interval (57−108 min periods), by processing seismograph records with a technique that makes it possible to calculate the oscillation frequencies more accurately than by using Fourier transforms. Taking into account the fulfillment of the condition $\delta\omega_l \ll \omega_l$ for this interval, the result of Petrova and Shved may be thought of as detecting atmospheric Lamb modes by seismic observations.
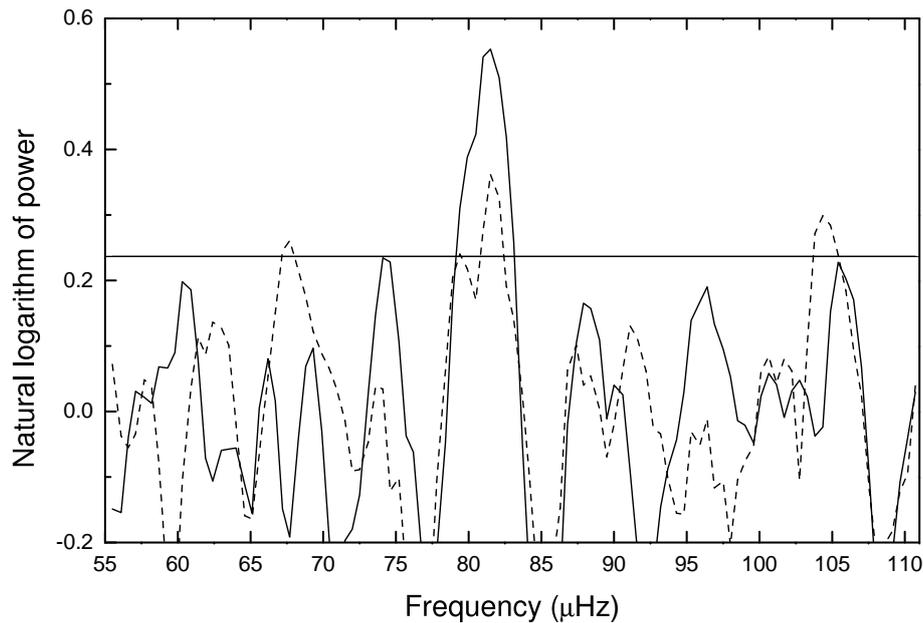
Fig. 4. As for Fig. 3 but for the 2.5−5-h period subrange and spring measurements.

It appears reasonable that some peaks of our spectra (Tables 2 and 3) are caused by the effect of atmospheric normal modes. This assumption makes it possible to associate seasonal differences in the spectra with corresponding variations in temperature and wind fields of the atmosphere. First of all, variations of these fields must result in a seasonal shift of mode frequencies. The existence of this shift can be seen from Eqs. (1) and (2), since H depends on temperature. Lindzen (1969) showed that the variations of background zonal winds can be treated as a variation of h. In accordance with Eq. (2), this means that the mode frequencies depend on background zonal winds.

Secondly, atmospheric normal modes are transient (e.g. Lindzen et al., 1984). The amplitude, lifetime, and mean pulse rate of a mode are controlled by features both of macro- and mesoscale atmospheric turbulence (forcing the mode), and by the background temperature and wind state of the atmosphere (determining the rate of oscillation decay). It is thought that the seasonal variations of this turbulence and the atmospheric state result in different sets of mode oscillations in different seasons.

The comparison of our spectra with spectra calculated for the realistic model of the atmosphere is required to reliably identify the spectral peaks observed. Modern 2-D steady-state numerical models of planetary atmospheric waves (e.g. Hagan et al., 1993; Pogoreltsev, 1999) exist, which could be extended to the period range of interest. Given the zonal wave numbers, these wave models make it possible to find the frequencies of normal modes as resonant frequencies for the response of the atmosphere to lower boundary forcing.

As noted in Sect. 4, product spectra reveal oscillations preferentially with steady frequencies and amplitudes. Since the atmospheric normal mode oscillations are transient and their frequencies vary with the atmospheric state change, it

is conceivable that the use of product spectra is not the best technique for the detection of these oscillations. This is particularly true for the annual average spectra. The processing of the available short records by the method used in Petrova and Shved (2000) may be a better way to reveal atmospheric normal modes.

The global oscillations of the atmosphere are also forced by external periodic sources. First of all, we will discuss the solar tidal harmonics, S_m, where m is the number of cycles per solar day. The harmonics result from diurnal variations of the heating of the atmosphere and ground, due to absorption of solar radiation. Their frequencies are shown in Figs. 1 and 2. Since the considered values of m are large ($m \geq 5$), it is believed that the S_m harmonics are weak and hard to detect. The detection is more probable if the frequency of S_m is close to that of an atmospheric normal mode. Nevertheless, the use of product spectra is favorable for revealing the S_m harmonics as highly steady oscillations. This is especially true regarding the annual average spectra. All three peaks of the pressure variation spectrum of the 2.5−5 h period subrange (Table 3, Fig. 2) are close in varying degrees to S_m frequencies. The peaks at 60, 81, and 105 μHz (4.6, 3.4, and 2.6 h) correspond to S_m, with $m = 5$, 7, and 9, respectively. The only peak in the seismic spectrum at 81 μHz corresponds to S_7. As seen from Fig. 1 and Table 2, some peaks of the pressure variation and seismic spectra for the 42−90 min period subrange are also very close to S_m frequencies. This is especially true for the pressure variation peaks at 210 μHz (79 min, $m = 18$) and 383 μHz (44 min, $m = 33$) and for the seismic peaks at 301 μHz (55 min, $m = 26$) and 359 μHz (46 min, $m = 31$). However, accidental proximity of the spectral peaks to the S_m harmonics must not be ruled out. For example, the 301 μHz peak is caused by the above mentioned $_0S_2$ mode oscillation.

Table 3. Frequencies of oscillations in the 2.5−5 h period sub-range, measured by microbarograph (B) and seismograph (S) at St. Petersburg (60° N, 30° E). The table shows the oscillations which exceed the 10% probability level (see Appendix). Close frequencies observed by both instruments are shown as bold-faced numbers

Season	Instrument	Frequencies (μHz)	Total number of peaks
Winter	B	60, 67	15
	S	73, 81, 100	14
Spring	B	74, **82**	13
	S	68, 79, **82**, 104	13
Summer	B	61, 90, 101	12
	S		19
Autumn	B		14
	S	98	13
Complete dataset	B	60, **81**, 105	11
	S	**81**	15

The S_m harmonics have previously been detected by observational studies of various types:

A. Smylie et al. (1993) have revealed the harmonics up to $m = 10$ in the product spectrum of ground pressure variation, based on four European continuous records of ∼2.5–4 years in length. All but S_6 were above the 95% confidence level. Moreover, the S_8 peak was found to be relatively weak. Since statistically significant oscillations at the S_6 and S_8 frequencies have not been revealed in our pressure variation spectrum, obtained from the complete data set, there is a similarity in our spectrum to that of Smylie et al. in the 2.5−5 h period interval. The observed strong nonuniformity of S_m harmonic intensities might be assumed to be caused by the different proximity of these frequencies to the frequencies of atmospheric normal modes. The closer the frequencies are, the stronger the resonant effect.

B. The S_m harmonics are also identified in SG continuous records of a similar length (Smylie et al., 1993; Hinderer et al., 1995; Florsch et al., 1995). For example, Florsch et al. have detected harmonics up to $m = 23$ from 5-year gravity records from Strasbourg.

C. Pil'nik (1984) has used classical astronomical observations of time from 1968−1978 to search for intradiurnal irregularity in the Earth's rotation. He has detected the S_m harmonics up to $m = 10$ in the nonuniformity of the Earth's rotation, using measurements in 1.2 h intervals. Once again, for the 2.5−5 h period interval there is an agreement with our pressure variation spectrum obtained from the complete data set. Namely, as distinct from the peaks for $m = 6$ and 8, those for $m = 5, 7,$ and 9 exceed the threshold 3σ, where σ is the standard

deviation of the temporal noise distribution. Similar to the pressure variation spectrum of Smylie et al. (1993), the S_6 harmonic was found from the time observations to be the least statistically significant S_m harmonic of the 2.5−5 h period interval. Since the angular momentum of the Earth and atmosphere combined must remain constant in time, Pil'nik (1989) has assumed that the S_m harmonics in the Earth's rotation might be caused by corresponding oscillations of the polar moment of inertia of the Earth.

The weakness of the forcing of the S_m harmonics with large m by solar heating does not rule out the possibility that some of them are instrumental artifacts. This reasoning is concerned with all of the above discussed observations, including our measurements. For example, the detection of a false S_m could be a result of the variation of readings due to a poorly protected instrument, resulting from the effect of air temperature diurnal change and/or from a practically imperceptible diurnal variation in electric current feeding an instrument. It is thought that the weakness of forcing the false S_m harmonics, in combination with high stability of their source, makes it possible to separate true and false S_m harmonics. As applied to our case, one might consider a S_m harmonic as being true if it is revealed in both the product spectra of one or more seasons and the annual average spectrum. By using this assumption, the 60, 81, and 210 μHz oscillations in pressure variation, and the 81, 301, and 359 μHz seismic oscillations may be considered as true oscillations of those which have frequencies very close to S_m frequencies.

The 81 μHz oscillation is identified with confidence in both the seismic and pressure spectra. Accidental proximity of this oscillation to S_7 is thought to be very probable. Petrova et al. (1996) were the first to determine the direction of the wave energy flux at the ground surface for common seismic and atmospheric oscillations. They have processed the only series of 6-day synchronous microbarograph and seismograph measurements. The coherence spectrum has shown the presence of the 81 μHz common oscillation, with an energy flux from the Earth to the atmosphere. This result arouses interest in the search for a terrestrial source for the 81 μHz oscillation.

The forcing of atmospheric oscillations at steady frequencies in the period subranges under consideration could be also due to the solar g-mode oscillations (e.g. Cox, 1990; Guenther et al., 1992). The action of the g-mode oscillations on the atmosphere could be accomplished through the corresponding oscillations in solar ultraviolet radiation absorbed by air. Unfortunately, the g-modes have not been observed with sufficient confidence and accuracy until now. The theoretical estimation of the g-mode oscillation spectrum, however, depends on the solar model used.

An exception is the 160.01-min global pulsation of the Sun, observed by systematic measurements of solar line-of-sight velocity (Kotov and Tsap, 1990; Kotov et al., 1991). The authenticity of this signal was in some doubt as 160 min is exactly the S_9 period (e.g. Elsworth et al., 1989). How-

ever, it is the 160.01-min periodicity associated with the solar oscillation that is the most statistically significant among the nearby periodicities, from the analysis of variations in the phase of the oscillations over the years 1974 to 1988 (Kotov and Tsap, 1990; Kotov et al., 1991). There is indirect evidence that this solar pulsation acts on the atmosphere. First, Bobova et al. (1985) have revealed the 160.01-min periodicity in the geomagnetic AE-index, while, second, in the $2.5-5$ h period interval, the spectral peak assigned to S_9 was found to be surprisingly strong in the spectra of both ground pressure (Smylie et al., 1993) and nonuniformity of the Earth's rotation (Pil'nik, 1984), in comparison with other S_m harmonics. The 105μHz pressure oscillation in our product spectrum (Fig. 2) is thought to also be associated with the 160.01-min solar pulsation.

Finally, we compare the frequencies of peaks in the annual average spectra (Figs. 1 and 2) with those of the lunar tidal harmonics, L_m, where m is the number of cycles during a lunar day. Some peaks are very close to the L_m harmonics. At present, we should treat this proximity as accidental.

7   Conclusion

The results of the present study can be summarized as follows:

1. The product spectra of different seasons are distinct from each other for both microbarograph and seismograph measurements. It is thought that a seasonal variation in the frequency and amplitude of the free oscillations of the atmosphere contributes to these distinctions.

2. There are seismic and ground pressure oscillations with close frequencies in the product spectra for both, for each season and when all seasons are combined. The pairs of coinciding oscillations within and close to the $300.0-318.5 \mu$Hz frequency range ($52.3-55.6$-min periods) of the Earth's $_0S_2$ multiplet may be considered to be due to the $_0S_2$ mode oscillation. However, only suggestions may be made regarding the origin of the other pairs.

3. Similar to the previous observational studies, which are of various types, both seismic and ground pressure product spectra show oscillations near the frequencies of the solar tidal harmonics, S_m. Some of these oscillations may be instrumental artifacts. The pressure oscillations at 60, 81, and 210μHz (4.6 h, 3.4 h, and 79 min; $m = 5$, 7, and 18, respectively) attract attention as those which are seen in both the spectra of one or more seasons and the annual average spectrum. The accidental proximity of these oscillation to S_m must not be ruled out. It should be emphasized that the 81μHz oscillation is also revealed with confidence in the seismic spectra.

4. The 105μHz pressure oscillation revealed in the annual average spectrum may be considered to be associated with action of the 160.01-min solar pulsation on the terrestrial atmosphere.

We think that increasing the number of records used for the product spectrum calculation will not result in qualitatively new findings. However, it is believed that further progress in the study of common seismic and atmospheric oscillations may be made by the simultaneous processing of the pairs of synchronous microbarographic and seismographic or SG records taken in great number. For example, an improvement would be expected regarding the origin of the common seismic and atmospheric oscillations if the separation of the oscillations by direction of wave energy flux was made, in the manner proposed in Petrova et al. (1996). In a later paper, we intend to report the results of a similar study based on all the available records.

Appendix A   Method for assessing the statistical significance of spectral peaks in the case of product spectra

The product power spectrum $[S(\omega)]$ is formed by multiplying n individual power spectra $[s_i(\omega)]$,

$$S(\omega) = \sqrt[n]{\prod_{i=1}^{n} s_i(\omega)}, \qquad (A1)$$

where ω is the angular frequency and i is the index denoting an individual record. The ith power spectrum

$$s_i(\omega) = a_i^2(\omega) + b_i^2(\omega), \qquad (A2)$$

where $a_i(\omega)$ and $b_i(\omega)$ are the coefficients of Fourier-series expansions in cosines and sines, respectively. For assessing the statistical significance of harmonics of the $S(\omega)$ spectrum, the analysis of $\ln S(\omega)$ is convenient to use,

$$\ln S(\omega) = \frac{1}{n} \sum_{i=1}^{n} \ln s_i(\omega). \qquad (A3)$$

We compare the $\ln S(\omega)$ spectrum obtained from observations with that of a hypothetical process.

It is reasonable to suppose that the hypothetical process is a random one which satisfies the two conditions.
Condition 1. The quantities $a_1, a_2, \ldots, a_n$ and $b_1, b_2, \ldots, b_n$ for some ω are considered as samples drawn from the normal universe. In this case, the density of probability is given by:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma_x} \exp\left[-\frac{(x - \mu_x)^2}{2\sigma_x^2}\right], \qquad (A4)$$

where x is the common designation for the variables a and b, μ_x is the universe mean, σ_x^2 is the universe variance (e.g. Hudson, 1964).
Condition 2. The statistical characteristics of harmonics do not depend on ω. In particular, the parameters μ_x and σ_x are not dependent on ω.

We use the value of χ^2 for two degrees of freedom,

$$u = \sum_{k=1}^{2} \left(\frac{x_k}{\sigma_x} \right)^2, \tag{A5}$$

where x_k is the quantity which is drawn at random from the normal universe (e.g. Hudson, 1964). Comparing (A5) with (A2), we obtain that

$$s_i(\omega) = \sigma_x^2 u. \tag{A6}$$

The density of probability for u is

$$\varphi(u) = \frac{1}{2} \exp\left(-\frac{u^2}{2} \right) \qquad (0 \le u < \infty). \tag{A7}$$

Using (A7), we obtain the density of probability

$$g(y) = \frac{1}{2\sigma_x^2} \exp\left(y - \frac{e^y}{2\sigma_x^2} \right) \qquad (-\infty < y < \infty) \tag{A8}$$

for the random value of

$$y = \ln s(\omega). \tag{A9}$$

The mean and variance of y are

$$\mu_y = \psi(1) + \ln(2\sigma_x^2) \tag{A10}$$

and

$$\sigma_y^2 = \psi'(1) = \frac{\pi^2}{6}, \tag{A11}$$

respectively, where $\psi(z)$ is the logarithmic derivative with respect to gamma function, $\psi'(z)$ is the derivative with respect to $\psi(z)$.

Using (A9), expression (A3) can be rewritten as

$$\bar{y} = \frac{1}{n} \sum_{i=1}^{n} y_i, \tag{A12}$$

where

$$\bar{y} = \ln S(\omega) \tag{A13}$$

is the sample mean for n quantities of y. The central limit theorem (e.g. Hudson, 1964) applies to $\bar{y}$. In the limit of $n \longrightarrow \infty$ the values of $\bar{y}$ are, therefore, normally distributed with mean

$$\mu = \mu_y = \psi(1) + \ln(2\sigma_x^2) \tag{A14}$$

and variance

$$\sigma^2 = \sigma_y^2/n = \pi^2/6n. \tag{A15}$$

Hence, the probability

$$p[(\bar{y} - \mu)/\sigma > \zeta_p > 0] = \sqrt{\frac{2}{\pi}} \int_{\zeta_p}^{\infty} \exp(-\frac{t^2}{2}) dt \tag{A16}$$

in this limit. It should be noted that the value of μ depends on the σ_x^2 parameter of the random process considered. The analysis of the $\ln S(\omega)$ spectra derived due to computer simulation of a random process has shown that the distribution of $\bar{y}$ and the value of σ^2 may be approximated by the normal distribution and expression (A15), respectively, at $n > 10$.

It should be taken into account that the $S(\omega)$ spectrum obtained from observations is calculated for N quantities of frequency, ω_j. Using Condition 2, the N values of $\bar{y}_j[= \bar{y}(\omega_j)]$ may be considered as the sample of $n(=N)$ quantities of $\bar{y}$. Correspondingly, μ may be approximated by

$$\mu = \frac{1}{N} \sum_{j=1}^{N} \bar{y}_j. \tag{A17}$$

In the case of large N, expression (A16) with (A17) can be used to assess the statistical significance of harmonics ω_j, characterized by a sufficiently large value of $(\bar{y}_j - \mu)/\sigma$. Using (A16), we find the value of ζ_p, corresponding to a sufficiently small p. This value is designated as the $100p\%$ probability level. It is believed that the statistically significant harmonics are found among n_p harmonics with $(\bar{y}_j - \mu)\sigma > \zeta_p > 0$, if n_p/N is considerably more than p.

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