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On the Ultra Long Propagation of Felt Ground Motion Due to the M_w 8.3 Deep-Focus Sea-of-Okhotsk Earthquake of May 24, 2013

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Abstract—This study uses macroseismic data and wave equations to solve the problem of ultra long propagation of felt ground motion (over 9000 km from the epicenter) due to the Sea-of-Okhotsk earthquake. We show that the principal mechanism of this phenomenon could be excitation of a previously unknown standing radial wave as a mode of the Earth's free oscillations, ${}_0S_0$, due to the superposition of an incident and a reflected spherical *P* wave in the epicentral area of the Sea-of-Okhotsk earthquake. The standing wave generates slowly attenuating *P* waves that travel over the earth's surface that act as carrying waves; when superposed on these, direct body waves acquire the ability to travel over great distances. We show previously unknown parameters of the radial mode ${}_0S_0$ for the initial phase of earth deformation due to the large deep-focus earthquake. We used data on the Sea-of-Okhotsk and Bolivian earthquakes to show that large deep-focus earthquakes can excite free oscillations of the Earth that are not only recorded by instrumental means, but are also felt by people, with the amplification of the macroseismic effect being directly related to the phenomenon of resonance for multistory buildings.

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INTRODUCTION

The present paper is concerned with an analysis of the data relating to the macroseismic effects of the large deep-focus Sea-of-Okhotsk earthquake of May 24, 2013 (M_w = 8.3, h = 630 km). The goal of the present study is to determine why felt ground motion can travel for ultra-long distances in a radius of approximately 9000 km around the epicenter. An explanation of this effect was briefly given in (Kuzin et al., 2016), while the present paper provides additional seismic information and a more detailed discussion of the issue.

The instrumental seismological observation for more than 100 years (since 1911) has recorded a single earthquake that had a similar effect, which is the deep-focus Bolivian event of June 9, 1994 (h ~640 km, M_w = 8.3). However, felt shaking was only recorded north of the epicenter at distances of between 5050 and 8680 km, i.e., for a length of 3600 km, while macroseismic information is available for 22 sites only. Because no information is available for the near zone (distances below 5000 km), it was difficult to find the cause of the observed effect. For this reason investigators hypothesized that the propagation of felt ground motion is affected by, on the one hand, a high-Q mantle beneath the northeastern United States and Canada and, on the other hand, poor soil conditions and higher residential buildings (Anderson et al., 1995).

One substantial difference for the situation with the Sea-of-Okhotsk earthquake compared with the Bolivian earthquake is that it was the first time in the history of instrumental seismological observations that records of a large deep-focus earthquake were acquired in the assumed near zone (in the range 378–1320 km, stations Petropavlovsk and Yuzhno-Kuril'sk) and for distances of 5470–7500 km (Arti and Garni stations), according to data provided by the Geophysical Survey of the Russian Academy of Sciences (GS RAS) [http://www.ceme.gsras...]. According to data acquired at the Global Seismic Network (GSN), the ground motion due to the Sea-of-Okhotsk earthquake was recorded at distances of 1390–9100 km [http://rev.seis.sc.edu/...]. In addition, seismologists in Kamchatka conducted telephone and internet surveys to acquire macroseismic data, at first for 160 sites at distances below 9000 km west-southwest of the epicenter and for 9470 km southeast of it (Ivanova et al., 2013) and later for additional 202 sites. Approximately 52% of all the data (104 sites) were for distances over 3000 km. In our case we cannot explain why felt ground motion could travel over ultra long distances only by invoking higher Q in the earth and local conditions (soils and taller buildings). The hypothesis that vast seismic energy released by the Sea-of-Okhotsk earthquake was the cause (1.78×10^{17} J) is not valid, because even such mega earthquakes as the March 11, 2011 Japanese event ($M_w = 8.9$, $E = 1.41 \times 10^{18}$ J) did not send their felt ground shaking farther than 1300 km [www.emsc-scem.org...]. Taking the case of the Sumatra–Andaman earthquake of December 26, 2004 ($M_w = 9.2$, $E = (1–2) \times 10^{18}$ J) (Lay et al., 2005), we find that the distance was approximately 2500 km [http://neic.usgs.gov...]. One notes that the records are dominated by the P waves on the z-component, not only at Russian stations at distances of 5470–7500 km (Fig. 1a) [http://www.ceme.gsras...] but also at GSN stations at distances of 1390–9100 km (see Fig. 1b) [http://rev.seis.sc.edu/...]. One also observes the peak accelerations on this component to be greater than those on the horizontal channels in the range $\Delta = 10°–175°$, as can be seen in a map from (Anderson et al., 1995). These data suggest a substantial role of P waves in producing the macroseismic anomaly of the Sea-of-Okhotsk earthquake. Since the macroseismic data provide a significant contribution to the overall picture of the phenomenon, they deserve special consideration.

The data. The data set was based on materials from the seismological surveys of the Russian Federation, the US (USGS), and of the European-Mediterranean Seismological Centre, as well as data from information agencies (RIA-Novosti in the first place), scientific publications, and information from the Internet.

The method. An analysis of original macroseismic data using wave equations (see, e.g., Gorelik (2007)), as well as data on the Earth's free oscillations (Zharkov, 1983).

RESULTS

A Description of the Macroseismic Data

Detailed descriptions of the macroseismic effects of the Sea-of-Okhotsk earthquake for Kamchatka (Δ ~800 km) can be found in (Ivanova et al., 2013; Chebrov et al., 2013; Chebrova et al., 2015). For this reason the present paper will focus on the global macroseismic effects of the earthquake.

The first information on the global distribution of felt effects due to the Sea-of-Okhotsk earthquake came from reports of the Seismological Survey of Russia (GS), America (USGS), and of the European-Mediterranean Seismological Centre (EMSC).

According to these data, the surveys had found, before the end of May 2013, shaking of intensity between II and III–IV at approximately 50 sites of Eurasia (Russia, southern Europe, Japan, China, Indonesia, and the UAE). For the western hemisphere such information was available for 12 sites, mostly in North America (the US, Canada, and Mexico). Later internet questionnaires yielded a very detailed list of intensity distribution over the same regions (Ivanova et al., 2013; Chebrova et al., 2015).

One rather unusual feature of the above list consists in the absence of any relationship between the level of ground shaking and the distance to the epicenter of the Sea-of-Okhotsk earthquake. As an example, shaking of intensity II was recorded at distances between 710 km (Talaya, Sakhalin I.) and 9470 km (Ixtaczoquitlán, Mexico), intensity II–III was recorded between 720 km (Tungor, Sakhalin I.) and 7420 km (Novorossiisk, Russia), and intensity III was recorded between 150 km (Sobolevo, Kamchatka) and 8255 km (Dubai, UAE). The range of distance rapidly decreases with increasing intensity; III–IV between 270 km (Ust'-Bol'sheretsk, Kamchatka) and 1835 km (Blagoveshchensk, Russia), intensity IV between 140 km (Krutogorovo, Kamchatka) and 1190 km (Aniva, Sakhalin I.), intensity IV–V between 300 km (Apacha, Kamchatka) and 1180 km (Gornoe, Kuril Is.). Along with these, one notes anomnalous ground shaking of intensity IV–V at a distance of 6716 km (Goleta, US) and III–IV at 7706 km (Rock Island, United States), as well as intensity III at 8255 km (Dubai, UAE). It is not known why abnormally high intensities were observed in the first two cases, while for Dubai the cause was the response of the world highest building, a 880-m tower. It is somewhat counter-intuitive to have intensity III at Ixtaczoquitlán compared with the long list of intensity II reports at shorter distances (Chebrova et al., 2015). In addition, all reports labeled *felt* should have been classified as intensity II cases, as defined in all macroseismic scales.

An Interpretation of Records of the Sea-of-Okhotsk Earthquake

Since all macroseismic information is based on subjective estimation, a realistic interpretation of such information requires objective data in the form of instrumental records at a variety of epicentral distances. With this in view, the present section will be concerned with records of the Sea-of-Okhotsk earthquake made at stations deployed in different geographic regions worldwide.

In this work one should not neglect the experience with records of North American stations due to the Bolivian earthquake of June 9, 1994 (h ~ 640 km, $M_w = 8.3$), which occurred before the Sea-of-Okhotsk event, at epicentral distances of 5050–8685 km where felt ground motion was roughly II–III on the Mercalli scale (Anderson et al., 1995). One significant circumstance in this case was that the start of felt shaking at each site was coincident with the arrival of P waves at the nearest seismic station. This group of waves lasted for below 40 s and was formed of direct P waves arriving at distances greater than 5650 km. The seismic effect was due to ground motion excited by P waves, with peak acceleration between 0.2 Gals at a distance of 5050 km and 0.03 Gals at 7400 km. However, these

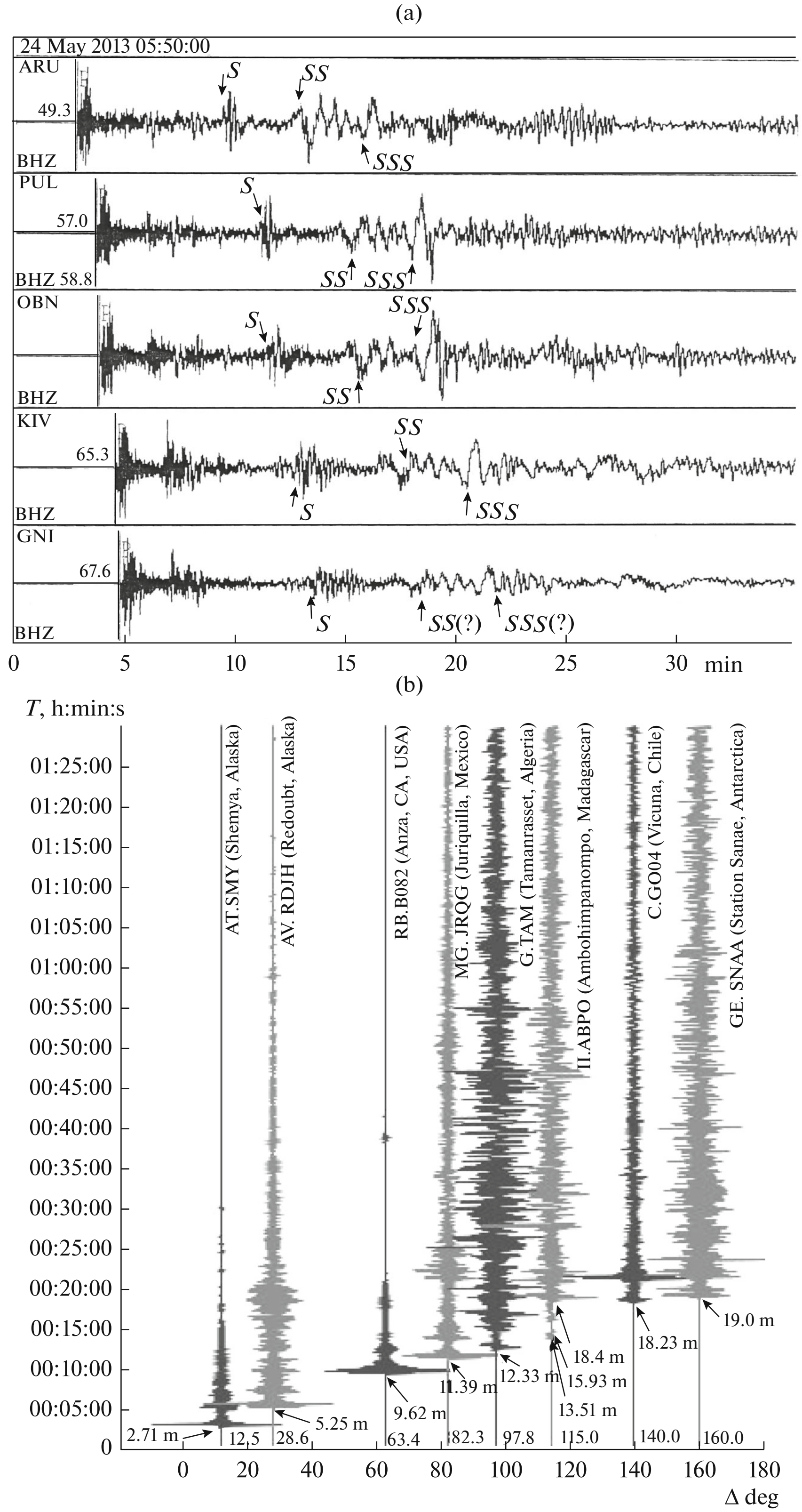

Fig. 1. The records of the Sea-of-Okhotsk earthquake: (a) at distant stations (Δ = 5470–7500 km) operated by the Unified Network of Seismic Observation, GS RAS [http://www.ceme.gsras.ru...]: Arti (ARU), Pulkovo (PUL), Obninsk (OBN), Kislovodsk (KIV), and Garni (GNI); (b) at some stations of the worldwide network (Δ = 1390–9100 km), see [http://rev.seis.sc.edu...]. Station codes are shown at the appropriate records, the numerals denote distances to the epicenter, the arrows with numerals give *P*-wave onsets and the appropriate times in minutes.

data are not very reliable, because real excitation should be found from the acceleration that is the mean over the entire *P*-wave group, since peak accelerations cannot excite the real seismic effect because they are very short. Along with the steady decay of acceleration at increasing distances, the above authors also noted an increase at sites on unconsolidated soils.

Among the causes that have produced ultra long propagation of felt ground motion, Anderson et al. (1995) mentioned the following:

(a) a more complex geometric spreading of seismic waves due to the Bolivian earthquake at critical distances (without further specifications);

(b) high regional coefficients of mechanical *Q* for the northeastern United States and Canada after (Der and McElfrish, 1977); most felt reports came from these regions;

(c) soil conditions and peculiarities of the buildings (many stories). Most reports came from those residing at upper stories.

The most detailed description of the macroseismic effect due to the Sea-of-Okhotsk earthquake is that for Moscow. Rogozhin et al. (2013) used reports from over 100 Moscow residents obtained by researchers at the Institute of Physics of the Earth, Russian Academy of Sciences to infer that felt shaking was mostly observed in buildings of 5–6 stories or higher. Similar information on a worldwide scale can be found in (Ivanova et al., 2013; Chebrova et al., 2015). In some cases, shocks also caused physiological effects like dizziness and nausea. To this should be added that Moscow felt three shocks due to the Sea-of-Okhotsk earthquake, with each lasting a few seconds over a span of 10–15 min (Rogozhin et al., 2013), which means that the excitation was not instantaneous, hence it could not be determined which of the shocks produced the physiological effect.

Brief Information on the Earth's Free Oscillations

Since this paper considers the possibility that the radial mode of the Earth's free oscillations (${}_0S_0$) could have affected the propagation of felt ground motion, we feel it necessary to provide a short account of the relevant section in the geosciences.

The first scientist to discover the Earth's free oscillations was Hugo Benioff (1958) who examined strainmeter records of the 1952 Kamchatka earthquake ($M_w = 9.0$), while final proof was obtained from an analysis of records of the great Chilean earthquake of 1960 with $M_w = 9.5$ (Benioff et al., 1961). Some information became available in the 1970s suggesting that such free oscillations could be excited even by magnitude 6.5 earthquakes or slightly greater (Block et al., 1970).

Theoretical research in the Earth's free oscillations undertaken by two teams of American investigators immediately on the discovery resulted in the subject becoming a major special section of the geosciences. Several applications can be found in (Bullen, 1963; Aki and Richards, 1980, among others).

It was known previously that there are two kinds of free oscillations of the Earth, that is, spheroidal (*S*) and toroidal (*T*) oscillations. Material particles in a spheroidal wave involve both a longitudinal component along the direction of propagation (*P* wave) and a transverse component, perpendicular to that direction (*SV* wave) in the plane of incidence of the *P* wave. The longitudinal component has an amplitude 1.47 times that of the shear wave, with the result that the combined motion is along a vertically elongate ellipse and is retrograde (Bullen, 1963; Savarenskii, 1972).

The motion in a toroidal wave is in the horizontal plane, perpendicularly to the direction of propagation (*SH* wave). The particle motion is similar to that for Love waves, i.e., on spheres of different radii (Bullen, 1963; Bolt, 1982).

The frequencies (periods) of free oscillations are denoted by two indices, a latitudinal one *n*, that is, the angular order (the right index) and by *j*, or the overtone number (the left index). Depending on the numerical values of these indices, we determine the order or mode of spheroidal and toroidal oscillations. As an example, the notation ${}_0S_2$ and ${}_0T_2$ denotes the fundamental modes of spheroidal and toroidal oscillations, with the figure of the Earth being deformed to become a spheroid in the former case, while the mode ${}_0T_2$ has a single surface that dissects the Earth along the equator and divides it into two hemispheres in relative motion. An increasing index *n* for spheroidal oscillations means that the Earth is deformed to make more complex geometrical figures; when $n = 0$ (${}_0S_0$), the spheroidal oscillations degenerate into radial oscillations where the motion is along the radius. For the toroidal oscillations an increasing *n* involves a diminution of the radius of the moving surface. It was found that the oscillations in the fundamental modes ${}_0S_2$ and ${}_0T_2$ have no volumes with zero amplitudes (nodes), while the overtones have more nodes with increasing *j*; $j = 1$, a single node, $j = 2$, two nodes; and so on. In addition, the increase in *n* produces higher modes and that in *j* produces overtones of higher orders, with the depth of penetration into the Earth's interiors decreasing (Zharkov, 1983).

Numerical calculations for Bullen's model A revealed that the periods of spheroidal oscillations of higher orders ($n \geq 20$) were identical with the periods of Rayleigh waves (Bullen, 1963; Savarenskii, 1972). From this it follows that, when $n > 20$, each spheroidal oscillation (harmonic) can be regarded as an interference of two waves of equal amplitudes that are propagating from the source in opposite directions. A similar picture would arise in Love waves for toroidal oscillations. The result was to derive fundamental relations that connect wavelength λ and phase velocity of these harmonics to period *T* and the number *n* for the steady state oscillations (Zharkov, 1983): $C_n = 2\pi R/(n + 1/2)T)$, $\lambda_n = 2\pi R/(n + 1/2)$, where R is the mean radius of the Earth in km and T is the period in seconds. As an example, the phase velocity for the harmonic ${}_0S_{20}$ with a period of 5.8^m (Bullen, 1963) is 5.61 km/s, with the wavelength being 1952 km.

To sum up, the high frequency harmonics of the Earth's free spheroidal oscillations characterize this type of oscillation for the upper part of its shell (crust and mantle), while the characteristics of low-frequency spheroidal harmonics (n <10) substantially depend on the properties of the earth as a whole (Bullen, 1963). This is the reason that the above relations do not apply to this case.

The observed period for the fundamental spheroidal mode ${}_0S_2$ is 54 min, while that for the toroidal mode ${}_0T_2$ is 44 min. The "irregular" mode ${}_0S_0$ has a period of 20.46 min; this mode involves displacement along radii, so that the Earth is breathing, as it were [www.iris.edu/hq/publications]. This value of the period is roughly the time of travel the strain wave takes to go along the Earth's diameter from an epicenter in the hemisphere where the earthquake occurred to its antipode (apocenter) in the other hemisphere (20.2 min).

It is known that the Earth's spheroidal oscillations affect the volume and shape of our planet, hence they are related oscillations of the elastic and the gravity field. At the same time, toroidal oscillations exert no effect of this kind, so that spheroidal oscillations can be recorded both by seismographs and gravity meters, while toroidal oscillations can be recorded by seismographs alone. As a consequence, the two modes are easily distinguished on records of long-period seismographs (Bullen, 1963).

On Determining the Radial Mode of the Earth's Free Oscillations ${}_0S_0$

In the previous part of this paper we hypothesized the superposition of body P waves on the radial mode ${}_0S_0$ as the most likely cause of ultra long propagation of felt motions. Clarification of this issue requires the statement and solution of the problem concerning the radial mode of the Earth's free oscillations as excited by the Sea-of-Okhotsk earthquake. The above discussion of seismological and macroseismic data led us to formulate the following two propositions toward the solution of the problem:

(1) The dominance of the P wave group on records of worldwide and Russian networks at distances of 12.4°–82.0° (1380–9100 km), which shows that the seismic effect is due to waves of this group (see Figs. 1a and 1b).

(2) The coincidence of the start of felt motion with the onsets of P waves at the nearest station as found for records of the deep-focus Bolivian earthquake of 1994 (Anderson et al., 1995).

The problem of excitation of the radial mode by deep-focus earthquakes has not been formulated in this aspect previously. The available equations for describing the fundamental radial mode ${}_0S_0$, both those which were derived immediately after the discovery of the Earth's free oscillations (Pekeris and Jarosh, 1958) and later (Bullen, 1963), were devised for determining the frequencies (periods) of steady state oscillations during 3–4 months (Bolt, 1982) and longer, until 5 months (Okal, 1996). As an example, taking an average homogeneous gravitating earth, Pekeris and Jarosh (1958) derived an equation for the radial mode ${}_0S_0$ as follows: $d^2U/dx^2 + (2/x)(dU/dx) - 2U/x^2 + k^2U = 0$. Its solution is $\tan x/x = 1/(1 - x^2/4(2 + \lambda/\mu))$, where $x = ka$, $k^2 = \rho(\omega^2 + 4A)/(\lambda + 2\mu)$, $\mu = 1.463 \times 10^{12}$ dyn/cm^2, $\lambda/\mu = 2.402$, $\rho = 5.52$ g/cm^3, $A = 4\pi G\rho/3 = 1.5424 \times 10^{-6}$ s^{-2} is the gravitational potential, $G = 6.67 \times 10^{-8}$ Newton's gravitational constant, a is Earth's radius, k is the bulk modulus, and ω is the circular frequency. All the above values are in CGS units. The first two roots of this equation are $x_1 = 2.788$ and $x_2 = 6.132$. In the basic model the period of the fundamental mode ${}_0S_0$ is 26.7 min, while that of the first overtone ${}_1S_0$ is 10.6 min. For the real Earth these periods are shorter, being 20.7 min and 10.1 min, respectively.

A similar equation of free oscillations for a homogeneous earth model with a constant density ρ_0 and bulk modulus k and shear modulus μ can be found in (Bullen, 1963).

In attacking our problem for the initial phase in the excitation of the radial mode ${}_0S_0$, we based our approach on an analysis of wave equations in the physics of oscillations and waves as set forth in the well-known works of Bullen (1963) and Gorelik (2007).

Consider the excitation of a spherical wave due to the impulse in the rupture zone of the Sea-of-Okhotsk earthquake (1.78×10^{17} J). Since we are primarily interested in the propagation of this disturbance along the Earth's radius to the ground surface at the epicenter and toward the interiors of the Earth, in the opposite direction to the apocenter at the antipode surface, we shall use D'Alembert's equation for the one-dimensional case (Bullen, 1963): $\partial^2y/\partial t^2 = c^2\partial^2y/\partial x^2$. For the case of a medium having a spherical symmetry and centered at 0, with distance r from the source, the equation can be transformed to the form $\partial^2(ry)/\partial t^2 = c^2\partial^2(ry)/\partial r^2$; its solution can then be written down as a sum of two functions: $y(r, t) = r^{-1}[f(ct - r) + F(ct + r)]$. The first term denotes the phase of a spherical wave that travels out from the source and the second term is the phase of the wave that converges toward the source. When the medium is uniform, the latter wave has no physical meaning, being acceptable only when reflected at an interface (Gorelik, 2007). Recalling that, when $\omega = 2\pi/T$, $\lambda = 2\pi/k$, where ω is circular frequency and k the wavenumber, one can represent the phase velocity c = λ/T as $c = \omega/k$. Then, the general solution of the equation would assume the form $y(r, t) = r^{-1}[f(\omega t - kr) + F(\omega t + kr)]$. As a harmonic spherical wave is propagating in the earth, the material particles are oscillating as *cos* or *sin*. We shall use the former law, because in our case the amplitude of the initial pulse is different from zero. The expression for a diverging spherical wave would then be $y_1(r, t) = A_o r^{-1}\cos(\omega t - kr + \varphi_o)$, where A_o is the initial amplitude, r^{-1} is the spreading coefficient for the wave front, and φ_o is the initial phase of motion that is not incorporated for propagation of the motion. When the medium is attenuating, one introduces the factor $e^{-\alpha r}$, where α is the attenuation coefficient (discussed in more detail below). The elastic pulse in the form of a diverging spherical wave due to the Sea-of-Okhotsk earthquake took 73.8 s (1 min 13.8 s) to travel from the source to the earth's surface at the epicenter at an average velocity of 8.54 km/s. Since the earth's surface is a perfect reflector, the incident wave excites an intensive reflected wave, $y_2(r, t) = A_o r^{-1}\cos(\omega t + kr)$, with a comparable amplitude. The reflected wave is superposed upon the incident wave to make a stationary wave $y_1 + y_2 = 2A_o\cos kr \cdot \cos\omega t$, which is a standing radial wave (Bullen, 1963). The expression $2A_o\cos kr$ characterizes an amplitude that attains the maximum $2A_o$, while $\cos\omega t$ characterizes synchronous oscillations of the Earth (Bullen, 1963). In application to the Sea-of-Okhotsk earthquake, the superposition of an incident elastic wave excited by the earthquake and the wave reflected from the surface at the epicenter means the experimental occurrence of an arising radial standing wave ${}_0S_0$ that was not known before. This result is of fundamental importance and leads to several corollaries.

(1) As the Earth began to be deformed by the source pulse of the large deep-focus Sea-of-Okhotsk earthquake, a previously unknown standing radial mode of the Earth's free oscillations was discovered (${}_0S_0$), supplementing those previously considered to be the main modes: the spheroidal mode ${}_0S_2$ due to Rayleigh waves and the toroidal mode ${}_0T_2$ due to Love waves (Zharkov, 1983; Bolt, 1982). Up to now the mode was thought to be "irregular" and was treated as a degenerated spheroidal mode, as it has lost its transverse (azimuthal) component (Zharkov, 1983).

The generation and evolution of a standing radial wave ${}_0S_0$ can be illustrated by the well-known example of a vibrating string, which is also described by D'Alembert's equation (Gorelik, 2007). A pull in the middle of a string fastened at both ends produces a disturbance that is similar to a standing wave whose maximum displacement (antinode) occurs at the center of it. The superposition of an incident and a reflected elastic wave is replaced with an outside force as the motion of a hand. The antinode is immovable, while disturbances are propagating as traveling waves from the center to the ends. The sum of the lengths of these waves is the length of the standing wave in the string, and the sum of the travel times is its period. However, the analogy is acceptable only for the initial phase of string vibration, since subsequent reflections from the ends produce overtones (Gorelik, 2007).

(2) The antinode of the standing radial wave ${}_0S_0$ due to the superposition of an incident and a reflected spherical P wave occurs at the epicenter. Perhaps for that reason the coseismic vertical ground displacements in the epicentral area of the Sea-of-Okhotsk earthquake showed the largest amplitudes of all previously known events as recorded in GPS observations (between +12 and −18 mm, with the range being 30 mm), after (Shestakov et al., 2014). At the same time, the antinodes of the spheroidal and toroidal modes are due, as pointed out in the preceding section, to the superposition of reversed traveling surface waves, (Rayleigh and Love waves) at distances of up to 10 000 km from the epicenter (Bolt, 1982).

(3) Since a standing wave reflects the frequency aspect of an oscillatory process, it is stationary over time and in space and cannot carry energy. This function is performed by traveling *P* waves into which it decomposes (see above) that propagate over the Earth's surface from the epicenter to the seismic "equator." The equations for radial traveling *P* waves have the following form (Gorelik, 2007): $y_3(r, t) = A_o\cos(\omega t - kr)$ and $y_4(r, t) = A_o\cos(\omega t + kr)$. One characteristic feature of a traveling wave is that its phase and velocity are constant. The requirement for constancy of phase for an outgoing wave $\omega t - kr = C$, (C = constant) allows one to find its velocity on differentiation with respect to t: $\omega dt - kdr = 0$ and

$$dr/dt = \omega/k = \lambda/T = v. \quad (1)$$

According to the macroseismic data, the first traveling wave propagates ESE of the epicenter for the farthest site with shaking intensity II for a distance of 9470 km (Ixtaczoquitlán) and the second propagates WSW for a distance of 8385 km (Milan) (Chebrova et al., 2015) (Fig. 2). Kuzin et al. (2016) set the distance to the farthest site toward the WSW equal to 9000 km (Dubai), according to the data in (Ivanova et al., 2013). As a later paper revised the distance to Dubai (8255 km), Milan was chosen as the farthest site. For this reason, all subsequent estimates of wavelength, period, and phase velocity have been diminished.

The Jeffreys–Bullen tables give $11^m32.7^s$ as the time of travel to Ixtaczoquitlán and $10^m42.6^s$ as the time to Milan. In that case the wavelength of the mode ${}_0S_0$ found as the sum of the lengths of the traveling waves is 17 855 km, while the total travel time or period is $22^m15.3^s$. However, it was pointed out at the beginning of the present section that the standing radial wave came into being $1^m13.8^s$ (73.8^s) later compared with the time of occurrence of the earthquake. It follows

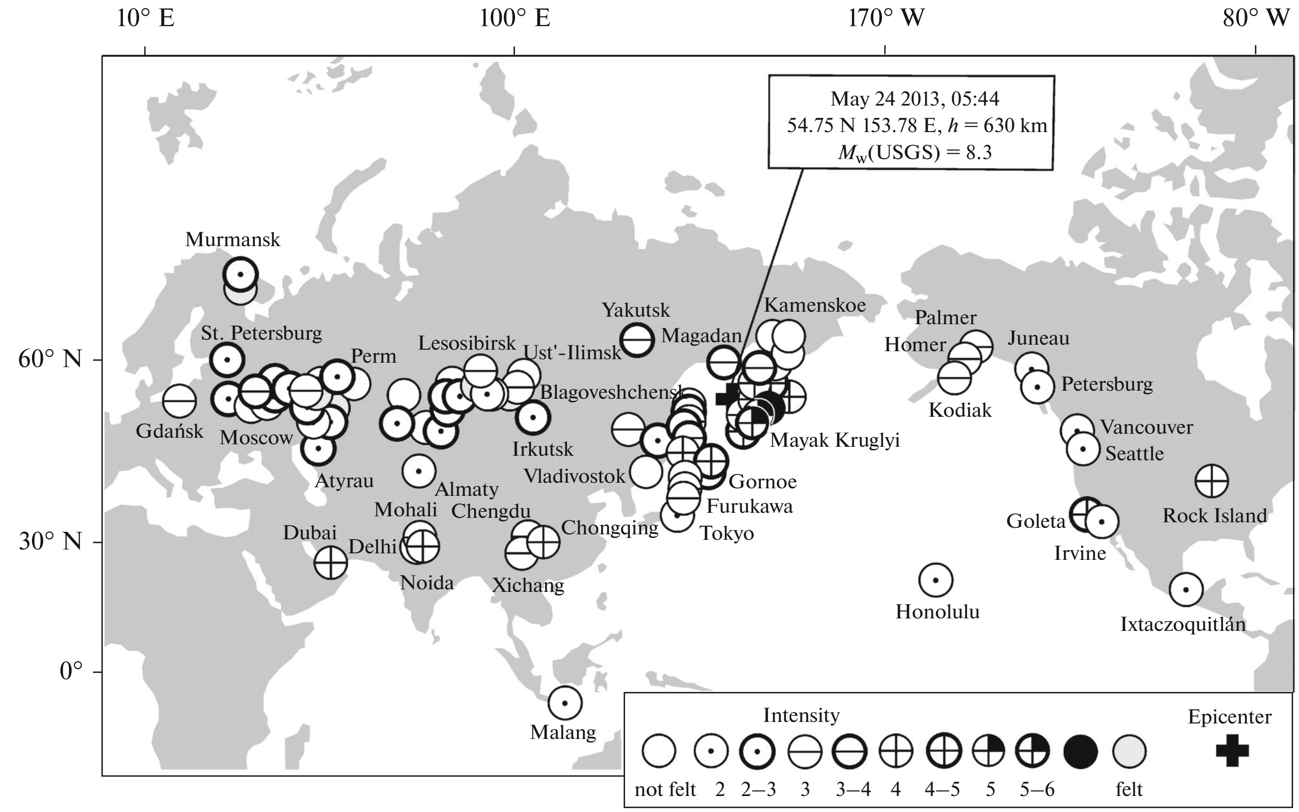

Fig. 2. The macroseismic effect of the Sea-of-Okhotsk earthquake after (Ivanova et al., 2013) with modifications.

that the total time it takes to be formed (period) must be diminished by $2^m 27.6^s$, i.e., it must equal $19^m 46.7^s$ (19.78^m). This value is very close to the period of the radial mode ${}_0S_0$ in the Earth's free oscillations as a whole based on the record of the Sea-of-Okhotsk earthquake made at the Obninsk station (20.47^m) (Molodenskii et al., 2014).

From relationship (1) with the values $\lambda = 17855$ km and $T = 19.8^m$ (1187.7^s) we obtain that the phase velocity of the radial mode is 15.03 km/s. This result, when combined with the fact that the standing radial wave occurred at the epicenter of the Sea-of-Okhotsk earthquake, means that the initial phase in the radial deformation of the Earth as recorded by the macroseismic information for the earthquake involved deformation of the northern hemisphere where the earthquake rupture was located. The Ixtaczoquitlán site, Mexico in the ESE flank was in an immediate vicinity of the seismic "equator" (9470 km and 10000 km, respectively). At the same time, the farthest site in the WSW flank (Milan, Italy, $\Delta = 8385$ km) was at a shorter distance (by 13%). We thus see that the distribution of the macroseismic effect showed a certain asymmetry.

Assuming the source radiation to be symmetrical, we obtain 18940 km as the wavelength at $\Delta_{max} = 9470$ km, with 20.64^m for the period and 15.29 km/s for the phase velocity. As a matter of fact, this wavelength is the arc length of the northern hemisphere (~95%).

The ultra-long propagation of felt ground motion due to the Sea-of-Okhotsk earthquake was thus due to body P waves being superposed upon traveling radial waves that make the standing radial wave ${}_0S_0$.

Along with the original pulse that propagated along the radius to the Earth's surface at the epicenter, the *P* wave propagated from the source toward the apocenter along the diameter, taking 19.2^m to reach it, according to the Jeffreys–Bullen tables. The apocenter at the antipode surface of the Earth is projected onto the seaward side of the Sandwich trench in the southern Atlantic ($\varphi = 54.76°$ N, $\lambda = 26.22°$ W).

It can be supposed that the expansion pulse of the northern hemisphere due to the generation of the radial standing wave ${}_0S_0$ gradually decays, because the elastic energy is transported outward by traveling waves toward the seismic "equator." When the equator has been crossed and the source pulse has traveled through the Earth's center the lower hemisphere begins to expand and the northern begins to contract. This is not however a one-pulse event; however, the task of following it until it reaches the stage of steady-state free oscillations of the Earth is outside the scope of the present study.

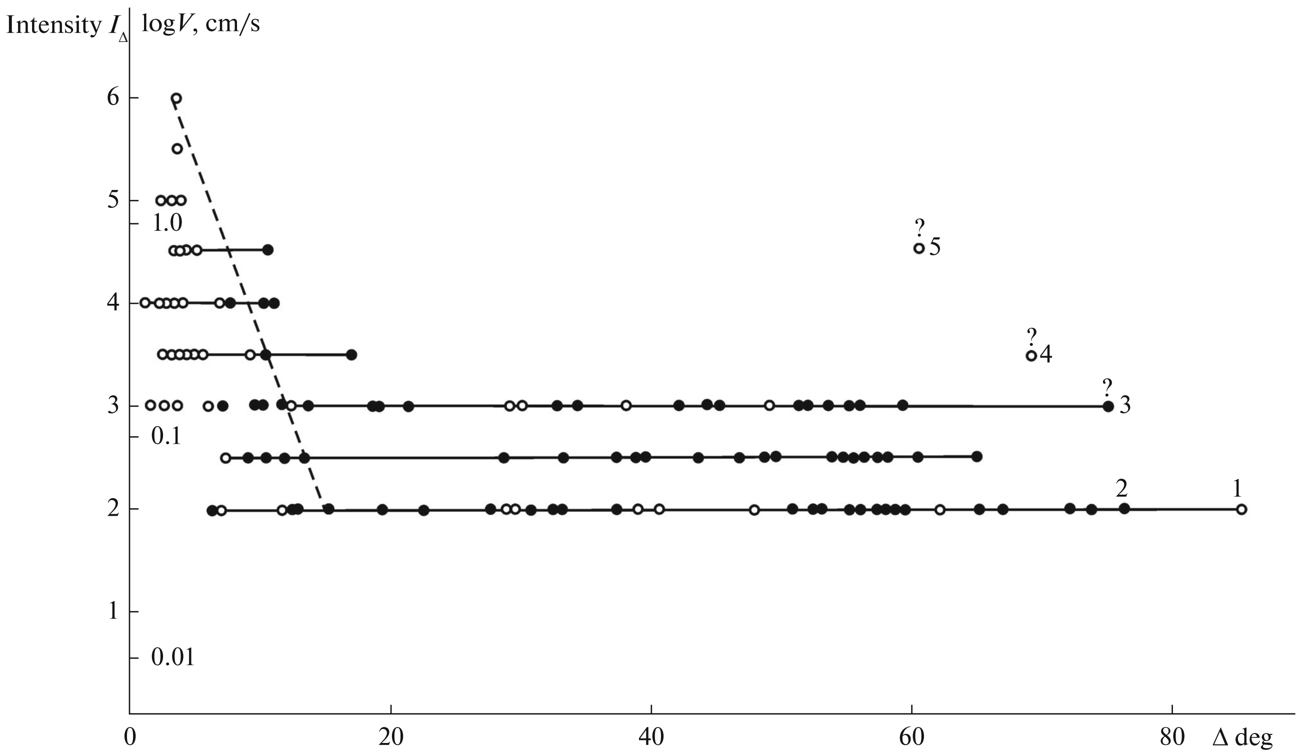

Fig. 3. A summary plot of the macroseismic effect due to the Sea-of-Okhotsk earthquake in the quantitative variant of ground velocity based on data from (*A project* ..., 2011). The dashes denote the intensity decay in the near zone. The continuous lines show the ground motion level. The filled circles mark the sites WSW of the epicenter, the open circles show the same for the ESE direction. (1) Ixtaczoquitlán, (2) Milan, (3) Dubai, (4) Rock Island, (5) Goleta. The question marks denote anomalous intensity values.

Once the cause of ultra long propagation of felt ground motion has been determined, it would be necessary to attack the problem of explaining the abnormally low attenuation of this motion, which is to be discussed in the next section.

On the Attenuation of Felt Ground Motion

The decay of macroseismic effect over distance can be approximately estimated only for the initial part of the macroseismic plot at $\Delta < 750$ km toward ESE and at 720–1330 km toward WSW (Fig. 3).

It should be noted that components of the macroseismic field such as subjective responses of people, differences in design and in the number of stories for buildings, as well as soil differences, cause significant distortions in this type of data. The above factors seem to control the variation in the level of ground shaking in the near zone between intensity VI and II, which is more pronounced in the ESE direction. The assumed result may have been due to a combined superposition of the incident direct wave and the reflected wave (the level of ground shaking) and by a simultaneous superposition upon the traveling wave (no dependence on distance). Speaking in quantitative terms, the decrease in the level of ground shaking from intensity VI to intensity II in the range 720–1330 km corresponds to a diminution of peak ground velocity from 3.8 cm/s to 0.05 cm/s (by a factor of 76), according to the Instrumental Appendix to the last variant of macroseismic scale for the Russian Federation (*A project* ..., 2011). An analysis of data on the decay of peak ground velocity based on records (Chebrova et al., 2015) within the same range of distance (after converting the hypocentral distances into the epicentral ones) revealed a decay of vertical ground velocity by a factor of approximately 21, i.e., 3.5 times slower compared with the macroseismic estimate.

The decay of felt ground shaking with distance is at first sight nonexistent for $\Delta > 12°$ (1330 km); this can be explained by a very low attenuation coefficient for the mode $_0S_0$. As an example, Molodenskii et al. (2014) examined the Obninsk records of the Sea-of-Okhotsk earthquake to find that the amplitude of $_0S_0$ diminished by a factor of e (2.718) in 19.24 days (27628 min) after the time of earthquake occurrence. This gives an attenuation coefficient equal to $\alpha \sim 1.6 \times 10^{-6}$ s^{-1}. In our case such an estimate can be derived using the formula for the decay of oscillations of the terrestrial sphere following Bolt (1982): $\alpha = \pi/QT$, where Q is the quality factor and T the period in seconds. Using the value $Q = 5300$ from (Molodenskii et al., 2014) and the period of the radial mode based on macroseismic data ($T = 1187.7$ s, or 19.8^m, see above), we obtain the value $\alpha \sim 0.5 \times 10^{-6}$ s^{-1}. It is clear that this change in amplitude is all but imperceptible to the human eye.

The ultra-long propagation of felt ground motion is thus supported by results from the solution of our problem of supposed superposition of *P* waves upon the radial mode $_0S_0$ due to the Sea-of-Okhotsk earthquake based on an analysis of macroseismic information. That same mechanism also explains the slow attenuation of felt ground motion with distance. However, this solution was derived on heuristic grounds with emphasis on seismological data. In terms of the physics of the Earth, one needs to study free oscillations in the terrestrial sphere excited by a source at depth incorporating the focal mechanism, the released seismic energy, and using the elastic parameters and characteristics of *Q* in the Earth. In addition, one should incorporate changes in the Earth's gravity field and the influence of long-period radial oscillations on the field (Zharkov, 1983).

RESULTS AND DISCUSSION

Since the present paper is concerned with a description of only the fundamental radial mode $_0S_0$, the generation of the spheroidal $_0S_2$ and the toroidal $_0T_2$ modes is not considered. We only wish to point out that the generation of the main modes is followed by the formation of higher-order modes (harmonics) and overtones, as well as of numerous singly and multiply reflected and refracted *P* and *S* waves, as well as converted waves (see the graphical appendix to the travel times based on the Jeffreys–Bullen Tables). The result was to produce a sonic effect similar to the ringing of a bell as described by many researchers (Bolt, 1982). In particular, a similar effect was noted in reports of certain observers of the 1994 Bolivian earthquake (Kerr, 1994; Monastersky, 1994).

Molodenskii et al. (2014) examined records of the Sea-of-Okhotsk earthquake made at the Obninsk station (Δ = 58.8° or 6527 km) to obtain data on some modes of the Earth's free oscillations, that is, the fundamental mode and overtones. The analysis of records for 60 days revealed the fundamental spheroidal mode $_0S_2$ with a period of 53.887 min, the radial mode $_0S_0$ with a period of 20.458 min, as well as all the higher spheroidal modes up to $_0S_{57}$ with a period of 2.659 min and overtones between $_1S_3$ (a period of 17.728 min) and $_5S_5$ (a period of 6.174 min). The list of toroidal modes contains harmonics from $_0T_3$ (a period of 28.41 min) to $_0T_{40}$ (a period of 3.35 min) and overtones from $_1T_1$ (a period of 13.407 min) to $_2T_7$ (a period of 6.01 min). The data acquired at the Kurchatov station, Kazakhstan allowed extension of the high-frequency spheroidal modes as far as $_0S_{97}$ (a period of 1.675 min) with some short gaps.

It should be noted that Tatevosyan et al. (2014) reported results from point estimates of the macroseismic effect due to the Sea-of-Okhotsk earthquake in Moscow. These authors interpreted records of the Z component at Moscow (Δ = 6450 km) and at Obninsk (Δ = 6530 km), as well as of the 1994 Bolivian earthquake at the Harvard station (US, Δ = 6270 km). Similarities in record shapes and near epicentral distances allowed the development of a combined set converted to a distance of 6500 km. The records in this set are dominated by the *P*-wave group and by the *SSS* phase. Recalling the physiological effects (dizziness and nausea), we are inclined to prefer the *SSS* phase as the only source of the macroseismic effect. However, the explanation of the origin of *SSS* based on the hypothesis of its superposition on Rayleigh wave is not convincing. The record of the Sea-of-Okhotsk earthquake available at Portland, United States at an approximate distance of 5700 km [http:www.iris.edu/hq/term...] shows that the intensity of the Rayleigh wave is below that of the P wave by approximately 1.5 orders of magnitude. In addition, it has not been taken into account that the ground shaking at Moscow was not instantaneous, but consisted in two to three short-lived shocks spread over a span of 10–15 min (Rogozhin et al., 2013).

In this situation one could form a more sound judgment by interpreting the three-component record of the Sea-of-Okhotsk earthquake at the Moscow station, which is also shown in (Tatevosyan et al., 2014) (Fig. 4). From this figure it follows that three more onsets of large amplitude were observed, apart from the *P*-wave group (the Z component), namely, *S*, *SS,* and *SSS*, which is in general agreement with the information supplied by Rogozhin et al. (2013). The *P* and *S* waves are more intensive in this record. Calculating the rms amplitude for *S* and *SSS* on all channels, we found that the amplitude of *S* is twice as high as that of *SSS* (0.11 cm/s and 0.053 cm/s, respectively). From this it follows that the main shock that caused the physiological effect was the shear wave, which arrived approximately 7–8 min after the *P*-wave group.

It can thus be thought that the shocks that caused physiological effects at Tomsk (Δ = 4140 km), Novosibirsk (Δ = 4330 km), and in Ufa (Δ = 5740 km) might have been caused by *S* onsets, while a third shock of lower amplitude in Moscow could result from the combination of *SS* and *SSS* that arrived at nearly the same time.

As to ground shaking of intensity II–III in Kamchatka at distances of 150 to 750 km from the epicenter according to the list in (Ivanova et al., 2013; Chebrova et al., 2015), the travel times to these sites vary between 1.3 and 1.9 min. The list of spheroidal and toroidal modes and overtones from (Molodenskii et al., 2014) contains times that correspond to modes from $_0S_{36}$ or $_0T_{36}$ and higher, while the nodes on the western and

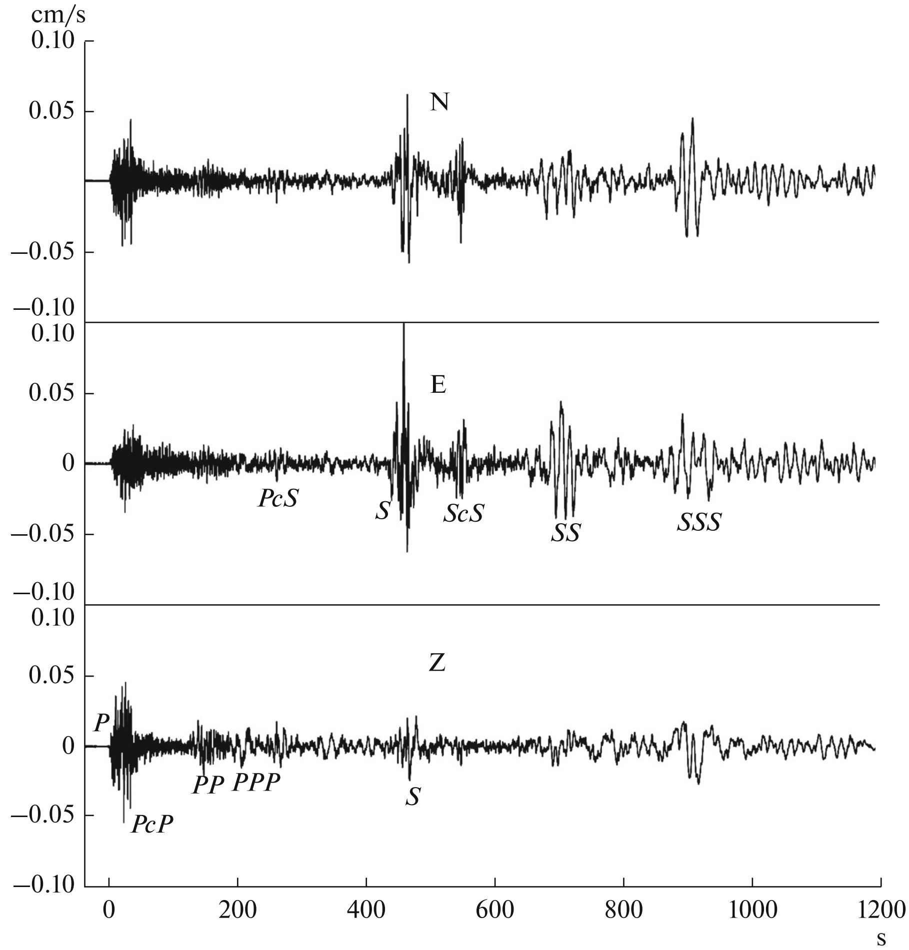

Fig. 4. The velocigram of the Sea-of-Okhotsk earthquake at the Moscow station (MOS, $\Delta = 58.1°$), after (Tatevosyan et al., 2014) with modifications. The letters N, E, and Z denote records on NS, EW, and Z components, respectively; *PP*, *PPP*, *PcP*, *PcS*, *S*, *ScS*, *SS*, and *SSS* are onsets of seismic phases.

eastern coasts of Kamchatka correspond to overtones of high orders as well.

CONCLUSIONS

Summing up the research carried out in this study, we arrived at the following conclusions.

(1) This study has stated and solved, in qualitative terms, the problem of ultra-long propagation of felt ground motions due to the deep-focus Sea-of-Okhotsk earthquake based on an analysis of macroseismic data using wave equations. It follows from the above analysis that the main mechanism for this phenomenon is the excitation of a previously unknown standing radial wave as a mode of the Earth's free oscillations ${}_0S_0$, as a result of superposition between a spherical *P* wave incident on the Earth's surface and a similar reflected wave around the epicenter of the earthquake. The *P* waves of this mode that travel along the surface have acted as a carrying wave for ultra long propagation of high frequency *P* waves that were superposed upon it and caused the observed macroseismic effect.

(2) According to macroseismic observations, the fundamental radial mode ${}_0S_0$ had the following parameters during the initial phase of earth deformation: a wavelength of 17855 km, a period of 19.78^m, and phase velocity of 15.04 km/s. Assuming the radiation from the source (at $\Delta_{max} = 9470$ km) to be symmetrical, we obtain 18940 km for the wavelength, 20.27^m for the period, and 15.19 km/s for the phase velocity. Actually, this wavelength would correspond to the arc length of the entire "northern" hemisphere of the Earth (~95%).

(3) As has been shown above, the initial phase in the Earth's deformation due to the Sea-of-Okhotsk earthquake produced the radial mode of the Earth's free oscillations ${}_0S_0$. Consequently, it can be stated that, along with the previously known spheroidal ${}_0S_2$ and toroidal ${}_0T_2$ modes of the Earth's free oscillations,

there is also the radial mode ${}_0S_0$ due to the propagation of strain on the Earth's surface as traveling *P* waves.

(4) There are differences between the standing radial mode ${}_0S_0$ from the spheroidal mode ${}_0S_2$ and the toroidal mode ${}_0T_2$, as follows:

(a) the occurrence at the center of seismic-energy radiation rather than somewhere on the periphery of the process (the distances reached 10000 km);

(b) the reverse relationship of the standing radial wave to traveling waves: the standing waves of the spheroidal and toroidal modes are formed by summing up traveling reverse Rayleigh and Love waves, while the radial mode forms *P* waves traveling on the Earth's surface and going from out the epicenter;

(c) simultaneous propagation of strain on the Earth's surface and along the Earth's diameter;

(d) a slow attenuation of the ground motion with distance ($\alpha \sim 0.5 \times 10^{-6}$ s^{-1}).

The above distinguishing features of the standing radial mode ${}_0S_0$ have not been discussed previously.

(5) The solution to the problem on the generation of the radial mode ${}_0S_0$ was derived in qualitative terms on a seismological basis. A rigorous rationale for the result requires solving the problem on oscillations of the terrestrial sphere caused by a source at depth incorporating the focal mechanism, released seismic energy, as well as elastic moduli and *Q*. In addition, we need incorporation of variations in the Earth's gravity field due to long-wavelength oscillations.

(6) The physiological impact of the Sea-of-Okhotsk earthquake near the epicenter and at distances below 6500 km might be caused by direct shear waves, while the effect in Moscow was also caused by the doubly reflected *SSS*.

(7) The examples of the Sea-of-Okhotsk and Bolivian earthquakes were used to show that large deep-focus earthquakes can produce the Earth's free oscillations that were not only recorded by instruments, but were also felt by people. Multistory buildings have become common; this facilitates the detection of anomalous macroseismic effects due to such earthquakes. Flexible buildings of this type have low fundamental frequencies (0.2–0.5 Hz); this will produce resonance even during rather low seismic excitations of these frequencies (up to intensity II) and thus will enhance the seismic felt effects.

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