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Original article

Long Wave Height Distribution in the Sea of Japan Caused by Typhoon Hinnamnor Passage: Observations and Modeling

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Abstract
Purpose. Observations of sea level oscillations and atmospheric pressure fluctuations on the Russian coast of the Sea of Japan during the passage of Typhoon Hinnamnor on September 5, 2022 are presented. The study is aimed at explaining physical mechanisms of anomalous changes in the sea level at the Preobrazhenie coastal location (Primorye, Russia) during this event.
Methods and Results. Numerical modeling of long waves induced by this typhoon is performed using the NAMI-DANCE computed package. It is demonstrated that the observed filtered records and computed mareograms are in good agreement. Special attention is paid to the sensitivity of the results to even weak variations of the typhoon trajectory and it is shown that the sensitivity is significant.
Conclusions. The phenomenon of anomalous changes in the sea level at the Preobrazhenie coastal location can be explained by the peculiar structure of the coastline. Presumably, focusing of surface waves generated by the changes in atmospheric pressure occurred. This result should be of interest when designing coastal infrastructure of the region. Three scenarios of numerical modeling of typhoon passage were investigated and the results showed that a slight change in the trajectory had a significant effect on the distribution of wave heights along the Russian coast of the Sea of Japan.

Keywords: meteotsunami, field measurements, long waves, numerical modeling, laser nanobarograph

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1. Introduction

Since low atmospheric pressure leads to an increase in the water level of a part of the marine region and high atmospheric pressure leads to a decrease in the water level of another zone (reverse barometer law), the seawater level is distorted. The generated waves in the storm area propagate over long distances and can be amplified due to resonant properties of coastal morphology. Generation of long waves by atmospheric disturbances (meteorological tsunamis) has different names

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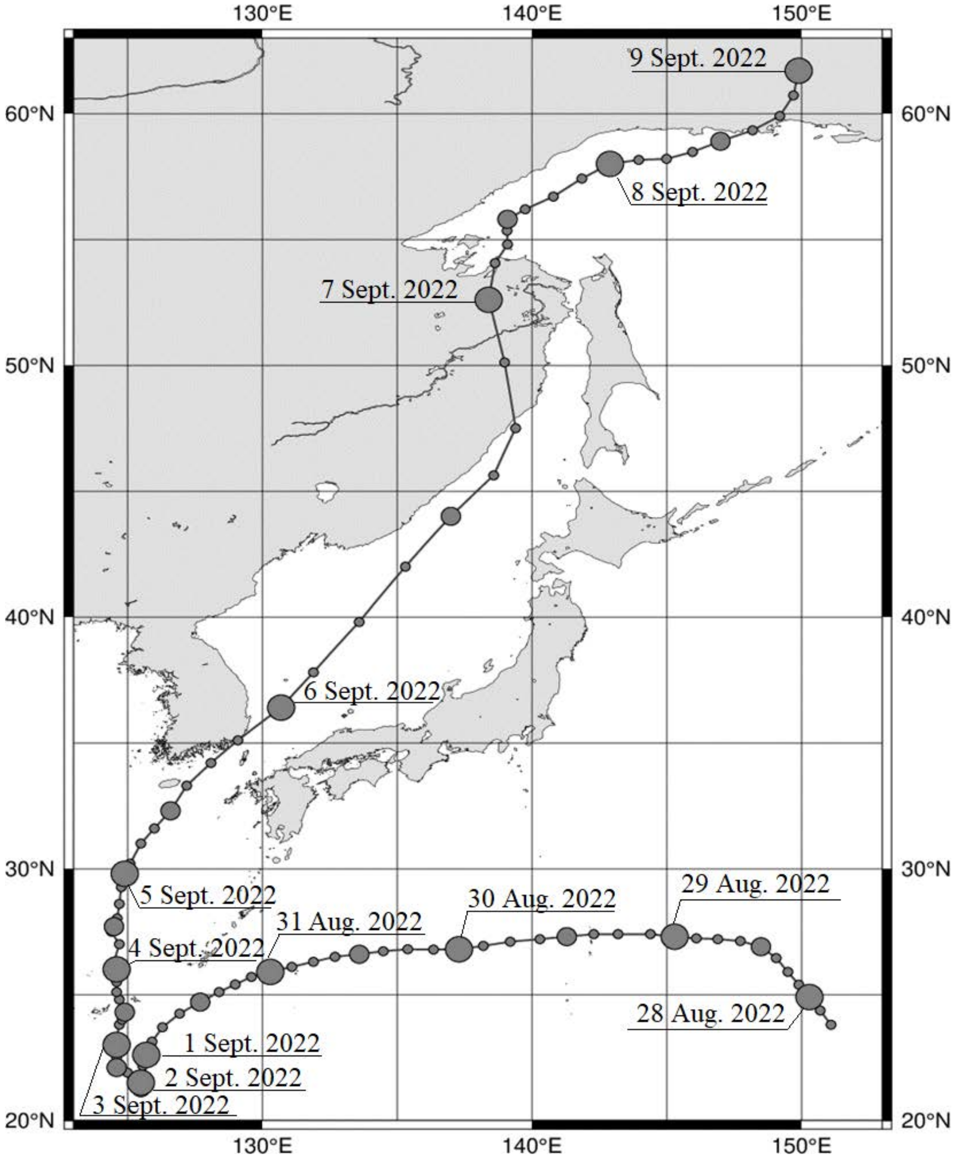
in various places: “rissaga” (Belerik Island), “marubbio” (Sicily), “milghuba” (Malta), “abiki” (Nagasaki Bay) and “Seebär” (the Baltic Sea). Some scientific papers are dedicated to the overview of meteotsunamis and their generation mechanisms [1–6]. Meteorological tsunamis have the same period range as conventional tsunamis and can cause loss of life and devastating effects in coastal zones.



F i g. 1. Trajectory of Typhoon Hinnamnor (August 28, 2022 – September 09, 2022) [1]

[1] NII. *Digital Typhoon: Typhoon 202211 (HINNAMNOR) - Detailed Track Information*. 2022. [online] Available at: http://agora.ex.nii.ac.jp/digital-typhoon/summary/wnp/l/202211.html.en [Accessed: 10 November 2023].

For a meteotsunami, source mechanisms such as spatial and temporal pressure distributions and atmospheric gravitational waves are important. Resonant effects play an important role in the origination of meteotsunamis, when the period of eigen oscillations of the water area and their propagation velocity is close to the period and propagation velocity of atmospheric disturbances. However, not every atmospheric front or atmospheric disturbance leads to the origination of a meteorological tsunami. The most important is the atmospheric pressure gradient, which directly affects the ocean [3]. There are many papers dealing with observations and modeling of tsunamis of meteorological origin [1, 2]. The goal of the present paper is to study the generation of waves in the Sea of Japan during the passage of Typhoon Hinnamnor in 2022. The characteristics of this typhoon are presented in Section 2. The observation results of this event in the Far East coast of Russia are summarized in Section 3. Numerical modeling of sea level disturbances caused by Typhoon Hinnamnor in the northern part of the Sea of Japan is described in Section 4. The main attention is paid to the sensitivity of wave characteristics to the typhoon trajectory variation. The obtained results are summarized in the Conclusion section.

2. Typhoon Hinnamnor characteristics

Typhoon Hinnamnor is the first tropical typhoon in 2022 to make direct impact on the weather in the south of the Russian Far East. In fact, it developed from the atmospheric disturbance zone (the eleventh storm) in the northwest of the Pacific Ocean recorded on August 27, 2022. It got its name from the Japan Meteorological Agency, which serves as a regional center. It is also the fourth typhoon and the first super typhoon of the 2022 season. Hinnamnor had a remarkable trajectory (Fig. 1). It is worth noting that the movement of Typhoon Hinnamnor was monitored and the movement line was predicted. On the night of September 4, it left for the East China Sea; on September 6, it approached Primorsky Krai of the Russian Federation. However, during its movement, the typhoon repeatedly changed directions.

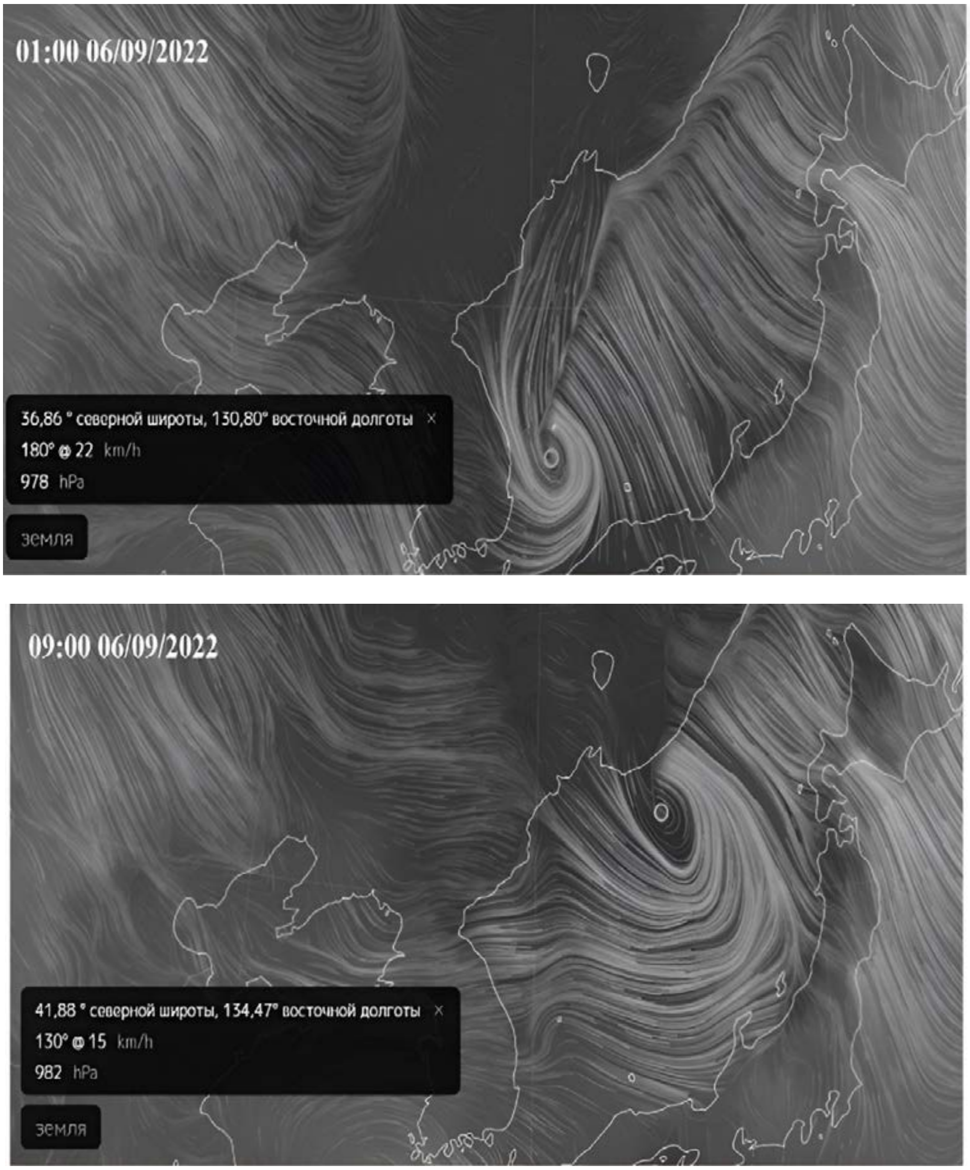
Emerging 920 km to the east-southeast of the Japanese island of Io, it rapidly intensified to the stage of a strong typhoon and then, weakening, moved to the west. The negative factors were colder water and the atmospheric front proximity. On September 3, as if “having received a second breath” Typhoon Hinnamnor sharply changed its trajectory near the Ryukyu Islands and headed north [2].

The pressure distribution for this region on September 6, 2022 (Fig. 2), obtained from the GFS/NCEP/US National Weather Service [3], shows that an abnormally low-

[2] Hydrometeorological Center of Russia. [*Typhoon Hinnamnor Brought Heavy Rains and Stormy Winds to Primorsky Krai*]. 2022. [online] Available at: https://meteoinfo.ru/novosti/18766-eks-tajfun-khinnamnor-prines-silnye-dozhdi-i-shtormovoj-veter-v-primorskij-kraj?ysclid=ll5ddnbmv2229296468 [Accessed: 01 September 2023] (in Russian).

[3] NCEI. *Global Forecast System*. [online] Available at: https://www.ncei.noaa.gov/products/weather-climate-models/global-forecast [Accessed: 01 September 2023].

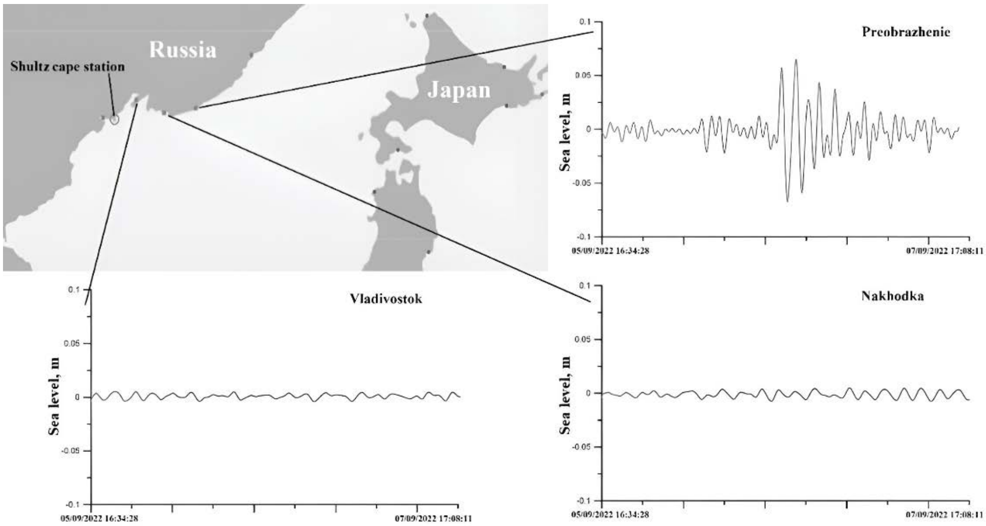
pressure front passed in the Sea of Japan. The minimum pressure in its center at its peak, on August 30, reached 920 HPA. The maximum speed was estimated at 195 km/h, with gusts of 260 km/h.



F i g. 2. Pressure distribution of Typhoon Hinnamnor on September 6, 2022 (01:00–09:00) (GFS/NCEP/US National Weather Service)

3. Observations on the Far East coast of Russia

During the passage of Typhoon Hinnamnor along the coast of Primorsky Krai of Russia, sea level disturbances, shown in Fig. 3, were observed at different locations [4]. The sea level disturbances related to the typhoon passage are clearly visible. It is noteworthy that at the coastal locations of Vladivostok and Nakhodka the wave heights do not exceed 10 cm, but at the village of Preobrazhenie, the wave heights reach up to 1 m, taking into account the tide.



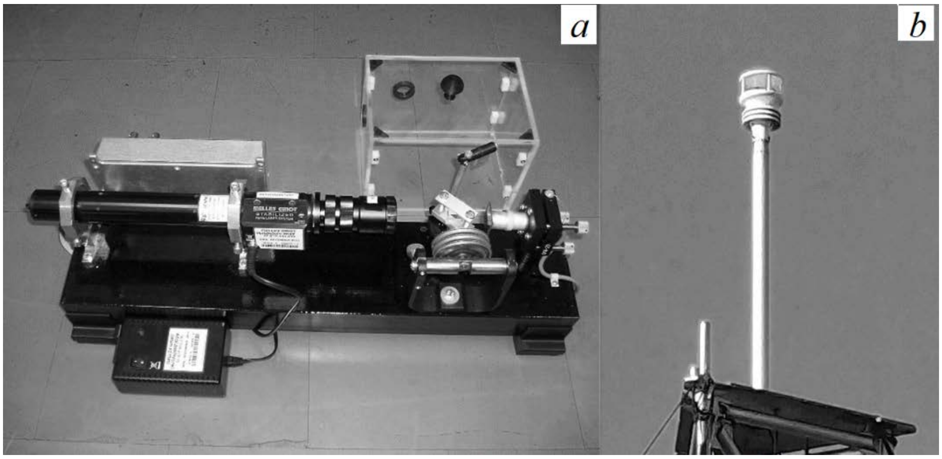
F i g. 3. Sea level station records

A seismoacoustic hydrophysical complex established at the Schultz Cape Marine Experimental Station of V.I. Il'ichev Pacific Oceanological Institute has been operating continuously since 2000 [7]. The complex includes laser strainmeters, a laser nanobarograph (Fig. 4), laser meters of hydrosphere pressure variations, a broadband seismograph, a weather station, a laboratory room, and auxiliary equipment. All laser meters are based on the Michelson interferometer using a frequency-stabilized helium-neon laser with a long-term stability frequency of 10^{-9} as a light source. The laser nanobarograph is created on the basis of the Michelson equal-arms interferometer, where the aneroid box is a sensitive element. The device is capable of detecting atmospheric pressure variations in the frequency range from 0 (conditionally) to 1000 Hz with an accuracy of 1 μPa and in an almost unlimited dynamic range [8].

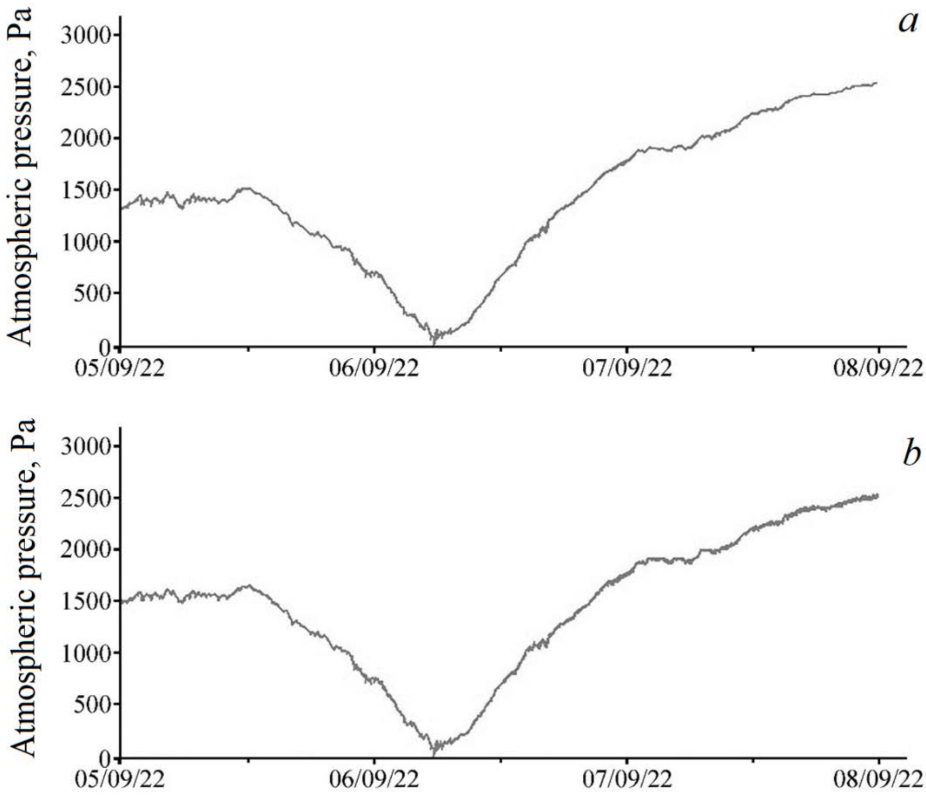
On September 6, 2022, an atmospheric disturbance caused by the passage of Typhoon Hinnamnor was registered on two devices that are part of the complex. It was recorded by a laser nanobarograph and a weather station (Fig. 4). The records of the laser nanobarograph and the pressure sensor of the weather station from

[4] UNESCO. *Sea Level Station Monitoring Facility*. 2023. [online] Available at: http://www.ioc-sealevelmonitoring.org/ [Accessed: 01 September 2023].

September 5 to September 7, 2022 are shown in Fig. 5. A low-pressure value was about 17 hPa.



F i g. 4. Laser nanobarograph (*a*) and weather station (*b*)



F i g. 5. A fragment of the laser nanobarograph recording (*a*) and the weather station recording (*b*)

From the full-scale data shown in Fig. 5, it can be seen that the atmospheric pressure decreased as the typhoon moved to the place where the instruments were installed. It decreased by 15 hPa in almost 18 hours. The lowest pressure was observed at maximum approach of the typhoon center to the Schultz Cape. The minimum distance from the measuring instruments to the typhoon center was more than 200 km. Then, as the typhoon center moved away from the installation site of the laser nanobarograph and the weather station, the pressure increased by 17 hPa in almost 18 hours. This abnormal pressure change can be attributed to a meteotsunami. Subsequently, it resulted in the formation of deformation waves with 1.5-hour period and excitation of abnormal isolated hydrosphere waves. In connection with this event, the task was set to study this phenomenon with a probable assessment of its spread and impact on the hydrosphere.

4. Numerical simulation of longwave disturbances

For numerical simulation of the long wave generation and propagation caused by Typhoon Hinnamnor, we used the NAMI-DANCE_P computational code solving the nonlinear shallow-water equations [9]. The atmospheric impact term is included in the numerical code. This mathematical model has been used many times for simulation of long waves of atmospheric origin and it passed various benchmarks [10]. Therefore, we have

$$\frac{\partial M}{\partial t}+\frac{1}{R\cos\theta}\frac{\partial}{\partial\lambda}\left(\frac{M^2}{D}\right)+\frac{1}{R\cos\theta}\frac{\partial}{\partial\theta}\left(\frac{MN\cos\theta}{D}\right)+\frac{gD}{R\cos\theta}\frac{\partial\eta}{\partial\lambda}+$$
$$+\frac{gn^2}{D^{7/3}}M\sqrt{M^2+N^2}+\frac{D}{\rho}\frac{1}{R\cos\theta}\frac{\partial p_{atm}}{\partial\lambda}=fN, \quad (1)$$

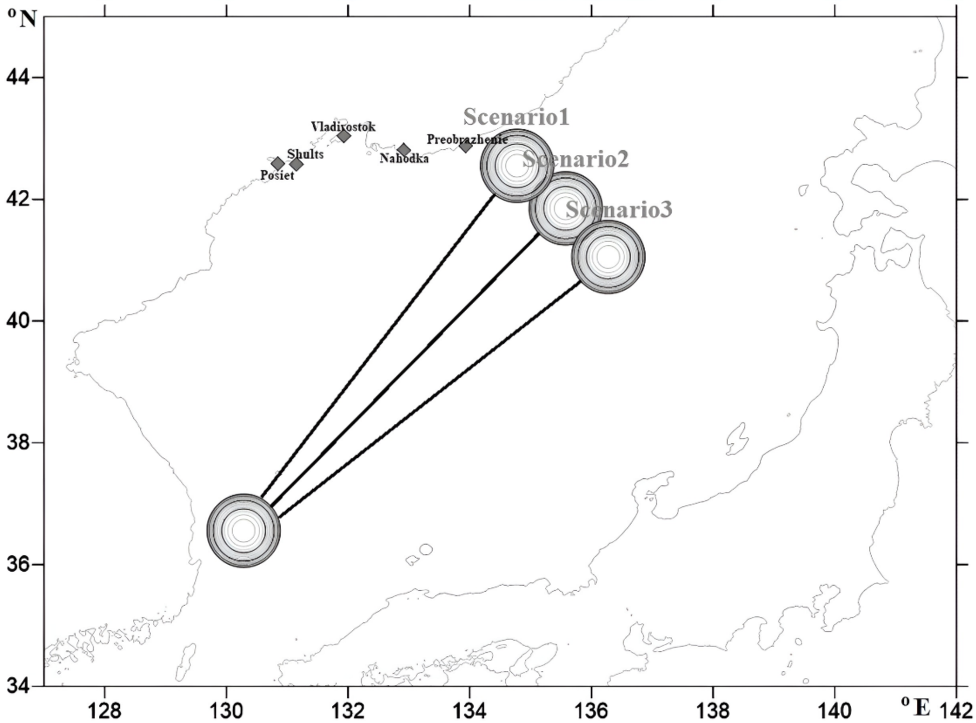
$$\frac{\partial N}{\partial t}+\frac{1}{R\cos\theta}\frac{\partial}{\partial\lambda}\left(\frac{MN}{D}\right)+\frac{1}{R\cos\theta}\frac{\partial}{\partial\theta}\left(\frac{N^2\cos\theta}{D}\right)+\frac{gD}{R}\frac{\partial\eta}{\partial\theta}+$$
$$+\frac{gn^2}{D^{7/3}}N\sqrt{M^2+N^2}+\frac{D}{\rho}\frac{1}{R\cos\theta}\frac{\partial p_{atm}}{\partial\theta}=-fN, \quad (2)$$

$$\frac{\partial\eta}{\partial t}+\frac{1}{R\cos\theta}\left[\frac{\partial M}{\partial\lambda}+\frac{\partial}{\partial\theta}\left(N\cos\theta\right)\right]=0, \quad (3)$$

where η is displacement of the water surface; t is time, M and N are components of the discharge fluxes along the coordinates λ and θ; $D = h(\lambda, \theta) + \eta$ is the total depth of the basin; $h(\lambda, \theta)$ is undisturbed water depth; g is gravitational constant; f is Coriolis parameter ($f = 2\Omega \sin\theta$); Ω is Earth rotation frequency (24-hour rotation period); R is Earth radius; p_{atm} is the value of atmospheric pressure in Pascal, which is taken from meteorological maps usually distributed to consumers at one-hour intervals. Pressure distribution maps at one-hour intervals were taken from the GFS/NCEP/US National Weather Service (https://earth.nullschool.net).

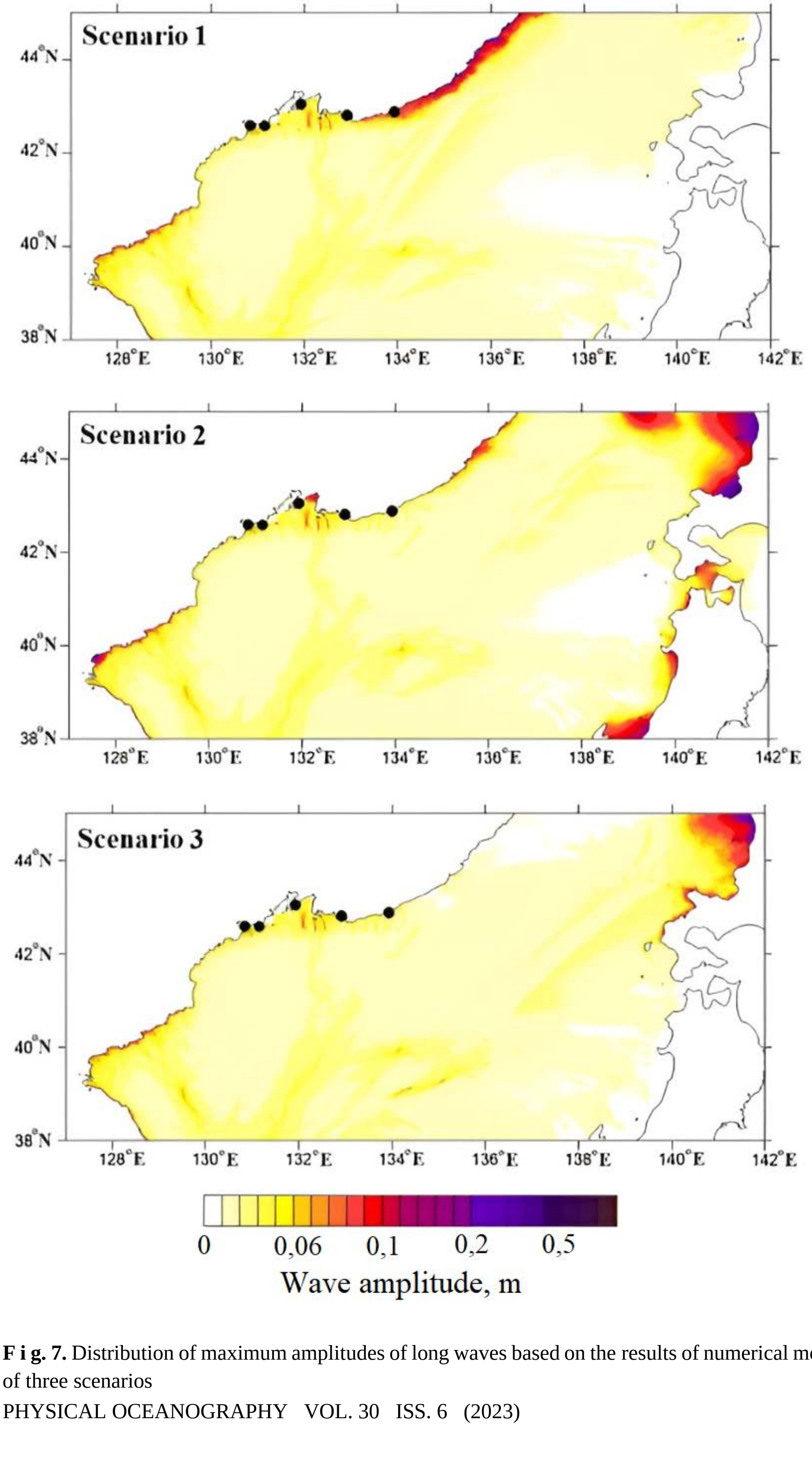
A digital pressure map was built for the period from September 5, 2022 to September 7, 2022. For calculations, these maps were interpolated in time in order to have the pressure field at every instant.

It is important to note that the typhoon trajectory in the vicinity of Primorye is only approximately known. Thus, we considered three different typhoon trajectories in the Sea of Japan, as shown in Fig. 6. Scenario 1 corresponds to the Typhoon Hinnamnor parameters. Two other scenarios correspond to the longer passage of the typhoon along the coast of Primorye. We use the SME charts of atmospheric pressure for simplicity “shifting” them accordingly.

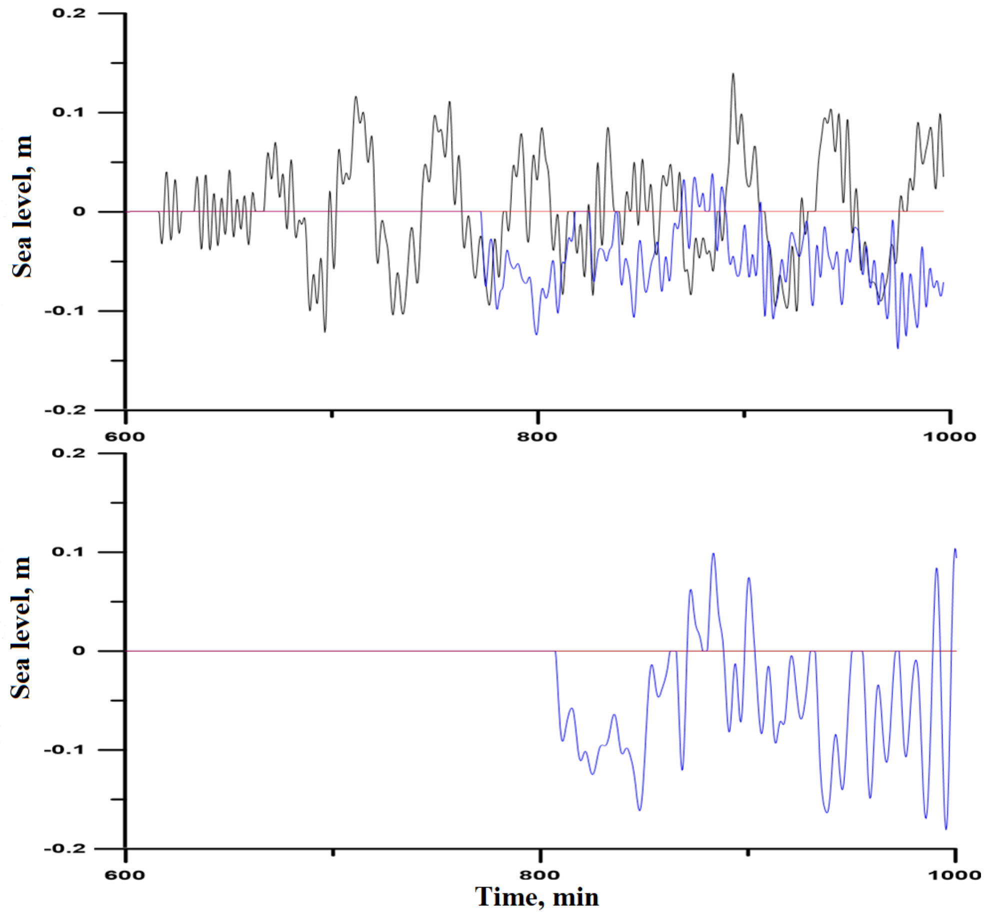


F i g. 6. Pressure scenarios of Typhoon Hinnamnor motion along the southern part of the Sea of Japan

Impact of the typhoon on the water surface was computed for 24 hours using the NAMI-DANCE_P computational code. According to the results of modeling three movement scenarios, the distribution of wave amplitudes caused by the typhoon movement is shown in Fig. 7. As we can see and as expected, the maximum heights are obtained for the Russian coast in Scenario 1 (nearest location to the typhoon) and on Hokkaido Island in Scenarios 2 and 3 (far sources). This demonstrates sensitivity of wave generation to the variations of the typhoon trajectory.



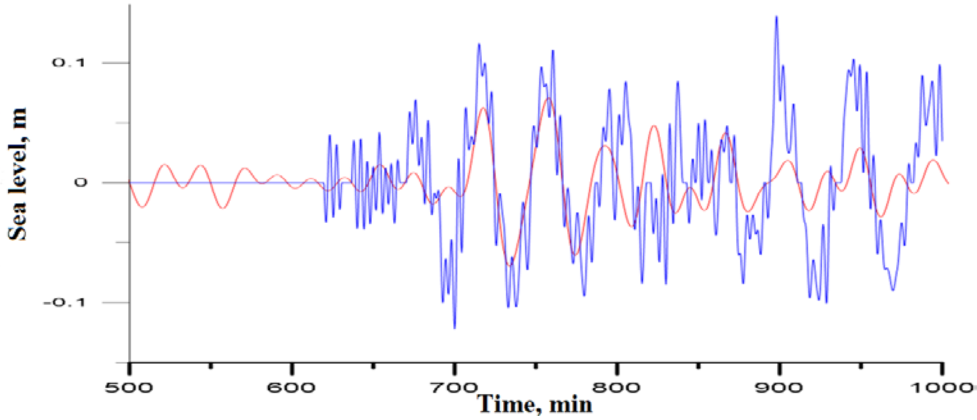
F i g. 7. Distribution of maximum amplitudes of long waves based on the results of numerical modeling of three scenarios



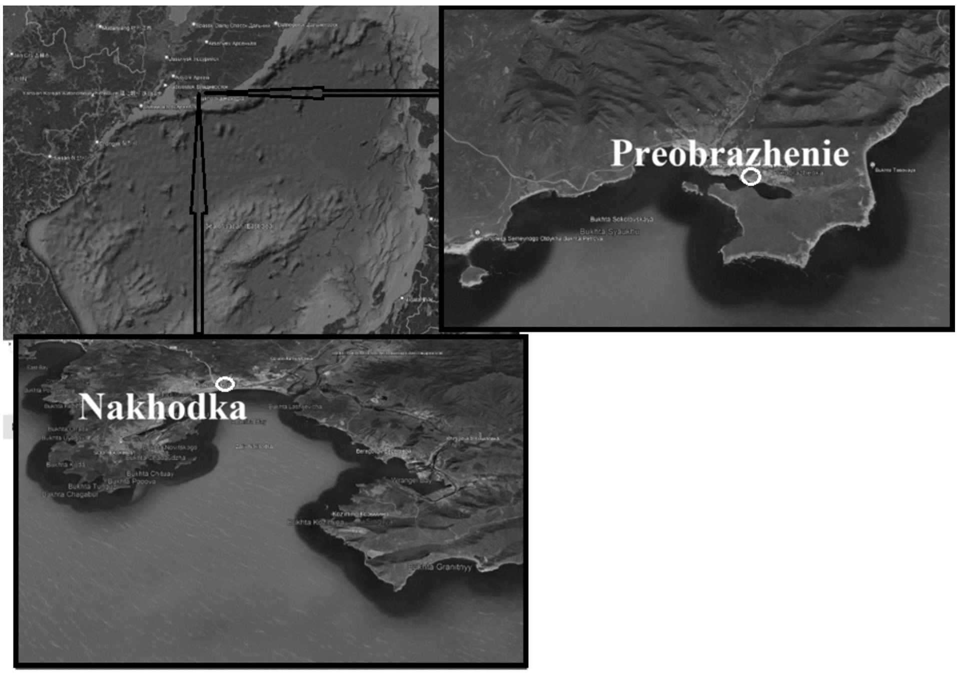
F i g. 8. Sea level change at the Preobrazhenie (*upper*) and Nahodka (*lower*) station points (black – Scenario 1; blue – Scenario 2; red – Scenario 3)

Computed mareograms of the long waves at Preobrazhenie and Nakhodka coastal locations are presented in Fig. 8. The computed data at Preobrazhenie show fluctuations with heights up to 20 cm in Scenario 1 and up to 10 cm in Scenario 2, oscillations were too weak in Scenario 3. As expected, the wave amplitude increases if the typhoon passes close to the coast. For comparison with observations, we filtered the tide and small-scale wind waves. Fig. 9 presents the results of the comparison of computed and observed long-wave mariograms for the coastal location at Preobrazhenie. Some long-wave fluctuations with heights of 20 cm and a period of about 80 minutes can be observed here. In general, the agreement is quite good. A significant response of the waves in this coastal location can, perhaps, be explained by the location of the Preobrazhenie Bay entrance (Fig. 10) opened to the first trajectory.

According to the computations, the maximum waves (up to 20 cm) at Nakhodka can be expected in Scenario 2 of the typhoon passage. The real mareogram in this coastal location (Fig. 3) demonstrates significant waves, but after the filtering procedure, the amplitude of long waves is very much in agreement with computations (Fig. 8). Significant waves in Scenario 2 can be associated with the better orientation of Nakhodka Bay (Fig. 10) and the second trajectory leading to the excitation of seiches.



F i g. 9. Sea level change at the Preobrazhenie point (blue - measurement, red - numerical simulation)



F i g. 10. A map of Preobrazhenie and Nakhodka bays demonstrates direction of their entrances in respect to typhoon trajectory

In other coastal locations, computed waves have small amplitudes in agreement with observed filtered records and they are not analyzed here.

5. Conclusion

This study aims to explain physical mechanisms of anomalous changes in the sea level at the Preobrazhenie coastal location (Primorye, Russia) on June 9, 2022 during Typhoon Hinnamnor. Observations of the sea level oscillations and atmospheric pressure fluctuations on the Russian coast of the Sea of Japan are presented. Numerical modeling of long wave generation was performed using meteorological information and the NAMI-DANCE model. The results of modeling are in good agreement with real filtered records, which made it possible to analyze the distribution of wave heights along the coast for this event. This phenomenon can be explained by the peculiar structure of the coastline near these coastal locations. Presumably, focusing of surface waves generated by changes in atmospheric pressure occurred. This result should be of interest when designing coastal infrastructure of the region. Three scenarios of typhoon passage were investigated and the results showed that a slight change in the trajectory has a significant effect on the distribution of wave heights along the Russian coast of the Sea of Japan.

REFERENCES

1. Pattiaratchi, C.B. and Wijeratne, E.M.S., 2015. Are Meteotsunamis an Underrated Hazard? *Philosophical Transactions of the Royal Society A*, 373(2053), 20140377. doi:10.1098/rsta.2014.0377

2. Monserrat, S., Vilibić, I. and Rabinovich, A.B., 2006. Meteotsunamis: Atmospherically Induced Destructive Ocean Waves in the Tsunami Frequency Band. *Natural Hazards and Earth System Sciences*, 6(6), pp. 1035-1051. doi:10.5194/nhess-6-1035-2006

3. Rabinovich, A.B. and Monserrat, S., 1998. Generation of Meteorological Tsunamis (Large Amplitude Seiches) near the Balearic and Kuril Islands. *Natural Hazards*, 18, pp. 27-55. doi:10.1023/A:1008096627047

4. Šepić, J., Vilibić, I., Rabinovich, A.B. and Monserrat, S., 2015. Widespread Tsunami-Like Waves of 23-27 June in the Mediterranean and Black Seas Generated by High-Altitude Atmospheric Forcing. *Scientific Reports*, 5, 11682. doi:10.1038/srep11682

5. Rabinovich, A.B., 2009. Seiches and Harbor Oscillations. In: Y. C. Kim, ed., 2009. *Handbook of Coastal and Ocean Engineering*. Singapore, Hackensack, N.J.: World Scientific Publ., pp. 193-236. doi:10.1142/9789812819307_0009

6. Kubota, T., Saito, T., Chikasada, N.Y. and Sandanbata, O., 2021. Meteotsunami Observed by the Deep-Ocean Seafloor Pressure Gauge Network off Northeastern Japan. *Geophysical Research Letters*, 48(21), e2021GL094255. doi:10.1029/2021GL094255

7. Dolgikh, G., Dolgikh, S. and Ovcharenko, V., 2022. Initiation of Infrasonic Geosphere Waves Caused by Explosive Eruption of Hunga Tonga-Hunga Haʻapai Volcano. *Journal of Marine Science and Engineering*, 10(8), 1061. doi:10.3390/jmse10081061

8. Dolgikh, G.I., Dolgikh, S.G., Kovalev, S.N., Koren, I.A., Novikova, O.V., Ovcharenko, V.V., Okuntseva, O.P., Shvets, V.A., Chupin, V.A. and Yakovenko, S.V., 2004. A Laser Nanobarograph and Its Application to the Study of Pressure-Strain Coupling. *Izvestiya, Physics of the Solid Earth*, 40(8), pp. 683-691.

9. Zaytsev, A., Kurkin, A., Pelinovsky, E. and Yalçıner, A.C., 2019. Numerical Tsunami Model NAMI-DANCE. *Science of Tsunami Hazards*, 38(4), pp. 151-168.

10. Dogan, G.G., Pelinovsky, E., Zaytsev, A., Metin, A.D., Tarakcioglu, G.O., Yalcıner, A.C., Yalcıner, B. and Didenkulova, I., 2021. Long Wave Generation and Coastal Amplification due

to Propagating Atmospheric Pressure Disturbances. *Natural Hazards*, 106(2), pp. 1195-1221. doi:10.1007/s11069-021-04625-9

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Contribution of the co-authors:

Stanislav G. Dolgikh – data processing, discussion of the results, and writing of the text

Grigory I. Dolgikh – problem statement, discussion of the results

Andrey I. Zaytsev – computational modeling

Efim N. Pelinovsky – discussion and analysis of the results

The authors have read and approved the final manuscript.
The authors declare that they have no conflict of interest.