Внутренние волны цунами, генерируемые при извержении подводного вулкана

Efim Pelinovsky, T. Talipova, E. Didenkulova

Institute of Applied Physics, Nizhny Novgorod, Russia

ИПФ РАН

ВЫСШАЯ ШКОЛА ЭКОНОМИКИ
НАЦИОНАЛЬНЫЙ ИССЛЕДОВАТЕЛЬСКИЙ УНИВЕРСИТЕТ

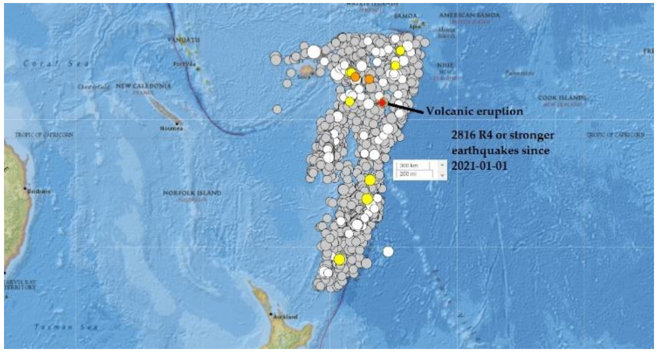
Тихоокеанский океанологический институт им. В.И. Ильичева ДВО РАН, Владивосток

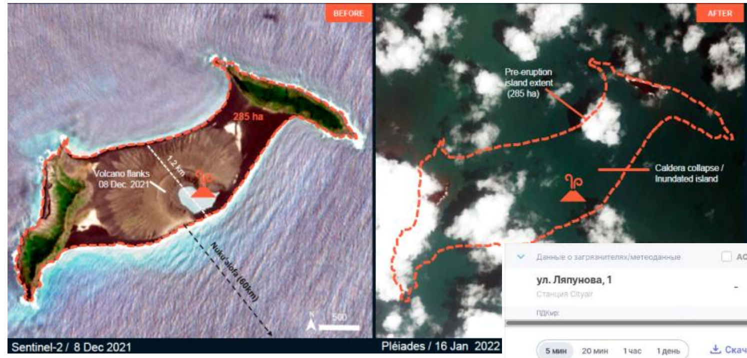
РНФ 24-27-00110

Мегагрант № 075-15-2022-1127

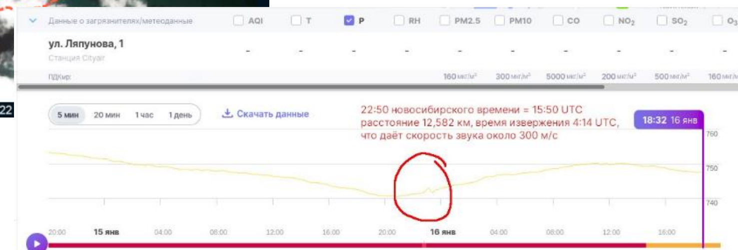
V Всероссийская конференция «ВОЛНЫ ЦУНАМИ: МОДЕЛИРОВАНИЕ, МОНИТОРИНГ, ПРОГНОЗ» 12.11.2024

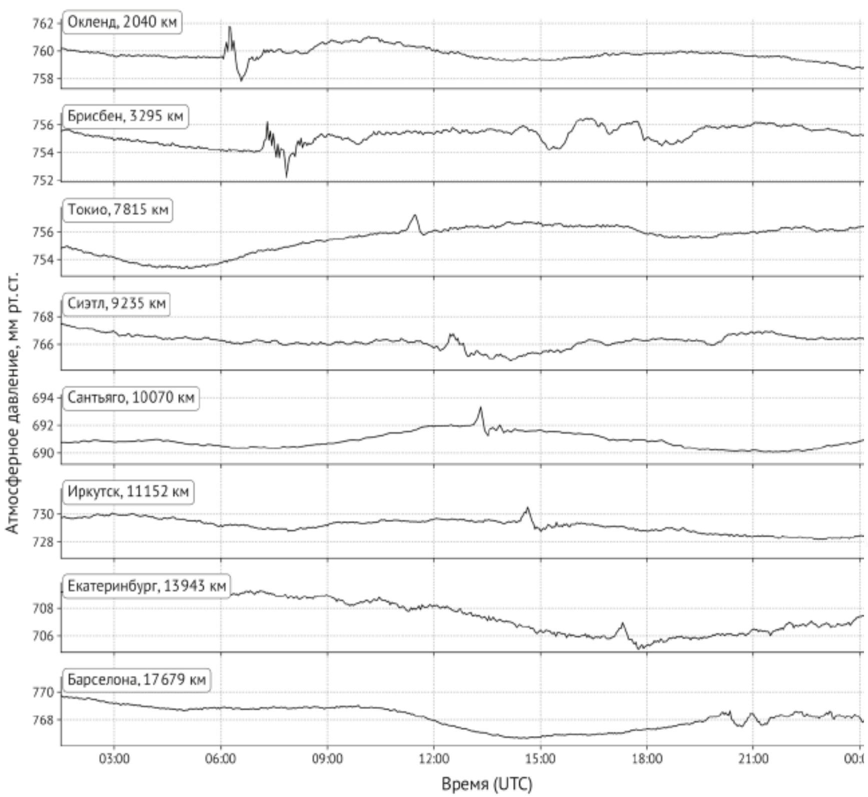
HungaTonga- Hunga Ha'apai Volcano, 15 Jan. 2022

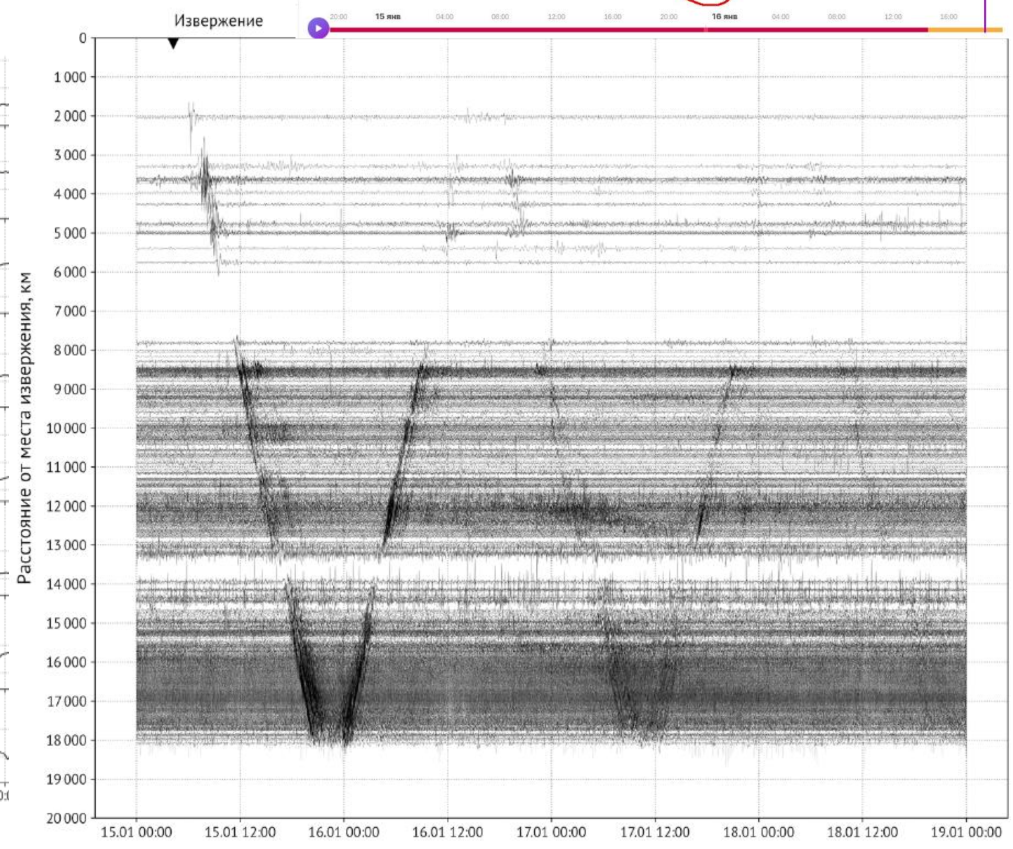




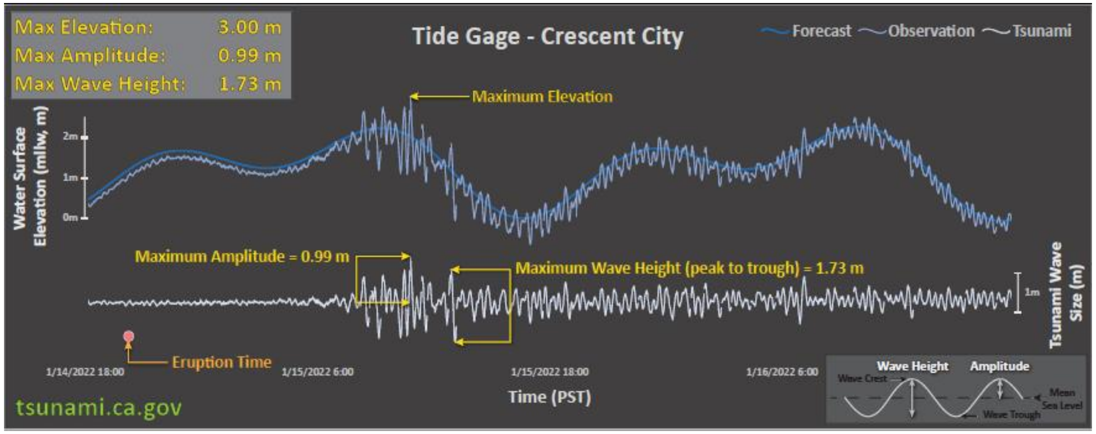
Sound Waves in Atmosphere

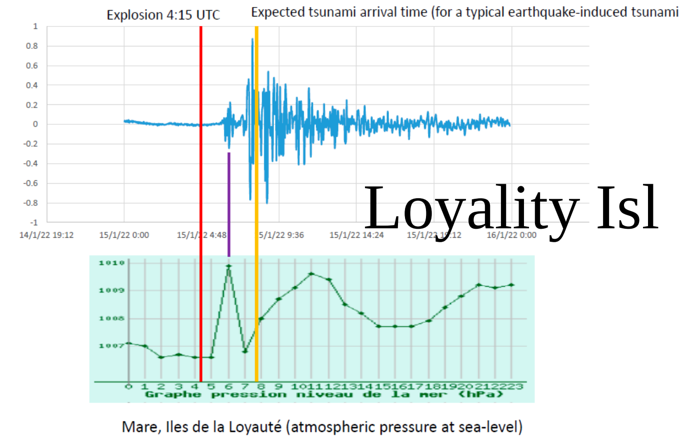


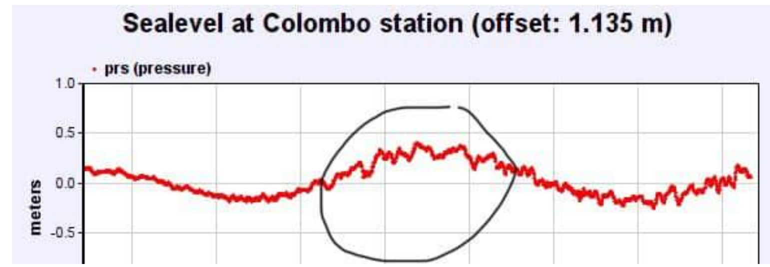


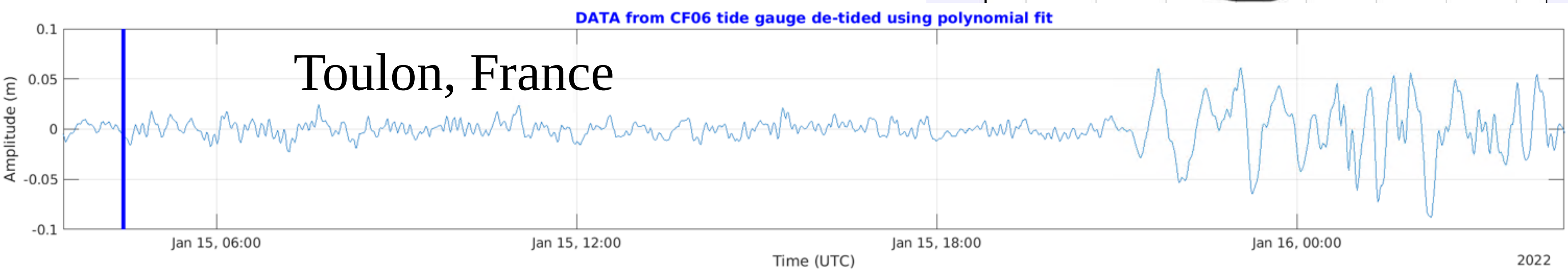


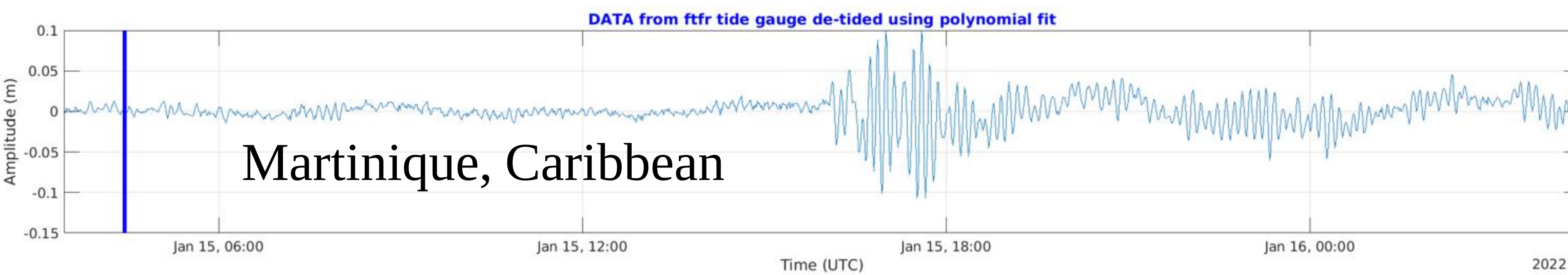
Tsunami Waves up to 15 m











ДОКЛАДЫ РОССИЙСКОЙ АКАДЕМИИ НАУК. НАУКИ О ЗЕМЛЕ, 2022, том 506, № 2, с. 259–264

ОКЕАНОЛОГИЯ

УДК 551.46

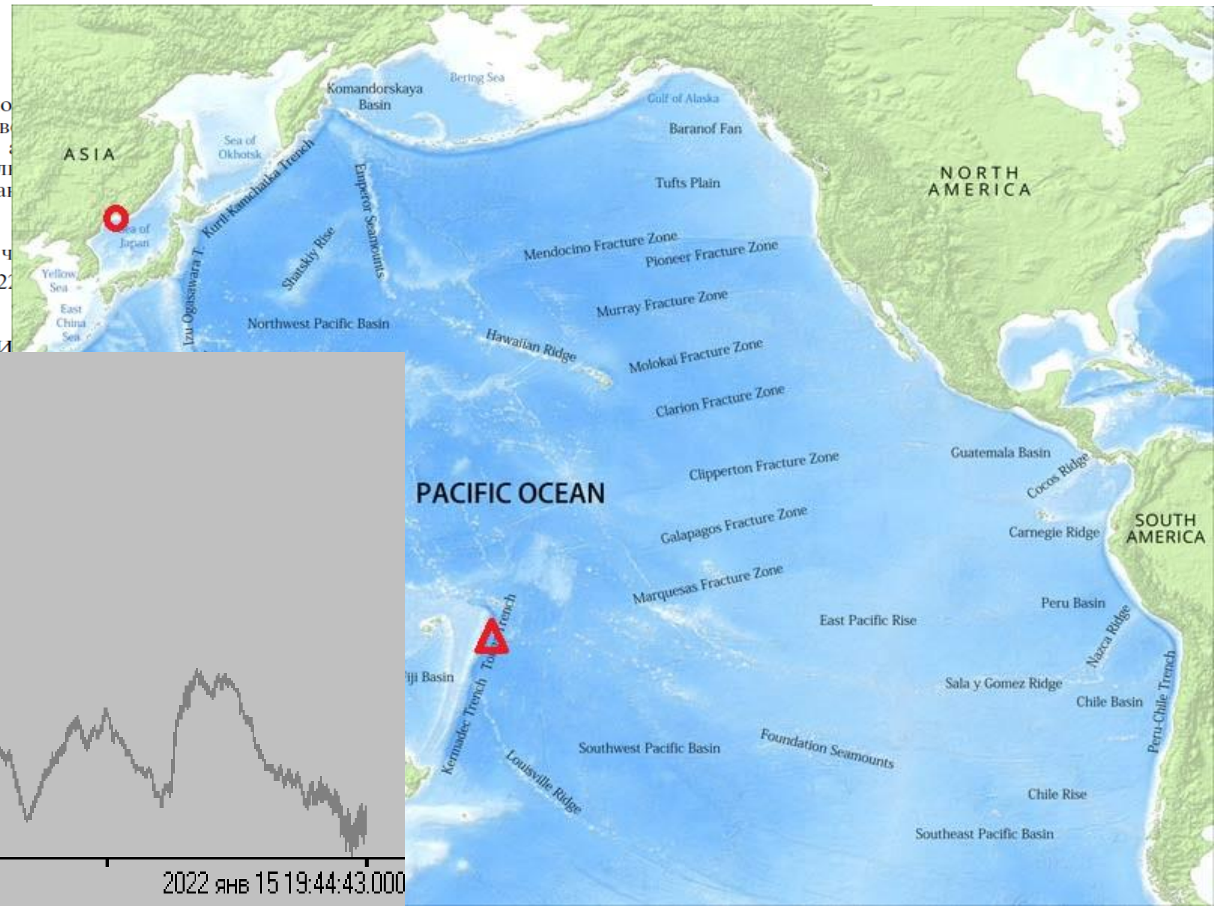
РЕГИСТРАЦИЯ ВОЗМУЩЕНИЙ В ЯПОНСКОМ МОРЕ, ВЫЗВАННЫХ ИЗВЕРЖЕНИЕМ ВУЛКАНА ХУНГА-ТОНГА-ХААПАЙ В АРХИПЕЛАГЕ ТОНГА 15.01.2022

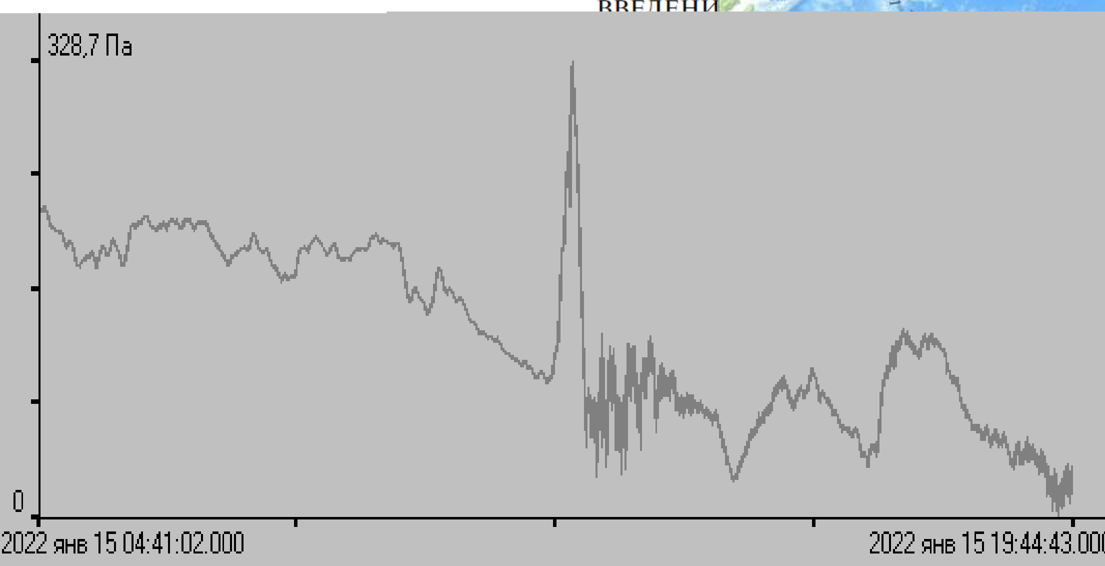
© 2022 г. Член-корреспондент РАН А. И. Зайцев[1,*], Е. Н. Пелиновский[2],
академик РАН Г. И. Долгих[3], С. Г. Долгих[3]

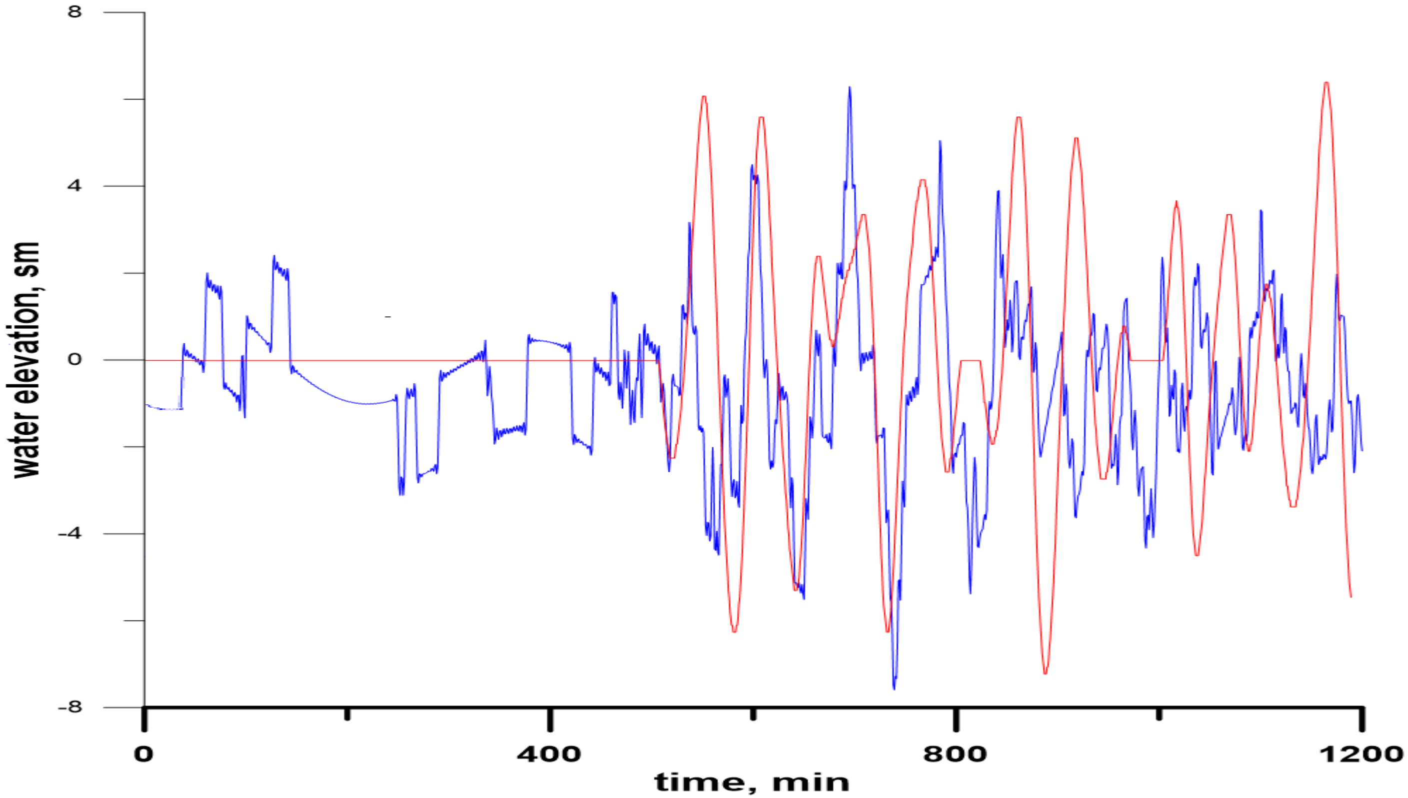
15 января 2022 г. случило
архипелаге Тонга, сопрово
расстояниях от вулкана,
уровня моря вдали от вул
вержением, зафиксирова

Ключевые слова: цунами, ч
DOI: 10.31857/S26867397

ВВЕДЕНИ

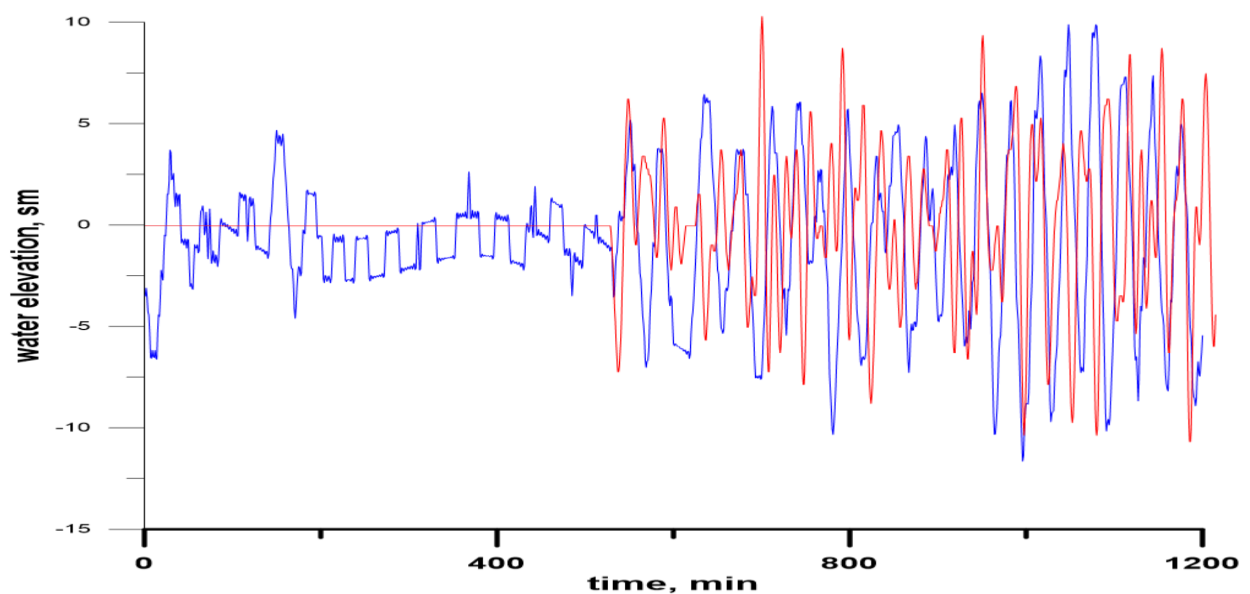






Посьет

Владивосток



Синяя – наблюдения

Красная - расчет

Acta Oceanol. Sin., 2022, Vol. 41, No. 8, P. 1–4
https://doi.org/10.1007/s13131-022-2056-7
http://www.aosocean.com
E-mail: ocean2@hyxb.org.cn

Cover Story

Oceanic internal waves generated by the Tongan volcano eruption

Xudong Zhang[1,2], Xiaofeng Li[1,2*]

[1] Key Laboratory of Ocean Circulation and Waves, Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China

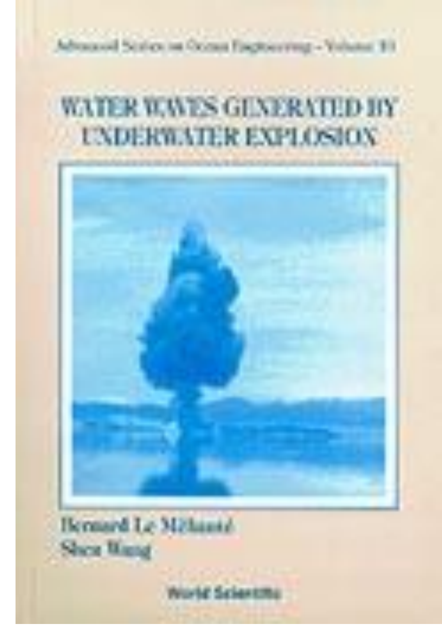
[2] Center for Ocean Mega-Science, Chinese Academy of Sciences, Qingdao 266071, China

Received 8 July 2022; accepted 26 July 2022

Internal waves (IW) are widely distributed at the marginal seas or continental shelves (Liu et al., 2013; Zhao and Alford, 2006; Zheng et al., 2007). They have an amplitude of up to hundreds of meters and wave crests of several hundreds of kilometers, and affect ocean environments significantly (Wyatt et al., 2019; Zhang et al., 2022). Satellite images have played an essential role in studying IWs owing to their global-scale observation ability and multi-band sensors in orbit (Alpers, 1985; Apel et al., 1976; Lindsey et al., 2018; Zheng et al., 2001). IW generations are generally reported closely related to wind, tides, topography, and currents (Li et al., 2008; Whalen et al., 2020). Large-amplitude long-wave-crest IW is frequently generated by tide-topography interactions, lee wave mechanism, resonant mechanism, or internal tide steeping in the marginal seas (Xie et al., 2022). Small-scale IW is generated by plume mechanisms or other small-scale disturbances in coastal ocean areas (Alford et al., 2015; Jackson et al., 2012). However, IWs are rarely observed in open ocean areas because of the strong dispersion effect in the deep ocean. Here we report the first observation of IWs generated by a volcano, the Tongan volcano, eruption in the southwest of the Pacific Ocean on January 15, 2022.

1. Пелиновский Е.Н. *Гидродинамика волн цунами*. Нижний Новгород: 1996.
2. Mirchina N., Pelinovsky E. Estimation of underwater eruption energy based on tsunami wave data. *Natural Hazards*, 1988, 1, 277 - 283.
3. Choi B.H. et al. Simulation of the trans-oceanic tsunami propagation due to the 1883 Krakatau volcanic eruption. *Natural Hazards and Earth System Sciences*, 2003, 3, 321 – 332.
4. Pelinovsky E. et al. Analysis of tide-gauge records of the 1883 Krakatau tsunami. *Tsunamis: case studies and recent developments*, Springer, 2005, 57-77.
5. Pelinovsky E. et al. Tsunami generated by the volcano eruption on July 12-13 2003 at Montserrat, Lesser Antilles. *Science of Tsunami Hazards*, 2004, 22, 44-57.
6. Torsvik, T. et al. Numerical simulation of tsunami event during the 1996 volcanic eruption in Karymskoe lake, Kamchatka, Russia. *Natural Hazards and Earth System Sciences*, 2010, 10, 2359-2369.
7. Dogan G. et al. Numerical simulations of December 22, 2018 Anak Krakatau tsunami and examination of possible submarine landslide scenarios. *Pure and Applied Geophysics*, 2021, 178, 1-20.
8. Talipova T., et al. Internal tsunami waves in the stratified ocean, induced by explosive volcano eruption: parametric source. *Physics of Fluids* 2024, 36, 4, 042110

Explosive Volcano Eruption



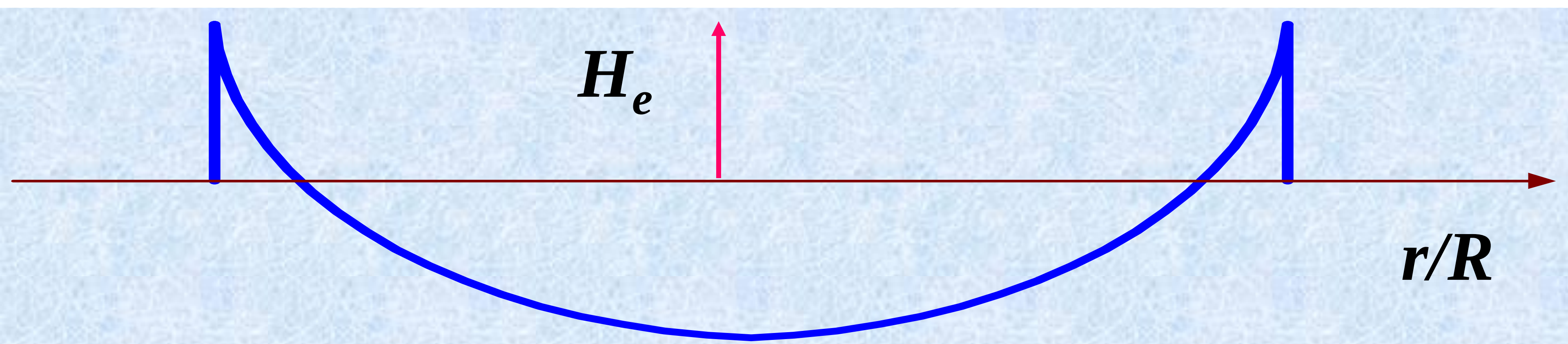
Equivalent Source (*Le Mehaute*)

$$H_e \sim E^{0.24}$$

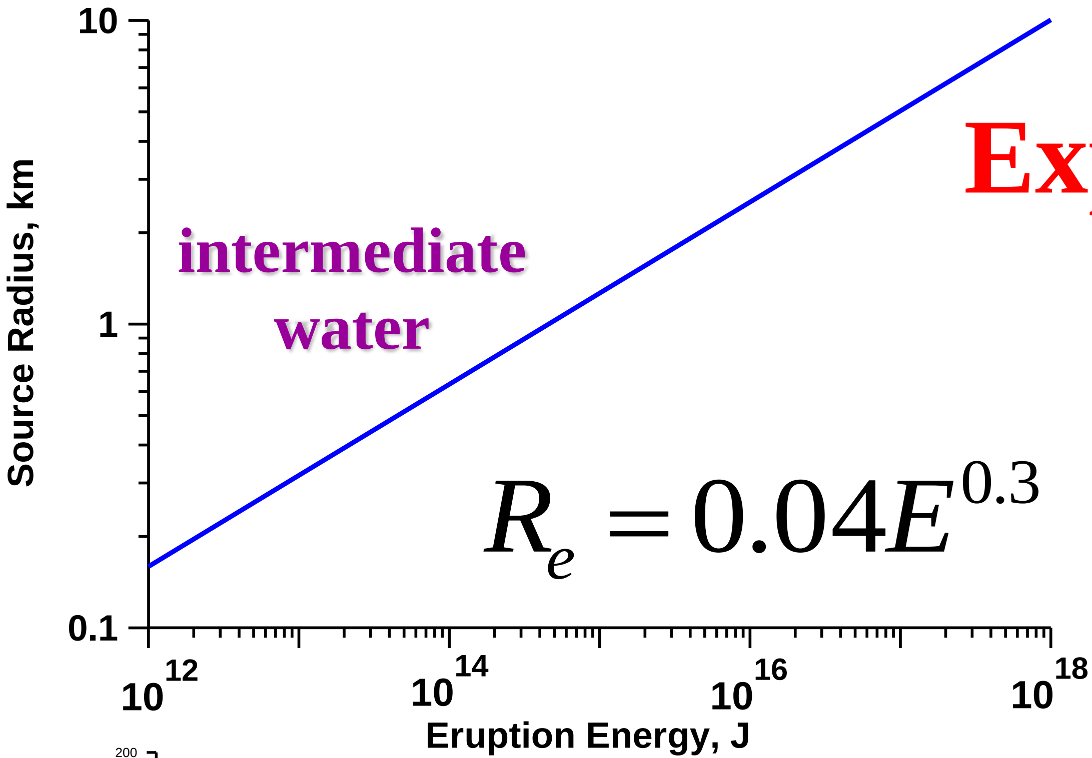
$$R \sim E^{0.3}$$

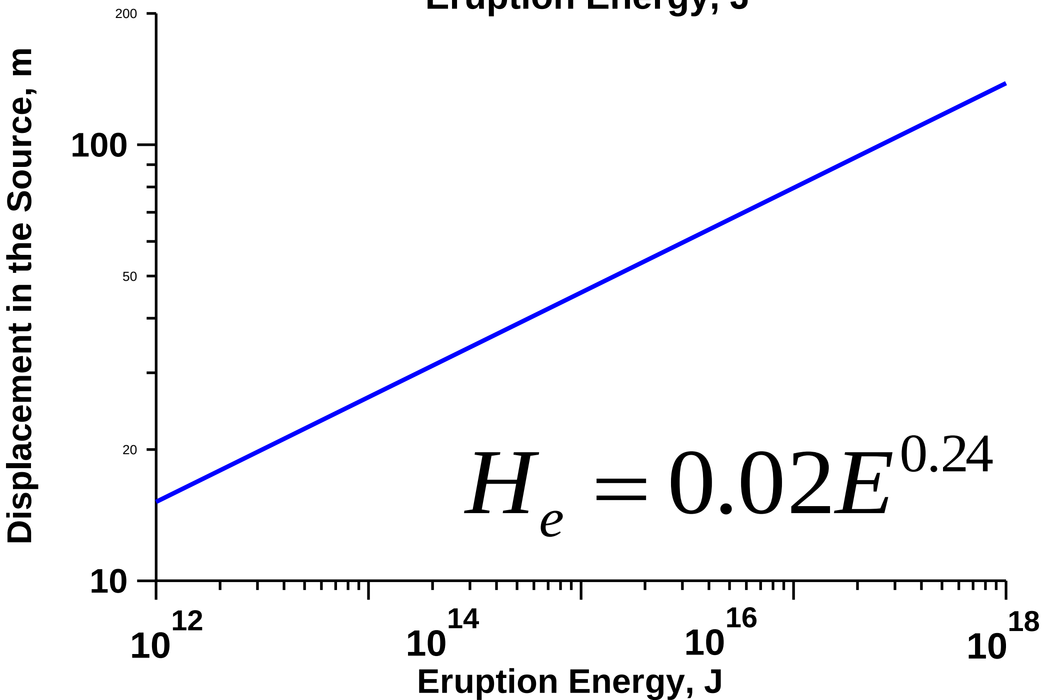
***W* - eruption energy**

$$\eta_e(r) = H_e[2(r/R)^2 - 1]$$



Explosive Tsunamis





1883
Krakatau eruption
8.4×10^{17} Joules
$R_e \sim 3.5$ km
$H_e \sim 220$ m

Linear potential model

$$\Delta\Phi + \frac{\partial^2\Phi}{\partial z^2} = 0$$

Free surface

$$\frac{\partial^2\Phi}{\partial t^2} + g\frac{\partial\Phi}{\partial z} = 0$$

Sea bottom

$$\frac{\partial\Phi}{\partial z} = 0$$

Water Displacement

$$\eta = -\frac{1}{g}\frac{\partial\Phi}{\partial t}(z=0)$$

Exact Linear Solution

$$\eta(r,t) = \int_0^\infty k\,dk\,S(k)\,J_0(kr)\cos\left(\omega(k)t\right)$$

with exact dispersion relation

$$\omega(k) = \sqrt{gk\tanh(kh)}$$

where

$$S(k) = \int_0^\infty r\,dr\,\eta(r)\,J_0(kr)$$

Method of Stationary Phase

$$\eta(r,t) = \int_0^\infty k\,dk\,S(k)\,J_0(kr)\cos\big(\omega(k)t\big)$$

for large time and distance

$$\eta(r,t) \approx \sqrt{\frac{k c_{gr}}{2\pi\,|\,dc_{gr}/dk\,|}}\,\frac{S(k)}{r}\cos[\omega(k)t - kr - \pi/4]$$

where

$$c_{gr}(k) = \frac{d\omega}{dk} = \frac{r}{t}$$

Variable Amplitude

$$H = \sqrt{\frac{kc_{gr}}{2\pi\,|\,dc_{gr}/dk\,|}}\,\frac{S(k)}{r} = \frac{Q(k)}{r}$$

Q(k) has one or several maxima

Max[H] = Max[Q]/r

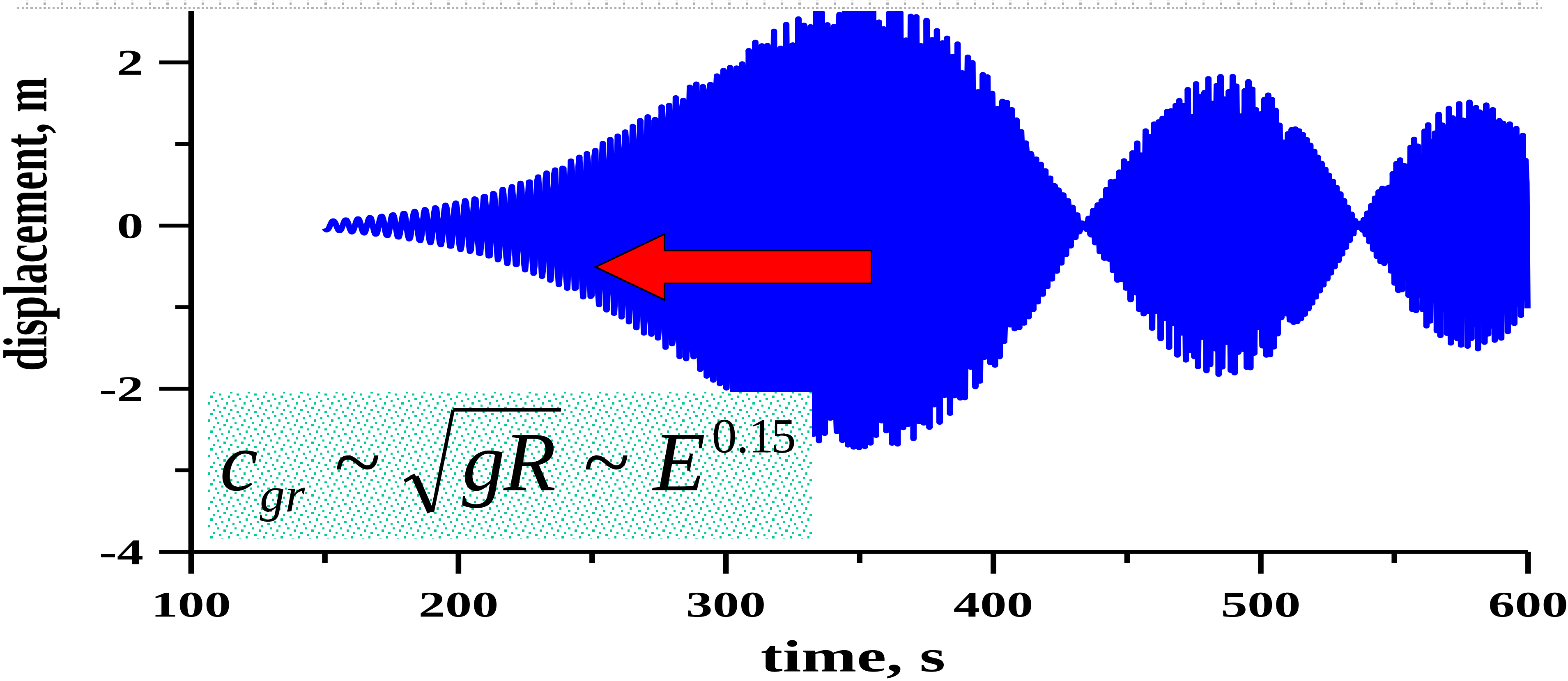
$$c_{gr}(k) = \frac{d\omega}{dk} = \frac{r}{t}$$

Location of maxima

Wave Field far from the Source

(linear deep water)

$$\eta(r,t) \approx \sqrt{2}\,\frac{H_m R}{r}\,J_3\left(\frac{gRt^2}{4r^2}\right)\cdot\cos\left(\frac{gt^2}{4r}\right)$$



$$c_{gr} \sim \sqrt{gR} \sim E^{0.15}$$

Wave of maximum amplitude

$$H \approx 0.6 H_e \frac{R}{r}$$

height

$$T \approx \pi \sqrt{R / g}$$

period

$$c_{gr} \approx \frac{\sqrt{gR}}{4}$$

speed

1952-1953 Myojin-sho volcano

Myōjin-Shō (ja:明神礁 みょうじんしょう) is a submarine volcano located about 450 kilometers south of Tokyo on the Izu-Ogasawara Ridge in the Izu Islands. Volcanic activity has been detected there since 1869.

Height 0.2-0.9 m Period 70-110 s

In tsunami 1% of energy $E \sim 10^{15}$ **J**

Mirchina N., Pelinovsky E.

Estimation of underwater eruption energy based on tsunami wave data.

***Natural Hazards*, 1988, 1, 277 - 283**

Myōjin-shō

Steam pours from the blocky summit of a lava dome formed at Myōjin-shō during a submarine eruption at the Bayonnaise Rocks volcano in 1952.

Elevation	-50 m (-164 ft)
Location	
Location	Izu Islands, Japan
Coordinates	31°55.1′N 140°1.3′E

The volcanic eruption from 1952 to 1953 was one of its biggest activities on record, with the repetitious appearance and disappearance of an island, which at one point reached over ten metres above sea level, before sinking after a severe volcanic explosion in September 1953. On September 24, 1953, a survey vessel, *No. 5 Kaiyo-Maru* of the Hydrographic Department of the Maritime Safety Agency, was destroyed by the volcano, with the loss of its crew of 31 (including the nine scientists studying the eruption). Consequently the Department developed *Manbou* (Sunfish), an unmanned radio operating survey boat, and has used it for the research of dangerous sea areas such as submarine volcanoes.

Tsunami generated by subaquatic volcanic eruptions

PAGEOPH, 2000, v. 157, 1135-1143

January 2, 1996, Karymskoye Lake, Kamchatka, Russia

"Explosions occurred every 4 to 12 min. Six explosions were observed with an average interval of 6 min"

Nat. Hazards Earth Syst. Sci., 10, 2359–2369, 2010
www.nat-hazards-earth-syst-sci.net/10/2359/2010/
doi:10.5194/nhess-10-2359-2010

Natural Hazards and Earth System Sciences

Numerical simulation of a tsunami event during the 1996 volcanic eruption in Karymskoye lake, Kamchatka, Russia

T. Torsvik[1], R. Paris[2], I. Didenkulova[3,4], E. Pelinovsky[4], A. Belousov[5], and M. Belousova[5,6]

[1]Bergen Center for Computational Science, Uni Research, Bergen, Norway
[2]CNRS-GEOLAB, Clermont-Université, 4 rue Ledru, 63057 Clermont-Ferrand, France
[3]Laboratory of Wave Engineering, Institute of Cybernetics, Tallinn, Estonia
[4]Department of Nonlinear Geophysical Processes, Institute of Applied Physics, Nizhny Novgorod, Russia
[5]Earth Observatory of Singapore, Nanyang Technological University, Singapore
[6]Institute of Volcanology & Seismology, Petropavlovsk-Kamchatsky, Russia

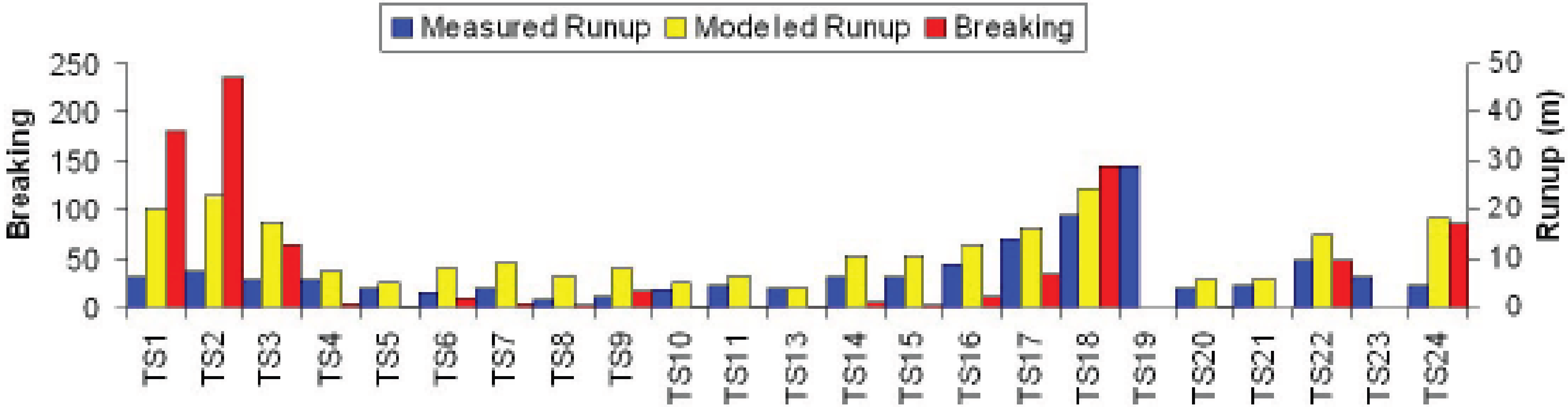
Based on predictions by Belousov and Belousova (2001) that the kinetic energy of the largest explosions were of the order $E \approx 2 \times 10^{12}$ J, the corresponding maximum initial surface displacement according to Le Mehaute's formula is $\eta_0 = 23.0$ m. The characteristic length scale $R = 200.0$ m is determined by the radius of the caldera created by the eruptions.

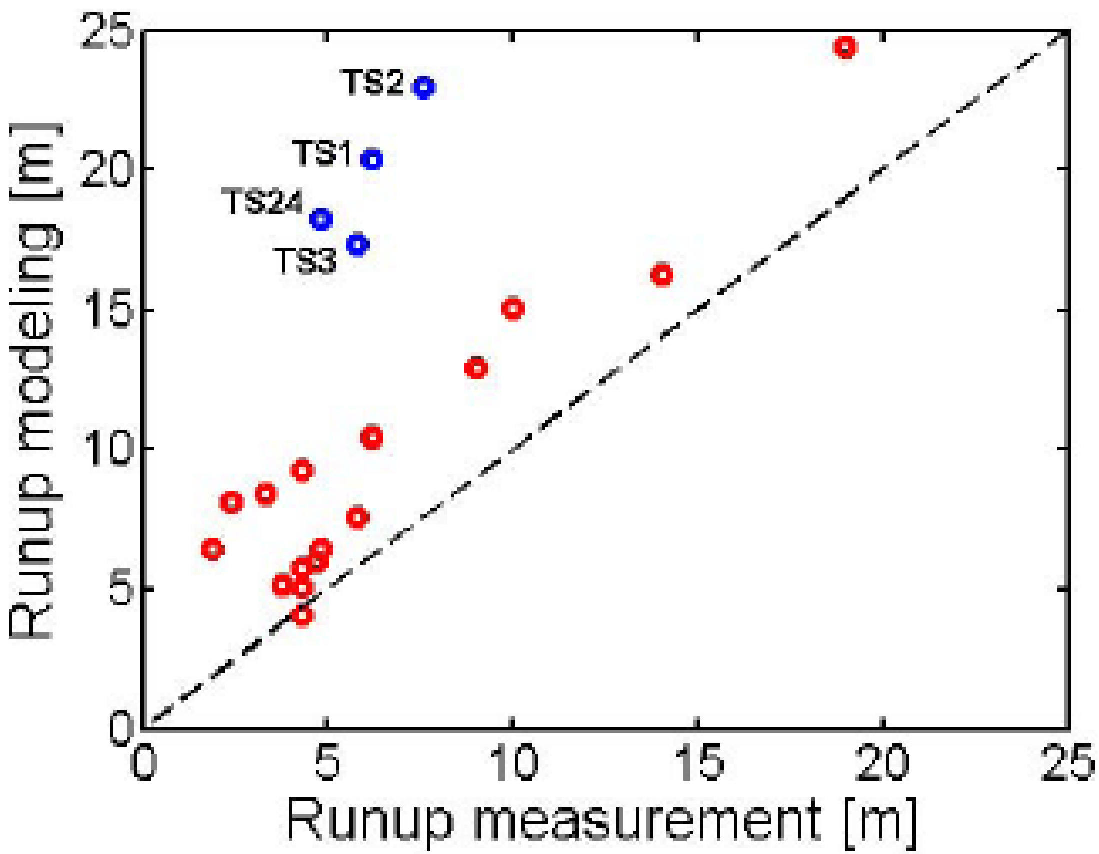
Numerical code of nonlinear –dispersive shallow-water theory

COULWAVE

Runup - analytical

$$\frac{R}{H_0} = 2\pi\sqrt{\frac{2L}{\lambda}}$$

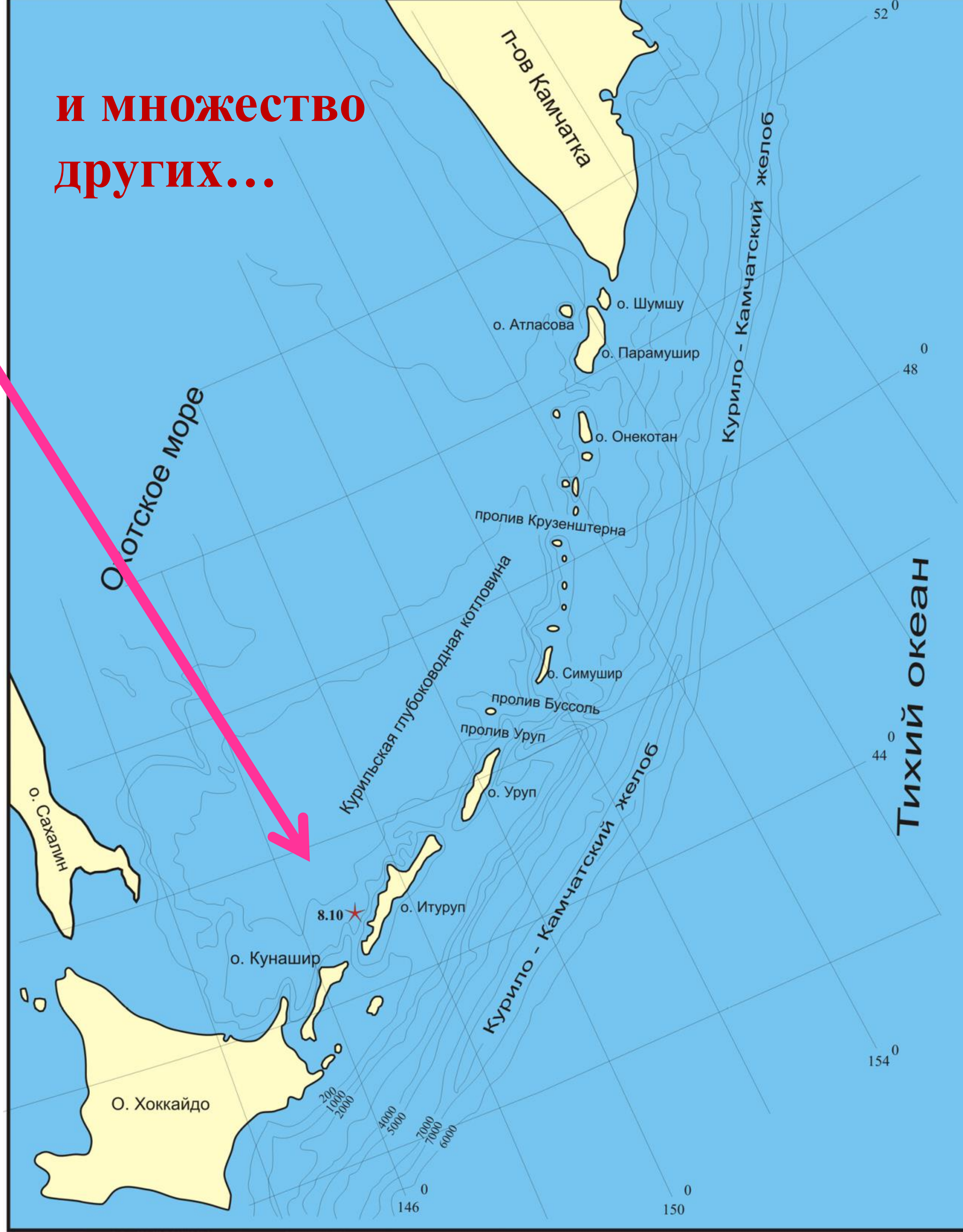




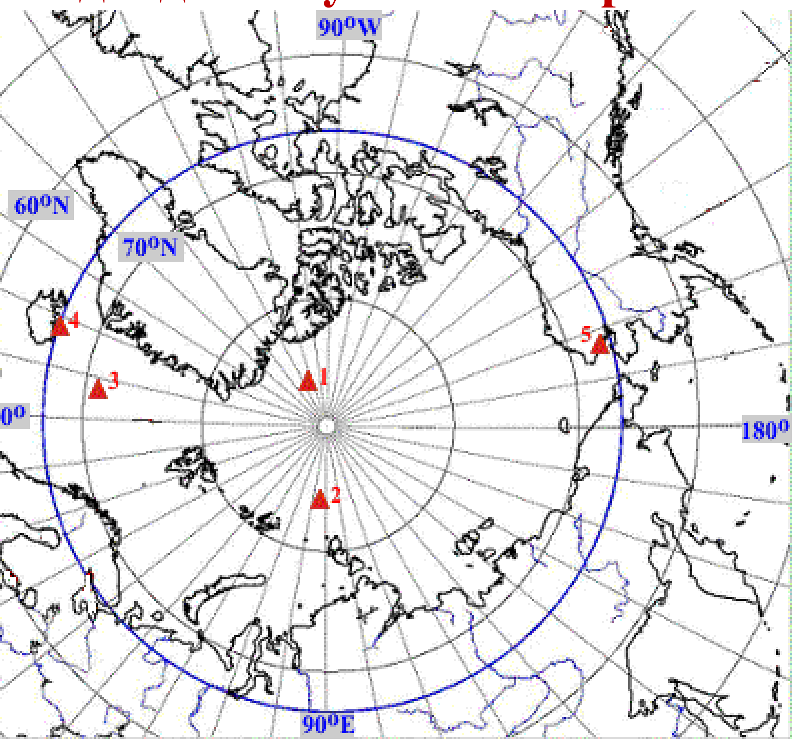
Very Good Comparison!

Ю.И. Блох и др.
ПОДВОДНЫЙ ВУЛКАН 8.10 (КУРИЛЬСКАЯ ОСТРОВНАЯ ДУГА)
ВЕСТНИК КРАУНЦ. НАУКИ О ЗЕМЛЕ. 2022. № 3. № 55

и множество других…



Подводные вулканы в Арктике



Physics of Fluids ARTICLE pubs.aip.org/aip/pof

Internal tsunami waves in a stratified ocean induced by explosive volcano eruption: A parametric source

Cite as: Phys. Fluids **36**, 042110 (2024); doi: 10.1063/5.0206121
Submitted: 29 February 2024 · Accepted: 2 April 2024 ·
Published Online: 18 April 2024

View Online Export Citation CrossMark

Tatiana Talipova,[1,2] Efim Pelinovsky,[1,3] and Ekaterina Didenkulova[1,3,a)]

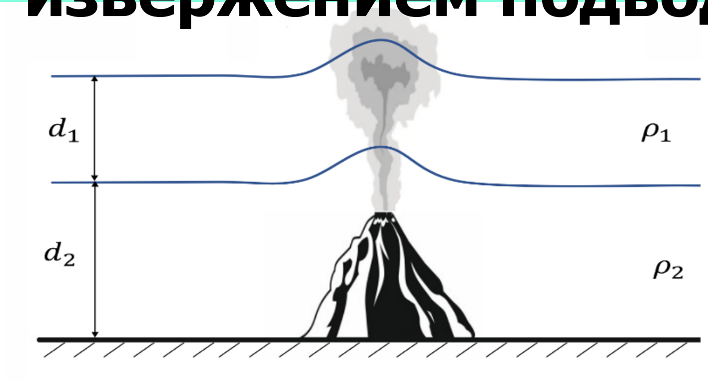
AFFILIATIONS

[1]A.V. Gaponov-Grekhov Institute of Applied Physics of the Russian Academy of Sciences, 46 Ulyanov Str., 603950 Nizhny Novgorod, Russia
[2]Il'ichev Pacific Oceanological Institute Far Eastern Branch, Russian Academy of Sciences, 43 Baltiyskaya Street, Vladivostok 690041, Russia
[3]Faculty of Informatics, Mathematics and Computer Science, HSE University, 25/12 Bolshaya Pecherskaya Street, 603155 Nizhny Novgorod, Russia

[a)]Author to whom correspondence should be addressed: edidenkulova@hse.ru

Open Access

Внутренние волны цунами, вызванные эксплозивным извержением подводного вулкана



нормировка: $K = kd_1$ $\Omega = \omega / N$ $N = g' / d_1$ $l = \dfrac{d_2}{d_1}$

монохроматическая волна:

$$\eta(x,t) = A\sin(kx - \omega t)$$

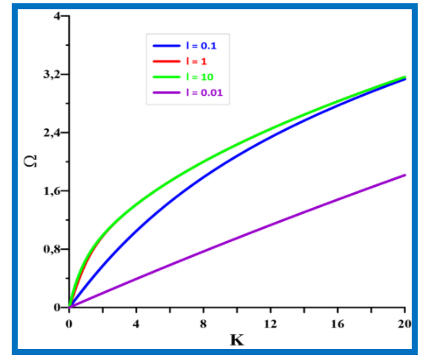
дисперсионное соотношение:

$$\omega^2 = g'\frac{k}{\coth(kd_1) + \coth(kd_2)}$$

$$g' = g\frac{\Delta\rho}{\rho} = g\frac{\rho_2 - \rho_1}{\rho}$$

дисперсионное соотношение:

$$\Omega^2(K;l) = \frac{K}{\coth(K) + \coth(Kl)}$$



групповая скорость:

$$c_{gr} = \frac{1}{2\Omega}\left\{\frac{1}{\coth K + \coth(Kl)} + \frac{K}{[\coth K + \coth(Kl)]^2}\left[\frac{1}{\sinh^2 K} + \frac{l}{\sinh^2(Kl)}\right]\right\}$$

1) $d_1 = d_2$:

(поверхностные волны)

$$\omega^2 = \frac{1}{2}g'k\tanh(kd)$$

2) d_2 бесконечен:

$$\omega^2 = g'\frac{k}{1 + \coth(kd_1)} = g'k\frac{\tanh(kd)}{1 + \tanh(kd)}$$

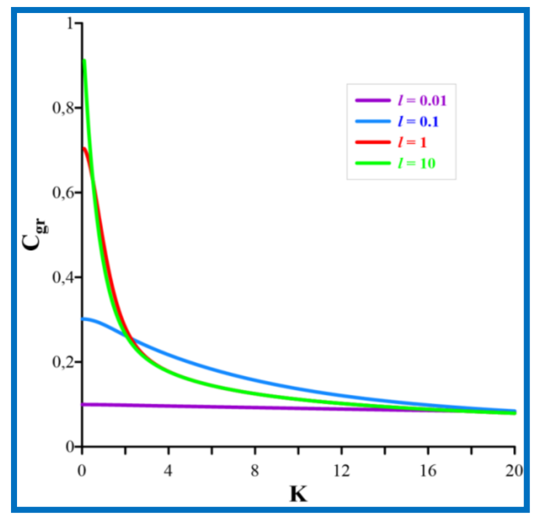
3) оба слоя тонкие:

(длинные волны)

$$\omega \approx \sqrt{g\frac{d_1 d_2}{d_1 + d_2}k\left[1 - \frac{k^2}{3}\frac{d_1^3 + d_2^3}{d_1 + d_2}\right]}$$

4) короткие волны:

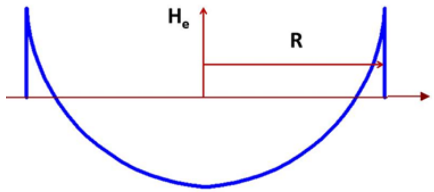
$$\omega^2 = \frac{1}{2}g'k$$



Внутренние волны цунами, вызванные эксплозивным извержением подводного вулкана

Параметрический очаг цунами (параболическая каверна):

$$\eta_e(r) = h\begin{cases} 2\left(\dfrac{r}{R}\right)^2 - 1 & r < R \\ 0 & r > R \end{cases}$$



Решение линейной задачи - решение Кранцера – Келлера (преобразование Ханкеля):

$$\eta(r,t) = \int_0^\infty kA(k)J_0(kr)\cos(\omega t)dk$$

$$A(k) = \int_0^\infty r\eta_e(r)J_0(kr)dr$$

$$\eta(r,t) = hR\int_0^\infty J_3(kR)J_0(kr)\cos(\omega t)dk$$

J_3 – функция Бесселя третьего порядка

волновое поле разбивается на группы

$$J_3(K\mu) = J_3(kR) = 0$$

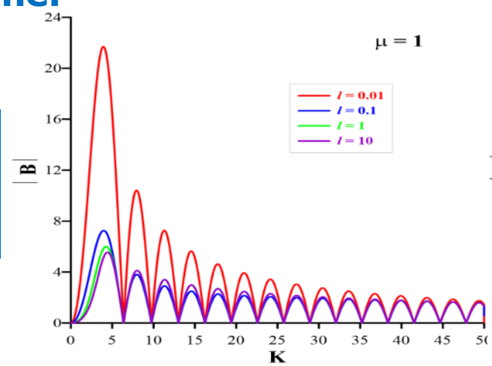
Характеристики внутренних волн в дальней зоне:

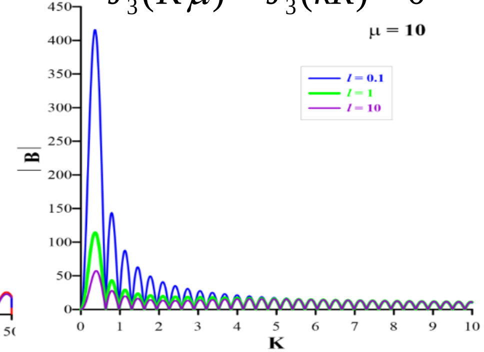
метод стационарной фазы:

$$\eta(r,t) \approx \frac{\eta_e R}{r}\sqrt{\frac{c_{gr}(k)}{k\,|dc_{gr}/dk|}}J_3(kR)\cos\left[kr - \omega(k)t - \frac{\pi}{4}\right]$$

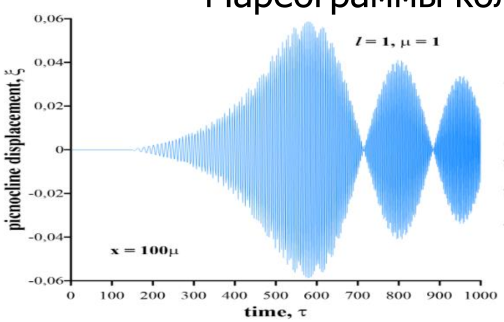
$$c_{gr}(k) = \frac{d\omega}{dk} = \frac{r}{t}$$

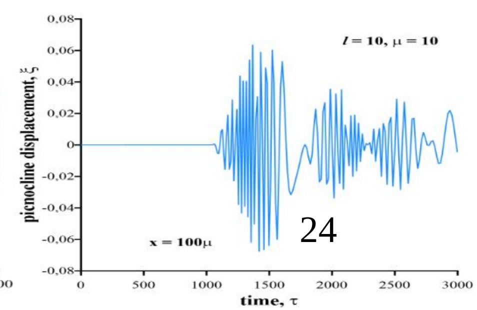
(поверхностные и внутренние волны)





Мареограммы колебаний пикноклина





Поле в безразмерных величинах:

$$\xi(x,\tau) \approx \frac{1}{x}B(K;l,\mu)\cos\left[Kx - \Omega(K)\tau - \frac{\pi}{4}\right]$$

$$c_{gr}(K) = \frac{d\Omega}{dK} = \frac{x}{\tau}$$

$$B(K;l,\mu) = \mu\sqrt{\frac{c_{gr}(K)}{K\,|dc_{gr}/dK|}}J_3(K\mu)$$

Поле течений на морской поверхности, вызываемое внутренними волнами

Поле горизонтальной скорости течений в верхнем слое:

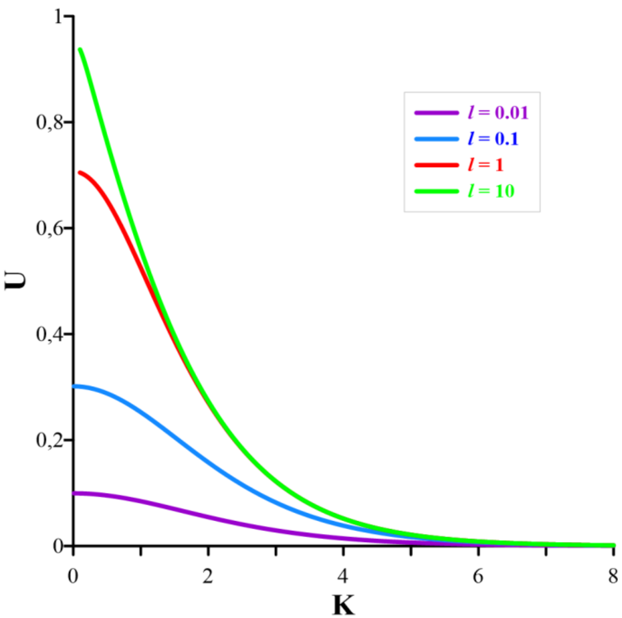
$$u(z,x,t) = \omega A \sin(kx - \omega t)\frac{\cosh(kz)}{\sinh(kd_1)}$$

на морской поверхности:

$$u(z=0,x,t) = \omega A \sin(kx - \omega t)\frac{1}{\sinh(kd_1)}$$

в безразмерном виде:

$$U(x,t) = \frac{u(z=0,x,t)}{NA} = \frac{\Omega}{\sinh(K)}\sin(kx - \omega t)$$



скорость течения на морской поверхности в дальней зоне:

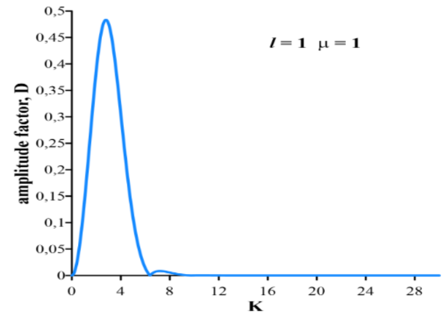
$$u(r,t) \approx \frac{\eta_e R\omega(k)}{r\sinh(kd_1)}\sqrt{\frac{c_{gr}(k)}{k\,|dc_{gr}/dk|}}J_3(kR)\cos\left[kr - \omega(k)t - \frac{\pi}{4}\right]$$

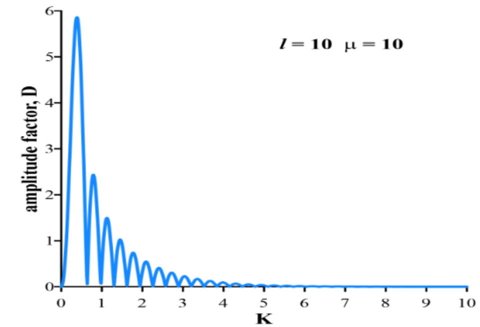
скорость течения в безразмерном виде:

$$u(r,t) = N\eta_e U(x,\tau;\mu,l)$$

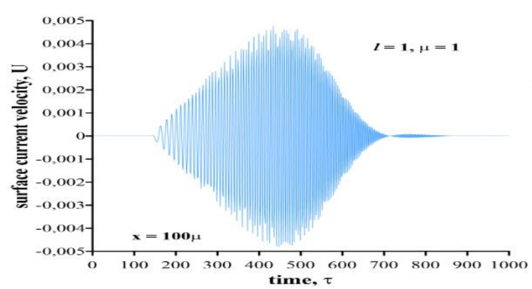
$$U(x,\tau) \approx \frac{1}{x}B(K;l,\mu)\frac{\Omega(K)}{\sinh(K)}\cos\left[Kx - \Omega(K)\tau - \frac{\pi}{4}\right]$$

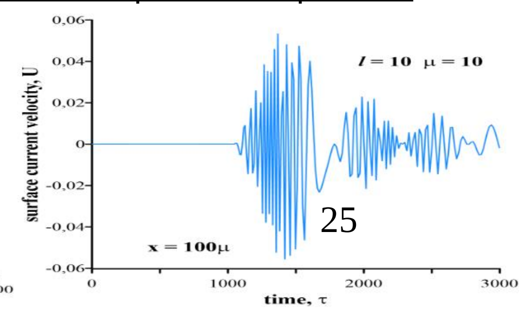
амплитуда вариаций скорости течений, *D*





Осциллограммы скорости течений на морской поверхности





Summary:

- ❖ Far-field can be analyzed with equivalent tsunami source
- ❖ Modeling of tsunami source in basic hydrodynamic equations
- ❖ Near-field modeling with strongly nonlinearity
- ❖ Parametrization of other volcano sources: pyroclastic flow

F. SCHINDELE, L. KONG, E. LANE, R. PARIS, M. RIPEPE, V. TITOV, and R. BAILEY. A Review of Tsunamis Generated by Volcanoes: Source Mechanism, Modelling, Monitoring and Warning Systems. *Pure and Applied Geophysics*, 2024 vol. 181, 1745–1792