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EFFECT OF SUBMARINE EARTHQUAKES ON A STRATIFIED OCEAN

M. A. Nosov

Temperature anomalies were discovered on the water surface above large submarine earthquakes in the Solomon Islands and Philippines regions. Physical mechanisms that generate these anomalies and possible accompanying phenomena are discussed.

Submarine earthquakes are known to produce strong disturbances in water near their epicenters where they manifest themselves, on eye witness evidence, as violent water swirling, water columns spurting upward, generation of very steep standing waves with amplitudes as large as 10 m, and water turbidity over tens of miles. These phenomena are called seaquakes. A seaquake will be treated in what follows as a set of hydrodynamic, usually nonlinear, phenomena initiated by coseismic bottom motion and occurring in the meizoseismal area (zone of maximum shaking) of a submarine earthquake. This above definition does not exclude the initial phase of tsunami generation, although a tsunamigenic earthquake is not bound to produce a seaquake; and conversely, an earthquake that produced a seaquake is not necessarily a tsunamigenic one. A seaquake can last as long as 10 min and the area involved can be as large as a few thousands of square kilometers.

The possibility that the ocean surface can be cooled by a submarine earthquake was mentioned in [1]. Soloviev and Go [2] reported the appearance of abnormal color patches on the ocean surface in the area of a submarine earthquake. In my previous paper [3] I showed by estimates derived using the theory of dimensionality and empirical relations for the source parameters of tsunamigenic earthquakes that the energy released by an earthquake is amply sufficient to mix the ocean (and hence to cool the surface) above the meizoseismal area down to uniformity in a matter of minutes. It goes without saying that the bare availability of enough energy is still not sufficient to produce the phenomenon in question; there should also exist a certain physical mechanism that would transmit energy from a moving bottom to the water layer, thus stimulating turbulent or translational vertical motion of the water.

We investigated a mechanism relying on the loss of stability in a fluid resting on an oscillating bottom using a physical model [4]. Our principal result was that we demonstrated the possibility of a dynamic regime in which vertical turbulent transfer increased by more than three orders of magnitude.

Ostrovskii and Papilova [5] provided a theoretical justification for the possible generation of nonlinear flows (acoustic wind) in a fluid above an oscillating bottom.

Another possible energy transfer mechanism for bottom-to-fluid exchange is resonance. When the water layer with a free upper surface and thickness H overlying a rigid bottom is assumed to be compressible, this layer will evidently be a natural resonator having the free frequencies

$$\nu_k = \frac{c(1+2k)}{2H},$$

where c is the velocity of sound in water, $k = 0, 1, 2, 3, \ldots$ The frequencies are 0.083, 0.25, 0.42, 0.58, ... Hz with a mean ocean depth of 4500 m and the velocity of sound in water equal to 1500 m. This set of

Moscow State University, Faculty of Physics.

Table 1

Major Seismic Events for Solomon Islands Area

Date (1996)	GMT Time	S. lat., deg	E. long., deg	Depth of focus	Magnitude		
					Mw	Mb	Ms
29 Apr	14 h 40 min 41.0 s	6.65	155.07	44.0	7.2	6.3	7.5
30 Apr	5 h 27 min 41.8 s	6.93	154.94	33.0	5.6	5.3	5.4
1 May	3 h 30 min 3.5 s	7.27	155.24	40.0	5.2	5.0	4.5
1 May	9 h 21 min 24.2 s	6.88	154.90	33.0	6.0	5.5	5.9
1 May	10 h 5 min 9.7 s	7.06	154.99	33.0	6.1	5.4	6.0
1 May	13 h 52 min 34.4 s	6.73	155.05	33.0	5.6	5.1	0.0
2 May	2 h 32 min 35.2 s	6.83	154.75	33.0	6.0	5.3	5.9
2 May	6 h 38 min 24.3 s	6.51	154.65	33.0	5.5	5.3	5.3
2 May	13 h 34 min 28.9 s	4.42	155.02	500.0	6.6	5.6	0.0
3 May	3 h 7 min 13.4 s	7.30	155.01	33.0	5.6	4.9	0.0
3 May	23 h 24 min 10.6 s	7.31	155.08	33.0	5.3	5.0	4.8
4 May	9 h 49 min 51.9 s	6.71	154.58	33.0	5.3	4.9	0.0
11 May	13 h 43 min 45.0 s	6.93	155.08	33.0	6.3	5.7	6.3
11 May	16 h 29 min 25.3 s	7.10	154.80	33.0	5.6	5.1	5.3

resonant frequencies falls in the range of seismic frequencies. It follows that energy can very effectively be transmitted from the moving bottom to the water mass with subsequent dissipation; the turbulent mechanism will dominate during the earlier phases of the process owing to considerable spatial extents of the associated motion, which too will intensify the vertical exchange.

Mixing involves the following possible consequences. 1. Deep water rising to the surface produces an extensive cold zone on the ocean surface with a corresponding response from the atmosphere. 2. Biogenes are transported to the surface layer which is usually depleted in these substances, hence a short-lived but appreciable increase in phytoplankton is possible similarly to that occurring in upwelling zones (some phytoplankton species can breed as fast as 2–3 fissions per day). Considering that phytoplankton is the initial link in the nutrition chain and controls the bioproductivity of water, phenomena like migrations of fish and sea animals are possible. 3. The evolution of a zone having a disturbed and, therefore, unstable stratification must produce large internal waves with amplitudes exceeding those of internal tsunami waves by many times, the latter being comparable with the residual bottom displacement [6, 7].

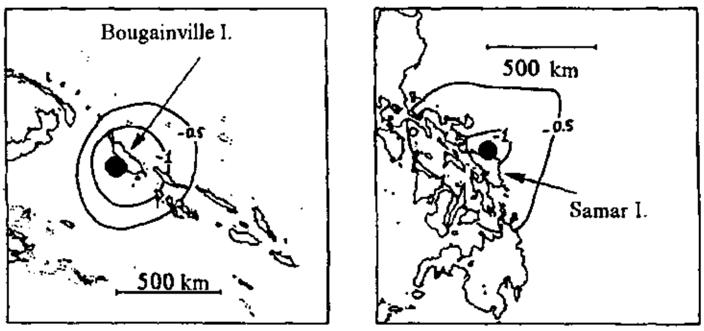
The three above-mentioned phenomena allow a search for and identification of these cases in nature: (1) ocean surface temperature is easily measurable from satellites by analysis of infrared photographs in the atmospheric transparence window; (2) phytoplankton concentration can also be determined by satellite observations from ocean color, i.e., from a-chlorophyll concentration [8]; (3) data of buoy stations on transformations of the vertical temperature profile in conjunction with weather observations would provide complete and compelling evidence of the event, provided the station was in a seaquake area; in addition, these stations can also record the passage of internal waves mentioned above.

In this study cold anomalies were discovered above large submarine earthquakes from a joint analysis of temperature anomaly maps for the world ocean and NEIS catalogs [9]. Two appearances of an anomaly were detected around Bougainville I. in the Solomon Islands on May 6 and 12, 1996. A cold anomaly was observed in the Samar I. area, the Philippines on June 13, 1996. These occurrences were preceded by large seismic shocks (Tables 1 and 2).

Table 2

Major Seismic Events for Samar I. Area

Date (1996)	GMT Time	S. lat., deg	E. long., deg	Depth of focus	Magnitude		
					Mw	Mb	Ms
11 June	18 h 23 min 5.6 s	12.74	125.41	28.5	7.1	6.0	7.0
12 June	0 h 30 min 18.5 s	13.24	125.51	33.0	5.5	4.9	0.0
14 June	15 h 4 min 41.3 s	12.97	124.93	27.4	6.1	5.6	5.8



a b

Fig. 1

Fragments of maps with isotherms showing the deviation of ocean surface temperature from the long-term mean for Bougainville I. (*a*) and Samar I. (*b*). The black circles indicate the epicenters of largest earthquakes.

Figure 1 shows fragments of maps with plotted isotherms (reflecting deviations of the temperature from long-term values) for Bougainville and Samar islands as determined for the dates May 6 and June 13, 1996, respectively. Each fragment is 1550 by 1550 km. The black circles indicate the epicenters of the largest earthquakes.

The maximum temperature deviations were 3 °C for Bougainville I. and 1 °C for Samar I. The typical horizontal size of these anomalies was about 500 km. They existed during as much as 3 days. The time behavior of the anomalies is discussed in more detail in [10].

The contour lines in Fig. 1 are based on data provided by the United States Fleet Numerical Meteorology and Oceanography Center (FNMOC). The Center reports a worldwide distribution of ocean surface temperature twice every 24 hours. The spatial resolution is about 40 km. We note that data from an independent source confirm the existence of temperature anomalies in the Bougainville and Samar islands areas for the time period in question (Bureau of Meteorology, Australia). These data have lower time and space resolutions: 7 days and 100 km, respectively.

An analysis of infrared satellite photographs of the areas (GMS-5, 10.5–11.5 μm channel) for the time periods of interest did not reveal any tropical cyclones or other atmospheric phenomena that might have caused these anomalies.

According to data provided by the 5S156E anchored buoy station (Tropical Atmosphere Ocean (TAO) Array), located about 100 km northeast of Bougainville I. with coordinates of 5° S and 156° E, that is, practically at the boundary of the zone of abnormal temperature, the maximum daily mean wind velocity at 4 m height was 4.7 and 9.6 m/s during the time period under study (April 20 to June 10, 1996) on May 3 and 11, respectively.

In addition to meteorological information, the TAO Array buoy stations measure water temperature at 11 depths between 1 and 500 m. Figure 2*a* shows an average (April 20 to June 10, 1996) temperature profile

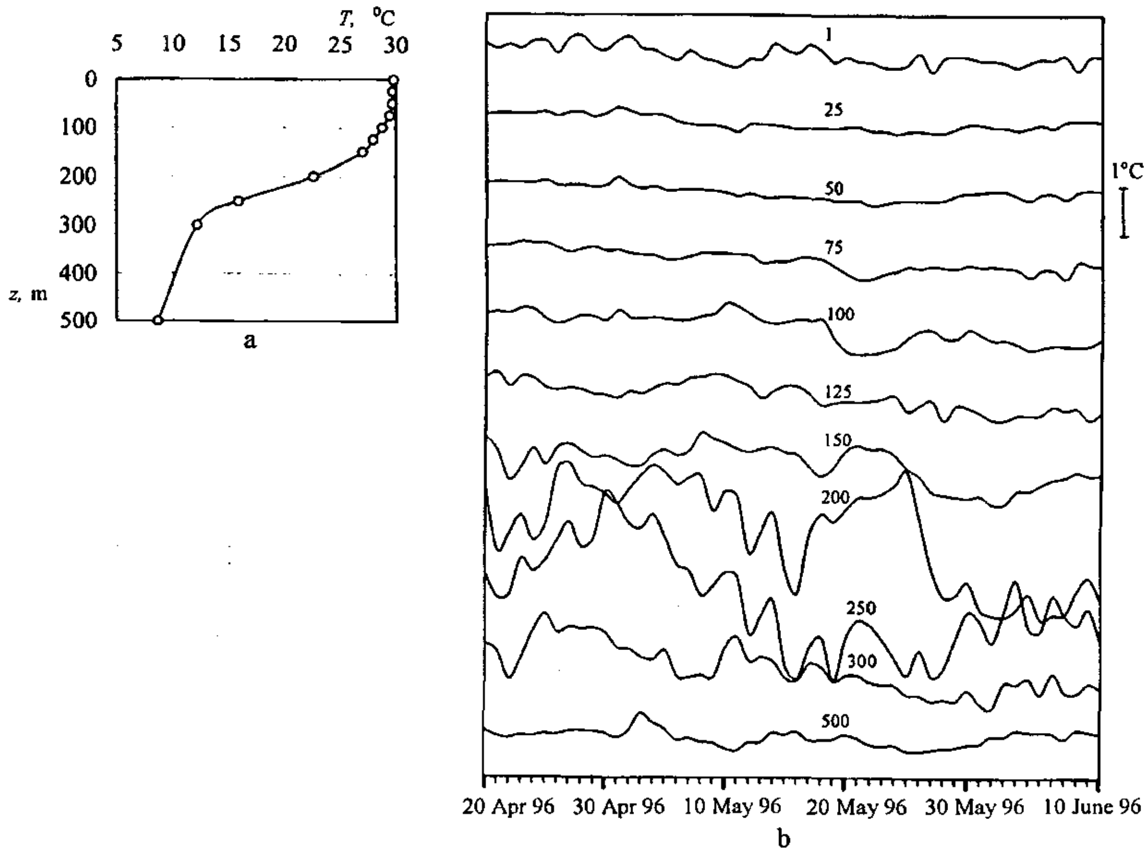


Fig. 2

Averaged (over April 20 to June 10, 1996) vertical temperature profile based on data from a buoy station with coordinates 5° S, 156° E (*a*) and the time behavior of water temperature (*b*) at various depths (depths in meters are above the curves).

based on data from the 5S156E buoy station. Figure 2*b* presents the time behavior of the temperature at the eleven depths. These data are shown as differences between actual daily means and average temperature for the same time period. Since the station was situated almost at the boundary of the anomalous zone, the temperature decrease at 1 m is poorly visible during the days of seismic activity. One notes, however, a long-period internal wave recorded by this station during the time of May 17–27, 1996. The passage of that wave caused an appreciable temperature decrease at depths of 75 and 100 m, and a temperature rise at 150 and 200 m, while the 125 m level was practically unaffected by any temperature changes. This internal wave might have resulted from the evolution of the volume of disturbed stratification due to intensive vertical mixing: temperature increased in the deeper layers and decreased in the upper ones. Knowing the approximate horizontal size of the surface temperature anomaly ($d \cong 500$ km) and the period of the internal wave ($T \cong 10$ days), this wave being possibly excited by the disintegration of the abnormally stratified volume, one can evaluate the velocity of the internal wave as

$$v = d/T.$$

The resulting velocity value (0.6 m/s) is quite reasonable by order of magnitude for an internal wave. We will note here that, since Bougainville I. was surrounded by the anomalous zone, the evolution of the latter must have been significantly affected by bottom topography, so that numerical modeling is needed to get a detailed picture of the evolution. Besides the 5S156E station, the anchored TAO buoy stations nearest to Bougainville I. were 2S156E and 0N156E. An analysis of correlation between temperatures as functions of time at thermocline depths among these three stations cannot yield reliable results because of insufficient number of data points (all data were daily means), so that one cannot definitely assert that an internal wave reached the 2S156E and 0N156E stations propagating from Bougainville I.

Note that the internal wave recorded by 5S156E could not possibly be an internal tsunami, because its amplitude found as

$$A = \frac{\Delta t_{\max}}{\partial t/\partial z},$$

was about 25 m ($\Delta t_{\max}$ is the maximum temperature deviation in the internal wave at one of the above depths, $\partial t/\partial z$ is the mean (over that time) vertical temperature gradient at the same depth). An internal tsunami wave of this amplitude could only be excited by a bottom movement of comparable amplitude, and the generation of an internal tsunami wave in the absence of an ordinary "surface" tsunami seems to be extremely unlikely. Note that this sequence of seismic shocks in the Bougainville I. area did not generate any appreciable tsunami waves.

We will note in conclusion that a recent publication in [11] describes the appearance of a temperature anomaly due to the 1995 Mexico earthquake and tsunami. The 15-hour records from sensors of two anchored buoy stations deployed near the earthquake epicenter (18° 51.5′ N, 104° 8.4′ W) showed an abrupt drop of water temperature (by 6 °C) and a salinity rise of 0.5‰ at 50 m depth. The anomaly was recorded 175 min after the tsunami wave arrived at the buoy stations and lasted for more than 3 hours. Very probably, it was just an internal tsunami wave that was observed. Unfortunately, no information is given in [11] as to the exact locations of the stations or the temperature and salinity profiles, which prevents one from ascertaining the origin of this phenomenon.

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REFERENCES

1. B.W. Levin, V. Kaistrenko, A. Kharlamov, et al., in: *Proc. IUGG/IOC Int. Tsunami Symp.*, Wakayama, Japan, p. 309, 1993,
2. S.L. Soloviev and Ch.N. Go, *A Tsunami Catalog for the Eastern Coast of the Pacific Ocean* (in Russian), Moscow, 1974.
3. M.A. Nosov, *Vulkanologiya i Seismologiya,* no. 2, p. 95, 1997.
4. M.A. Nosov and P.S. Ivanov, *Vulkanologiya i Seismologiya,* no. 1, p. 102, 1997.
5. L.A. Ostrovskii and I.A. Papilova, *Akusticheskii Zhurnal,* vol. 20, no. 1, p. 79, 1974.
6. S.F. Dotsenko, *Issledovaniya Tsunami,* no. 3, p. 7, 1988.
7. J.L. Hammack, *J. Phys. Oceanography,* vol. 10, no. 9, p. 1455, 1980.
8. M.J. Behrenfeld and P.G. Falkowski, *Limnology and Oceanography,* vol. 42, no. 1, p. 1, 1997.
9. M.A. Nosov, in: *Abstracts, All-Union Sci. Conf. "Interaction in the Lithosphere-Hydrosphere-Atmosphere System"* (in Russian), p. 70, Moscow, 1996.
10. B.V. Levin, M.A. Nosov, V.P. Pavlov, and L.N. Rykunov, *Dokl. Ross. Akad. Nauk,* vol. 358, no. 3, p. 1, 1998.
11. A.E. Filonov, *EOS,* vol. 78, no. 3, p. 21, 1997.