Meteorological tsunamis: Destructive atmosphere-induced waves observed in the World Ocean

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S. Monserrat, I. Vilibić, A. Drago and I. Fine
Sumatra tsunami of 26 December 2004

Casualties: >226,000

13 countries:
Indonesia
Thailand
India
Sri Lanka
Maldives
Mynmar
Malaysia
Bangladesh
Somalia
Kenya
Tanzania
South Africa
Seychelles Is

Citizens of > 60 countries all over the World…
Thailand coast: First arrival + 15 minutes

First the water went out -- some went to look

Phuket, Thailand
(Photos by Ernesto Rodriguez)
Then the water came in....

Krabi, Thailand
.... death and destruction...

Phuket, Thailand

(photos by Helmut Issels)
... not everyone was concerned
Meteorological tsunami ("šćiga")

Vela Luka, Croatia

21 June 1978
Meteorological tsunami (‘rissaga’)

Ciutadella Harbour, Menorca Island, Baleares, Spain

Rabinovich and Monserrat, 1996, 1998
Monserrat et al., 1998

21 June 1984
Meteorological tsunami

“Rissaga”
waves in
Ciutadella
Harbour
(Menorca I.)
15 June 2006

More than 40
damaged boats.
Total loss:
~ 30 mln euros.

(Montserrat, Vilbic, and Rabinovich, 2006)
Two “tsunamis” at the same site (Beaufort, NC, USA) (1) MT: generated by a passing storm (meteotunami); (2) T: associated with the Sumatra 2004 tsunami.
2001 Peru Tsunami \((M_w = 8.4)\)

British Columbia, Canada

Langara: 9.5 cm
Queen Charlotte: 3.7 cm
Bella Bella: 6.7 cm
Port Hardy: 5.4 cm
Winter Harbour: 12.9 cm
Tofino: 15.1 cm
Bamfield: 9.7 cm
Victoria: 7.4 cm

2001 Queen Charlotte Tsunami \((M_w = 6.3)\)

Port Hardy: 14.5 cm
Winter Harbour: 22.7 cm
Tofino: 18.2 cm
Bamfield: 11.3 cm
“...The spectra of tsunamis from different earthquakes are similar at the same location but are quite different for the same event for nearby locations...” [Omori, 1902]
Source functions of tsunami and meteotsunami recorded at the same site (Ibiza Island, Baleares)
The **Mediterranean Sea** is a region where **meteotsunamis** are common.
<table>
<thead>
<tr>
<th>Region</th>
<th>Local name</th>
<th>Typical period</th>
<th>Maximum height (m)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nagasaki Bay, Japan</td>
<td>Abiki</td>
<td>35 min</td>
<td>4.78</td>
<td>Honda et al. [1908], Akamatsu [1982], Hibiya and Kajiura [1982]</td>
</tr>
<tr>
<td>Pohang Harbour, Korea</td>
<td>-</td>
<td>25 min</td>
<td>&gt; 0.8</td>
<td>Chu [1976], Park et al. [1986]</td>
</tr>
<tr>
<td>Longkou Harbour, China</td>
<td>-</td>
<td>2 h</td>
<td>2.93</td>
<td>Wang et al. [1987]</td>
</tr>
<tr>
<td>Ciutadella Harbour, Menorca</td>
<td>Rissaga</td>
<td>10.5 min</td>
<td>&gt; 4.0</td>
<td>Fontseré [1934], Ramis and Jansà [1983], Jansà [1986], Tintoré et al. [1988], Montserrat et al. [1991], Gomis et al. [1993], García et al. [1996], Rabinovich and Monserrat [1996, 1998], Montserrat et al. [1998, 2006], Rabinovich et al. [1999]</td>
</tr>
<tr>
<td>Gulf of Trieste, Italy</td>
<td>-</td>
<td>3.2 h</td>
<td>1.56</td>
<td>Caloi [1938], Defant [1961], Wilson [1972]</td>
</tr>
<tr>
<td>West Sicily, Italy</td>
<td>Marubbio</td>
<td>14.6 min</td>
<td>&gt; 1.5</td>
<td>Plattania [1907], Oddone [1908], Defant [1961], Colucci and Michelato [1976], Candela et al. [1999]</td>
</tr>
<tr>
<td>Malta, Mediter.</td>
<td>Milghuba</td>
<td>~20 min</td>
<td>~ 1.0</td>
<td>Airy [1878], Drago [1999]</td>
</tr>
<tr>
<td>West Baltic, Finland coast</td>
<td>Seebäär</td>
<td>~ 2.0</td>
<td></td>
<td>Credner [1988], Doss [1907], Meissner [1924], Defant [1961]</td>
</tr>
<tr>
<td>Vela Luka and Stari Grad Bays, Adriatic</td>
<td>-</td>
<td>10-15 min</td>
<td>~ 2.5</td>
<td>Hodzic [1979]; Orlie, [1980], Vilibic et al. [2004, 2005]</td>
</tr>
</tbody>
</table>
Tsunami/Meteotsunami Physics:

- Generation
- Propagation
- Run-up, inundation and local resonance
Generation mechanism

82% SEISMIC

Initial sea surface elevation
Residual seabed deformation
Fault
Tectonic plate movement
Earthquake epicenter

5% VOLCANIC

Initial sea surface elevation
Submarine volcano eruption

3% METEOROLOGICAL

Abrupt atmospheric pressure change
Moving storm front
Sea level anomaly

6% LANDSLIDE - ROCKFALL

Generated sea surface disturbances
Submarine landslide or mud flow
Sediment layer
Earthquake epicenter

+ COSMOGENIC + ARTIFICIAL…
Munk [1962]: ‘...The most conspicuous thing about long waves in the open ocean is their absence’
Generation of long ocean waves
Generation of IG-waves

‘IG-waves’ = ‘Infragravity waves’ (high-frequency long waves produced by nonlinear interaction of wind waves and swell)
Meteorological tsunami
Proudman resonance

Wave amplitude

\[ a = \frac{-\Delta P_a (x - Ut)}{\rho g \left(1 - \frac{U^2}{c^2}\right)} \]

Formation of “abiki” waves
(period of 35 min)

Monserrat, Vilibic, Rabinovich (2006)
Meteorological tsunami

“Rissaga” waves in Ciutadella Harbour, Menorca Island, Baleares (July 1989)

Wave height > 2 m
Period 10.6 min
27 June 2003, Croatia

Times (UTC) of the first air-pressure maximum

Air pressure

Sea level (cm)

Wind (m/s)

Atm. Pressure (hPa)
Four conditions to generate meteorological tsunamis (destructive atmosphere-generated tsunami-like waves)

(1) Significant atmospheric disturbance (pressure, jump, gale, frontal passage, squall, atmospheric gravity waves, etc.)

(2) Resonant conditions in the open ocean or on the shelf:

- **Proudman resonance** [Proudman, 1929]: $U = c$
- **Greenspan resonance** [Greenspan, 1956]: $U_l = c_n$
- **shelf resonance**: disturbance period/wavelength = resonant period/wavelength of the shelf

![Proudman resonance diagram]
(3) Strong resonant amplification (high Q-factor) of the bay/ inlet/ harbour (long narrow inlets, ‘bottle-like’ bays and well protected harbours → “harbour paradox” [Miles and Munk, 1961])

and/or

topographic amplification due to wave geometric focusing (‘V-shaped bays’)

(Common situation is combination of these two factors, like in Vela Luka)

(4) Harbour resonance: matching of arriving and harbour frequencies
Seiches (‘eigen oscillations’) in closed and open-ended basins

Closed basin

- $n = 1$
- $n = 2$
- $n = 3$
- $n = 4$

Open-ended basin

- $n = 0$
- $n = 1$
- $n = 2$
- $n = 3$
Harbour oscillations in basins of various shapes

<table>
<thead>
<tr>
<th>Basin type</th>
<th>Description</th>
<th>Dimensions</th>
<th>Profile equation</th>
<th>Periods of free oscillation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fundamental $T_0$</td>
</tr>
<tr>
<td>Rectangular</td>
<td></td>
<td></td>
<td>$h(x) = h_1$</td>
<td>2.006 $[2L/(gh_1)^{3/2}]$</td>
</tr>
<tr>
<td>Rectangular</td>
<td></td>
<td></td>
<td>$h(x) = h_1 + x/L$</td>
<td>2.618 $[2L/(gh_1)^{3/2}]$</td>
</tr>
<tr>
<td>Triangular</td>
<td></td>
<td></td>
<td>$h(x) = h_1(1 - x^2/L^2)$</td>
<td>2.220 $[2L/(gh_1)^{3/2}]$</td>
</tr>
<tr>
<td>Rectangular</td>
<td></td>
<td></td>
<td>$b(x) = b_1 + x/L$</td>
<td>1.308 $[2L/(gh_1)^{3/2}]$</td>
</tr>
<tr>
<td>Triangular</td>
<td></td>
<td></td>
<td>$b(x) = b_1 + x/L$</td>
<td>1.653 $[2L/(gh_1)^{3/2}]$</td>
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<td>Semielliptic</td>
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</table>
Resonant properties of Malokurilsk Bay (Shikotan Island)
Eigen modes of Malokurilsk Bay

Helmholtz mode
Spectra of tide gauge records (BC coast)
Amplification factor

Observed spectrum on the coast

\[ S_{\text{obs}}(\omega) = S_0(\omega)H^2(\omega) \]

- \( S_0(\omega) \): is the open ocean spectrum
- \( H^2(\omega) \): is the topographic admittance

\[ S_0(\omega) \approx A\omega^{-2} \]

is stable and almost uniform

Topographic amplification function

\[ H_j(\omega) = \sqrt{\frac{S_{j\text{ obs}}(\omega)}{S_0(\omega)}} = \sqrt{\frac{S_{j\text{ obs}}(\omega)}{A_0\omega^{-2}}} \]
26 December 2004: North Atlantic

Tsunami’s passage through Atlantic
Scientists uncovered evidence Thursday that last week’s tsunami was felt along the East Coast 28-30 hours after the earthquake. The new data is being used to model the tsunami movement through the Atlantic Ocean.

Source: Dr. Alexander B. Rabinovich, Canadian Institute of Ocean Sciences, Dr. Vasily V. Titov, National Oceanic and Atmospheric Administration.

The New York Times, January 7, 2005

(in 10 days after the event)
NW Atlantic Ocean. Double jeopardy: Concurrent arrival of the 2004 tsunami and storm-generated waves

Thomson, Rabinovich, and Krassovski (GRL, 2007)
Maximum tsunami wave heights

Tsunami
Recorded at: 32 stations
All stations are on the outer coast
Max wave height at Halifax (NS): 39 cm (corrected ~ 80 cm)
• “Meteorological tsunamis” are very similar to ordinary tsunamis; they have the same temporal and spatial scales and affect the coast in a similar destructive way, despite that the generation mechanism of these waves is quite different.

• “Meteorological tsunamis” are produced by atmospheric processes (atmospheric waves, pressure jumps, squalls, frontal passage, etc.) and have strongly resonant nature.

• “Meteorological tsunamis” are regularly observed at the same sites with pronounced local resonant properties and commonly have some local names (“rissaga”, “abiki”, “šćiga”, “death waves”, “marrubio”, “milghuba”, …)
• “Meteorological tsunamis” are produced by the *resonant superposition* of *internal factors* (pronounced resonant properties of a specific bay or harbour) and *external factors* (strong atmospheric disturbance resonantly interacting with open-ocean waves)
In general, the meteorological tsunamis have a multi-resonant generation mechanism. The needed coincidence of several resonant factors significantly diminishes the possibility of occurring such events, which is the main reason why these phenomena are rare and restricted to specific locations.

The combination of these factors at such locations is like a “tickling time-bomb”: sooner or later – when the atmospheric disturbance is intense and the parameters of the disturbance coincide with the resonant parameters of the corresponding shelf topography and embayment geometry – it will explode. Vela Luka is probably one of such “tickling time-bomb” sites...
Thank you!

Questions? Pitanja?