Meteorological tsunamis along the East Coast of the United States

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1. Introduction

Meteorological tsunamis (meteotsunamis) are large amplitude short period (from a few min to a few hrs) sea level oscillations generated by meteorological disturbances. They have approximately the same time and spatial scales as ordinary tsunami waves in affects coasts in a similar destructive manner, but are induced not by seismic sources or submarine landslides, but by atmospheric processes. This preliminary study of meteotsunamis on the East Coast of USA was done in the frame of the TMEWS project.

The main purpose of this specific study was to find significant meteotsunami events that can be investigated as part of the TMEWS project in addition to the Daytona Beach 1992 and Booth Bay 2008 events. This work included three main parts:

(i) Assessment of events from the U.S. tsunami catalogues which may be associated with meteotsunamis.

(ii) Literature search, identifying and overviewing papers related to meteotsunamis and extreme seiches in inlets, bays and harbours of the East Coast.

(iii) Analysis of long-term high frequency 1-min tide gauge series along the Atlantic U.S. coastline, detection and extraction of the strongest events.

2. Analysis of the US tsunami catalogues

To identify possible meteotsunami events along the East Coast we examined all available tsunami catalogues for this region. Specifically we examined the following publications and tsunami databases:

(a) Lander, J.F., Whiteside, L.S.. and Lockridge, P.A., 2003: Two decades of global tsunamis, *Sci. Tsunami Hazards*, 21 (1), 1-88.

(b) O'Loughlin, K.F., and Lander, J.F., 2003: *Caribbean Tsunamis.* Kluwer Acad. Publ., Dorderecht, The Netherlands, 263 p.

(c) Dunbar, P.K., 2011: Tsunami Database of the National Geophysical Data Center, Natural Hazards (NGDC), Boulder, Colorado.

(d) Gusiakov, V.K., 2011: ITDB/WLD, Integrated Tsunami Database for the World Ocean, Version 5.16 of December 31, 2011, CD-ROM, Tsunami Laboratory, ICMMG SD RAS, Novosibirsk, Russia. Web-version: http://tsun.sscc.ru/WinITDB.htm

The results of this search were not very encouraging: very few potential meteotsunami events were found in these catalogues and information about these events was very scanty (insufficient to study them). There are three main reasons why information on such events was so limited in these catalogues:

(a) Traditionally tsunami research is focused on two geographical regions (where these events are most often): (1) Pacific Ocean, and (2) Mediterranean Sea. Tsunamis in the Atlantic Ocean are rare and before 2004 did not attract much attention. Consequently, little attention was also paid to other related events, such as meteotsunamis.

(b) "Meteorological tsunamis" is a new scientific topic which began to be studied systematically only in the middle of 90's. Even this term ("meteorological tsunamis") became being widely accepted by the scientific community only recently. That is why corresponding events had not been cataloguing; instead the extreme non-seismic destructive events were described as "events of unknown origin".

(c) The sea-level observational network in the Atlantic Ocean before 2004 was based exclusively on digital tide gauges with 6-min and 15-min sampling intervals or on archaic pen-and-paper analog gauges. Such instruments are almost unsuitable for measurements of meteotsunamis. Only after the 2004 Sumatra tsunami, which was clearly observed on the Atlantic coast of USA [cf. *Thomson et al.*, 2007], modern tide gauges with 1-min sampling were deployed along the East Coast.

3. Literature search

An intensive literature search of description and examination extreme sea level oscillations of atmospheric origin was done for the Atlantic coast of the United States and adjacent coast of Canada. Significant help in this search was provided by scientists and specialists of many countries through the ITIC Tsunami Bulletin Board network. The list of the most interesting and important publications on this topic is attached. In particular, the discovery and scientific explanation of edge waves was done based on analysis of the extreme atmospherically-induced sea level oscillations moving along this coast [*Munk et al.*, 1956; *Grenspan*, 1956; *Redfield and Miller*, 1957]. Very similar case was described by *Beardsley et al.* [1977]. The destructive Daytona Beach (1992) event [*Churchill et al.*, 1995; *Sallenger et al.*, 1995] is probably the best known example of a meteorological tsunami. However, there were several other interesting events [cf. *Donn and McGuinness*, 1960; *Donn and Balachandran*, 1969; *Paxton and Sobien*, 1998; *Mercer et al.*, 2002; *Mecking et al.*, 2009]. *Thomson et al.* [2007] described a unique case when a tsunami (the 2004 Sumatra tsunami) and meteorological tsunami (strong seiches generated by a storm moving northward along the East coast) were observed almost simultaneously.

In general, based on analysis of these publications we can conclude that extreme tsunami-like events of atmospheric origin (i.e. meteorological tsunamis) are quite common on the East coast of USA. The main sources of these extreme events are approximately the same as in other region of the World Ocean: hurricanes and strong storms, trains of atmospheric internal gravity waves, atmospheric pressure jumps, gale and squall lines, frontal passages, etc. [*Wiegel*, 1964; *Wilson*, 1972; *Raichlen and Lee*, 1992; *Korgen*, 1995; *Rabinovich*, 1993, 2009]. However until present not much attention has still being paid to this phenomenon along the East Coast.

4. Analysis of tide gauge data

As a result of the catastrophic 2004 Sumatra tsunami, the entire tide gauge network of the US National Oceanic and Atmospheric Administration (NOAA) was updated and modernized. New precise digital instruments with 1-min sampling were deployed along the entire Atlantic coast of USA, including the Caribbean region and the Great Lakes. The total number of tide gauges in the Atlantic region is approximately 100. Sea level time series with 1-min time resolution are available on the NOAA Center for Operational Oceanographic Products and Services (CO-OPS) website: http://opendap.co-ops.nos.noaa.gov/axis/webservices/waterlevelrawonemin/index.jsp. At most stations, 1-min measurements began in 2007. This means that at present we have 5-year time series of high-resolution sea level observations along the entire East Coast. *Jadranka Šepić* selected 20 tide gauges and analyzed the entire 5-year records for these stations targeting to identify extreme events (*Possible meteotsunami events along the east coast USA*, 2011). Based on her analysis and known publications, it is possible to conclude that there are four main regions of frequent and strong meteotsunamis:

(1) Northeasternmost coast of USA (close to the Canadian border): states Maine (ME), New Hampshire (NH) and Massachusetts (MA).
(2) Central part of the East Coast, states New Jersey (NJ) and North Carolina (NC).
(3) Southeastern coast, states Georgia and Florida.
(4) The Caribbean region and the Gulf of Mexico.

The main reason of extreme events in regions (3) and (4) are hurricanes. Strong hurricanes, which are quite common in this region (especially in July-October), are frequently accompanied by destructive floods and strong seiches [*Paxton and Sobien*, 1998; *Mecking et al.*, 2009]. Apparently, it is important to analyze all these associated events – hurricanes, storm surges and extreme seiches – together; this could be a subject of a future project.

Region (1), together with adjacent Canadian provinces of Nova Scotia, New Brunswick, Prince Edward Island and Newfoundland, is known as the region of several strong events [cf. *Donn and McGuinness*, 1960; *Donn and Balachandran*, 1969; *Mercer et al.*, 2002], in particular the recent extreme Booth Bay (2008) event. This event is intensively examined now in the frame of this project.

In this study we focused on analysis of region (3). Several strong events are known to occur in this region [cf. *Munk et al.*, 1956; *Redfield and Miller*, 1957; *Beardsley et al.*, 1977]. We selected station Atlantic City (NJ) as the *reference station* for this region and for the East Coast, in general. For example, *Jadranka Šepić* based on analysis of 20 stations on the Atlantic coast of USA, selected 9 strongest events of possible meteotsunamis; 7 of them were clearly recorded at Atlantic City. Apparently this station for meteotsunamis on the East Coast plays the same role as Crescent City for ordinary tsunamis on the West Coast. We can assume, that if a particular event occurred in Region (3), it has to be recorded at Atlantic City; *vice versa,* if no noticeable seiches were recorded at Atlantic City, it is unlikely that they can be observed at other sites of this region.

The most laborious part of our analysis involved the careful examination and verification of the observed tide gauge time series. We worked with the raw data, so that almost all yearly time series had problems, in particular, lots of gaps. Spikes and time shifts in the data also occurred. All these errors were found and corrected. Relatively short gaps (<1-2 days) were linearly interpolated; the data with long gaps were separated into individual segments. Tides were estimated using harmonic analysis and then subtracted from the original series. The residual (de-tided) time series were used in the subsequent analysis.

To isolate the meteorological tsunami frequency band and simplify extreme seiches (meteotsunami) detection, we high-pass filtered the residual tide gauge series following application of a 4-hour Kaiser-Bessel window [*Emery and Thomson*, 2003]. In the following analysis we used both these filtered and non-filtered series. The former were used to identify the events and to construct the respective plots; the latter were applied to estimate more precisely some statistical characteristics of the waves, which can be distorted by the filtering, and to correlate seiches events with synoptic situations (storms and cyclone passages are characterized by the low-frequency sea-level elevation, while anticyclones are associated with the sea-level lowering).

The Atlantic City sea-level records were found to be very rich in significant seiches events. Altogether, for the period 2007-2011 more than 40 events with wave heights > 30 cm were detected. (For comparison, similar analysis of the Canadian tide gauge records for the Pacific coast enabled us to identify only a few such events). From these events we selected 12 most interesting (Table 1). For all of them, except one, maximum trough-to-crest wave heights are more than 40 cm. Five of these events (including four strongest) had also been indicated by *Jadranka Šepić* [2011]; seven are new.

Table 1. Strongest seiche events (possible meteotsunamis) observed at Atlantic City in 2007-2011.

#	Date	Maximum wave height (cm)	Event # in the Jadranka's table	Comments
1	16-17 December 2007	41	-	Seiches with HF noise (IG-waves)
2	30-31 December 2007	35	-	Seiches
3	5-6 March 2008	71	Event 1	Strong negative wave (-54 cm); the entire wave range > 80 cm
4	12 May 2008	48	-	Seiches
5	6-7 September 2008	53	-	Positive wave +32 cm
6	7-8 January 2009	45	Event 3	Negative wave -27.5 cm; significant high-frequency noise combined with seiches
7	29 January 2009	61	Event 4	Negative wave -45 cm
8	21 August 2009	43	-	Intensive high-frequency oscillations (IG-waves)
9	25-26 January 2010	48	-	Negative wave -32 cm
10	13-14 March 2010	95	Event 7	Positive wave +59 cm
11	17 April 2011	48	-	Seiches with IG-waves; negative wave -26 cm
12	27-30 August 2011	60	Event 9	Seiches with IG-waves; negative wave -26 cm

Very preliminary analysis of the observed oscillations for these selected events shows that they may be separated into three main types:

(1) High-frequency noisy oscillations with predominant periods <5 min. A typical example is Event #8 on 21 August 2009.

(2) Seiche oscillations with typical periods of 30-60 min superimposed by high-frequency oscillations (Events ##1, 6, 11 and 12).

(3) Significant seiches oscillations without noticeable high-frequency activity (Events ##2-5, 7, 9 and 10).

The joint examination of the filtered and de-tided unfiltered data indicates that events of Types (1) and (2) are mainly associated with sea-level uplift, i.e. with a cyclone passage, while events of Type (3) are associated with the sea-level decrease (i.e. with a high-pressure system) or with neutral sea level. We may assume that the oscillations of Type (1) are related to *infragravity waves* (IG-waves) generated by non-linear interaction of strong wind-waves associated with a storm passage [*Rabinovich*, 1993, 2009]. Stormy wind appears to be the main factor responsible for development of these oscillations. The oscillations of Type (2) are also apparently related to storm passages; however these storms produce not only high-frequency wind-induced IG-waves but also lower-frequency seiches. Typical example of storm-generated seiches along the East Coast is described by *Thomson et al.* [2007]. What is the exact generation mechanism of these seiches is not clear, but probably irregularities of the atmospheric pressure fields in deep cyclones or cyclone-related frontal zones.

Type (3) is a "classical" type of meteorological tsunamis: specifically this type of oscillations, normally associated with calm weather, regularly occurs in Spain (Ciutadella Harbour), Japan (Nagasaki Bay), Croatia (Vela Luka, Stari Grad) and in several other regions of the World Ocean being responsible for destructive floods and catastrophic effects in harbors [cf. *Rabinovich et al.*, 2009]. Internal atmospheric gravity waves and pressure jumps combined with local resonant effects are the best known reasons of these oscillations, however some other factors may also be crucial at particular sites. Observations around the world demonstrate significant influence of local properties of the individual sites on the intensity of the generated seiches [*Rabinovich*, 2009].

Atlantic City is probably the station with well defined resonant properties and strong response to atmospheric forcing. However, it is important to understand what the situation is with other sites located in the same region and where dangerous events could be expected. To answer this question we selected 15 stations (in addition to Atlantic City) beginning from Boston (Massachusetts) in the north to Wilmington and Wrightsville Beach (North Carolina) in the south. The list of these stations is presented in Table 2. For each station and for each event listed in Table 1 we downloaded 10-day segments of 1-min sea level data. These data were prepared and verified in the same manner as it was done for the yearly series at Atlantic City. This enables us to examine 12 specific events and compare individual responses of various stations. This analysis is expected to be finished in the near future.

Table 2. The tide gauge stations on the East Coast of the USA that were selected to examine for 12 specific events (listed in Table 1).

#	Station	State	Station ID	Latitude	Longitude
1	Boston	MA	8443970	42.3550	-71.0517
2	Woods Hole	MA	8447930	41.5233	-70.6717
3	Nantucket Island	MA	8449130	41.2850	-70.0967
4	Montauk	NY	8510560	41.0483	-71.9600
5	The Battery	NY	8518750	40.7006	-74.0142
6	Sandy Hook	NJ	8531680	40.4667	-74.0100
7	**Atlantic City**	**NJ**	**8534720**	**39.3550**	**-74.4183**
8	Cape May	NJ	8536110	38.9683	-74.9600
9	Lewes	DE	8557380	38.7817	-75.1200
10	Ocean City Inlet	MD	8570283	38.3283	-75.0917
11	Wachapreague	VA	8631044	37.6078	-75.6858
12	Duck	NC	8651370	36.1833	-75.7467
13	Oregon Inlet Marina	NC	8652587	35.7950	-75.5483
14	Beaufort	NC	8656483	34.7200	-76.6667
15	Wrightsville Beach	NC	8658163	34.2133	-77.7867
16	Wilmington	NC	8661070	33.6550	-78.9183

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