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Double jeopardy: Concurrent arrival of the 2004 Sumatra tsunami and storm-generated waves on the Atlantic coast of the United States and Canada

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[1] A detailed analysis of over one hundred tide gauge records from the Atlantic coast of North America reveals that the arrival of the 26 December 2004 Sumatra tsunami on this coast coincided with the presence of tsunami-like waves being generated by a major storm tracking northward along the eastern seaboard of the United States. According to the tide gauge records, waves from the two events coalesced along the shores of Maine and Nova Scotia on 27 December where they produced damaging waves with heights in excess of 1 m. Tsunami waves were identified in almost all outer tide gauges from Florida to Nova Scotia with maximum tsunami heights for the northern regions estimated to be 32–39 cm. In the south, maximum tsunami wave heights were in the range of 15 to 33 cm.
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1. Introduction

[2] The $M_w = 9.3$ Sumatra-Andaman megathrust earthquake of 00:59 UTC 26 December 2004 generated a catastrophic tsunami that caused widespread damage in coastal areas of the Indian Ocean where it killed over 226,000 people. Waves from the event propagated throughout the world ocean [*Titov et al.*, 2005], making this the first global-scale tsunami to be observed during the "instrumental era". The tsunami was recorded by tide gauges in near-source regions of the Indian Ocean [*Merrifield et al.*, 2005; *Rabinovich and Thomson*, 2007] as well as remote regions of the North Pacific and North Atlantic [*Titov et al.*, 2005; *Rabinovich et al.*, 2006].

[3] Tsunamis are much less common in the Atlantic than in the Pacific Ocean. Unlike the Pacific, the Atlantic Ocean is not bordered by subduction zones which are the main source regions for major tsunamis [*Lockridge et al.*, 2002]. Among the few tsunami records available for the Atlantic are those generated by some local earthquakes [cf. *Lockridge et al.*, 2002; *Fine et al.*, 2005] and by the 1883 explosion of Krakatau Volcano in the Sundra Strait (Indonesia) [cf. *Pelinovsky et al.*, 2005]. The Atlantic Ocean has no Tsunami Warning System and no instruments designed for tsunami measurement. Moreover, because the primary purpose of Atlantic gauges is to measure relatively low-frequency variations such as tides, storm surges, and long-term trends, digital gauges used for sea level measurements have long sampling intervals (6 min to 1 hour) and are often installed at locations that are not optimal for recording tsunamis.

[4] So uncommon are tsunamis in the Atlantic Ocean that, immediately following the 2004 Sumatra earthquake, few experts expected the ensuing tsunami would be recorded in the Atlantic, let alone the North Atlantic more than 25,000 km from the source area. It was, therefore, a surprise when tsunami waves were detected a few days after the earthquake at the tide gauge at Halifax, Nova Scotia and subsequently at nine other tide gauge sites in the North Atlantic (Department of Fisheries and Oceans, Institute of Ocean Sciences, 2007, http://www-sci.pac.dfo-mpo.gc.ca/osap/projects/tsunami/tsunamiasia_e.htm). Global tsunami propagation models [*Titov et al.*, 2005; *Kowalik et al.*, 2007] indicate that the Mid-Atlantic Ridge served as a wave-guide, efficiently transmitting tsunami energy from the source area to far-field regions of the Atlantic Ocean. These models predicted that the first waves would strike the east coast of North America roughly 30 to 31 hours after the earthquake and generate trough-to-crest wave heights of 20–30 cm along the outer coast (Figure 1).

[5] Visual inspection of tide gauge records for the time of the 2004 tsunami [cf. *Rabinovich et al.*, 2006] reveals that records for the NW Atlantic have low signal to noise ratios compared with those for the Indian Ocean [*Rabinovich and Thomson*, 2007], and that this creates a major problem for tsunami detection. In the case of the 2004 Indian Ocean tsunami, the problem was exacerbated by the fact that the expected tsunami arrival time coincided with large waves being generated by a major O(100) km radius storm tracking northward from 25 to 28 December along the eastern seaboard of the United States and Canada (Figure 1). The storm generated significant tsunami-like waves on the continental shelf and marked seiches in bays and lagoons along the Atlantic Coast. These oscillations, which can be classified as "meteotsunamis" [cf. *Rabinovich and Monserrat*, 1996; *Monserrat et al.*, 2006], had frequencies and amplitudes similar to those for the seismically generated 2004 tsunami. The purpose of this paper is two-fold: (1) To examine the evolution of the late December 2004 tsunami and storm-generated wave events along the

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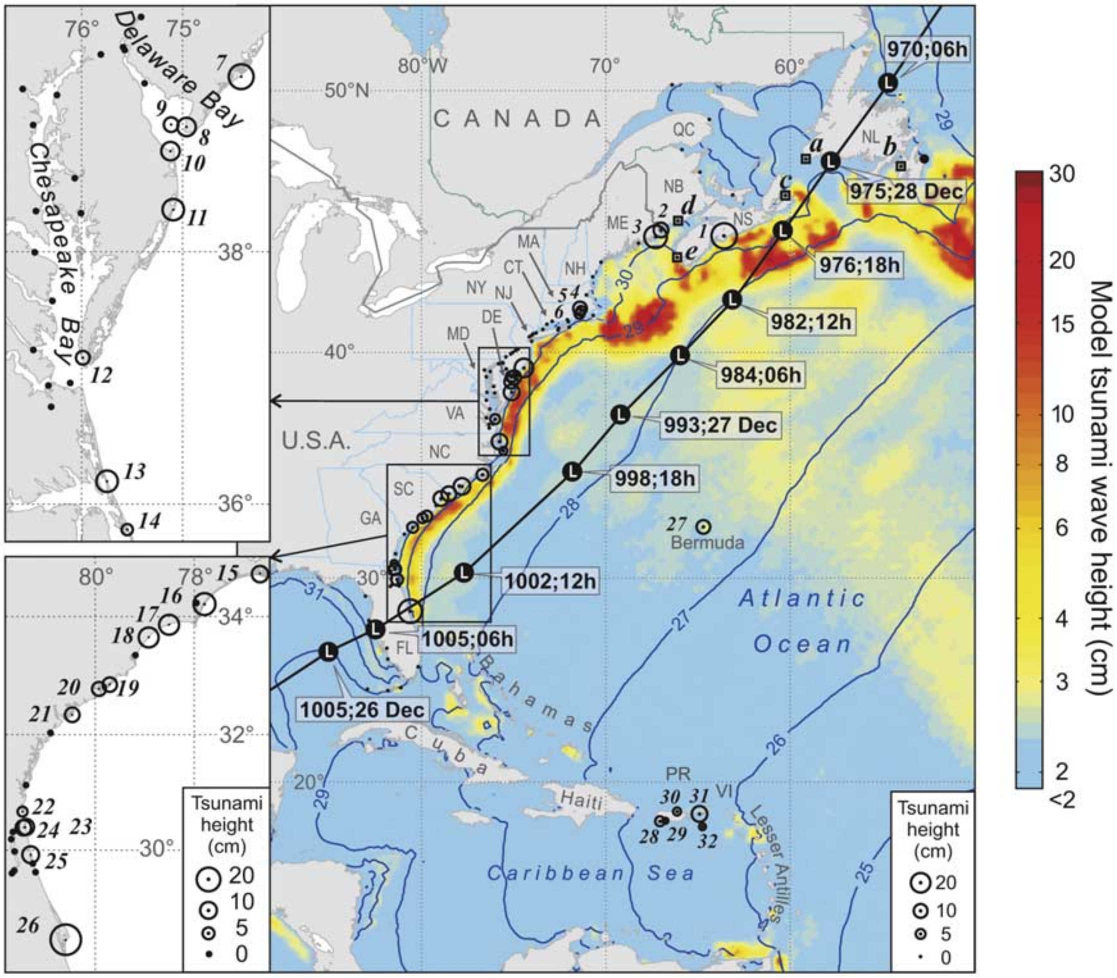

Figure 1. Tide gauge locations in the North Atlantic Ocean along with numerically modeled wave heights for the 2004 tsunami from *Titov et al.* [2005]. Solid blue lines are the computed isochrones of tsunami travel time. Solid circles denote the center of the storm for the period 26 to 28 December 2004; boxes give the date (or time) and atmospheric pressure (hPa) along the storm track. The 32 stations which recorded the tsunami are indicated by empty circles with area proportional to the trough-to-crest wave height. Numbers refer to gauge sites: 1 Halifax (NS), 2 Eastport (ME), 3 Cutler Naval Base (ME), 4 Providence (RI), 5 Conimicut Light (RI), 6 Quonset Point (RI), 7 Atlantic City (NJ), 8 Cape May (NJ), 9 Brandywine Shoal Light (DE), 10 Lewes (DE), 11 Ocean City Inlet (MD), 12 Kiptopeke (VA), 13 Duck (NC), 14 Oregon Inlet (NC), 15 Beaufort (NC), 16 Wrightsville Beach (NC), 17 Sunset Beach (NC), 18 Springmaid Pier (SC), 19 South Capers (SC), 20 Charleston (SC), 21 Hunting Island (SC), 22 Fernandina Beach (FL), 23 Mayport Naval Sta. (FL), 24 Bar Pilots Dock (FL), 25 Vilano Beach (FL), 26 Trident Pier (FL), 27 Bermuda, 28 Magueyes Island (PR), 29 Punta Guayanilla (PR), 30 San Juan (PR), 31 Charlotte Amalie (VI), and 32 Lime Tree Bay (VI). Empty boxes with lower-case letters denote the five Canadian tide gauge stations for which it was not possible to distinguish tsunami from storm waves: *a* Port aux Basques (NL), *b* Argentia (NL), *c* North Sydney (NS), *d* Saint John (NB), and *e* Yarmouth (NS). Small solid circles denote tide gauges for which no tsunami was recorded.

Atlantic seaboard; and (2) to detail the characteristics of the 2004 tsunami along the Atlantic coast of North America.

2. Observations and Analysis

[6] We have analyzed all available tide gauge records for the Atlantic coast for the time of the 2004 tsunami. This encompasses 95 tide gauge records from the U.S. National Oceanic and Atmospheric Administration (NOAA) and 12 records from the Canadian Hydrographic Service (CHS). Instrument sampling intervals for the two data sets are 6 and 15 min, respectively. Tides calculated using least squares harmonic analysis were subtracted from the original records to obtain the residual (detided) time series. To separate the low and high-frequency residual oscillations in the late December event, the residual records were next filtered with a high-pass Kaiser-Bessel filter [cf. *Emery and Thomson*, 2001] with a 4-hour window. The dominant features emerging from this analysis are the roughly 50-cm amplitude, low-frequency storm surge motions (Figure 2a) and the two groups of roughly 10 cm amplitude high-frequency longwave oscillations (Figures 2b and 2c). The high-frequency wave signals have similar heights and frequencies but markedly different source mechanisms.

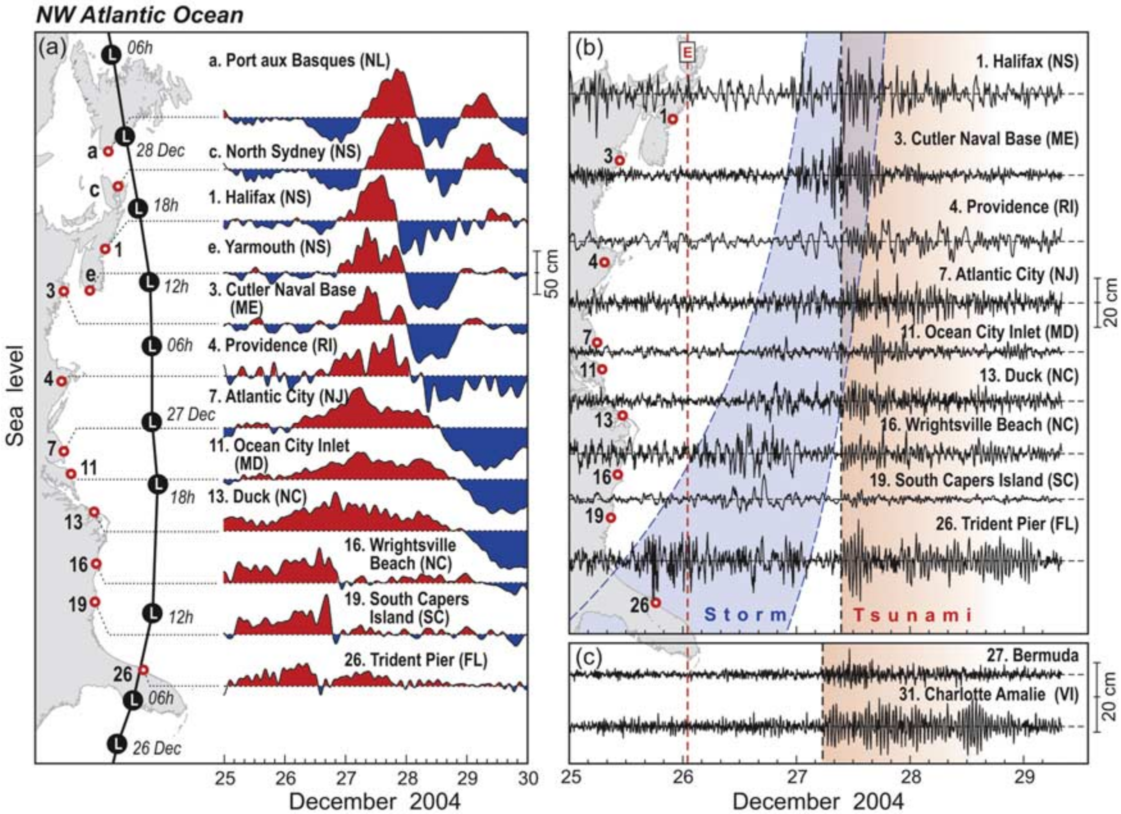

Figure 2. Residual (detided) sea level records for the 2004 Sumatra tsunami in the NW Atlantic. (a) The center of the storm track and low-frequency (storm surge) sea level oscillations for selected sites on the mainland coast; (b) high-frequency tsunami and storm wave oscillations for selected mainland sites; and (c) as for Figure 2b but for two island sites. The curved pale blue band and vertical light red band indicate times of storm-generated and tsunami waves, respectively.

[7] The first group of high-frequency waves was initially observed on 25 December 2004 at stations along the coasts of Florida (FL) and South Carolina (SC). Similar wave groups were subsequently observed on 26–27 December along the coasts of North Carolina (NC), Maryland (MD) and New Jersey (NJ) and on 27–28 December on the coasts of Rhode Island (RI), Massachusetts (MA) and Nova Scotia (NS). Because the timing of these waves closely corresponds to the passage of a major cyclonic depression travelling at a speed of about 60 km/hr from the Gulf of Mexico north-eastward towards Nova Scotia and Newfoundland, these are readily identified as storm-generated waves.

[8] The second group of waves arrived at all stations along the Atlantic seaboard almost simultaneously at 08:30–09:30 UTC 27 December roughly 31.5 to 32.5 hrs after the main 2004 Sumatra earthquake. The observations are consistent with numerical computations [*Titov et al.*, 2005] which show the Sumatra tsunami arriving at the outer shelf of the Atlantic Coast nearly simultaneously about 30 to 31 hrs after the earthquake (Figure 1). Thus, the observed arrival times of the waves in the second group agree closely with the theoretical estimates for tsunami waves arriving from the Indian Ocean. Several additional criteria were used to determine the arrival of the 2004 Sumatra tsunami in the Atlantic records: (1) agreement in arrival times among nearby stations (it is much easier to define tsunami wave arrival for a group of tide gauge stations than for a single tide gauge station); (2) the presence of dominant periods in the recorded waves (observations in the Indian and Pacific oceans indicate that the dominant periods of the 2004 tsunami were 30–60 min [*Rabinovich et al.*, 2006; *Rabinovich and Thomson*, 2007]); (3) relatively abrupt amplification and temporal change in the observed long-wave oscillations; and (4) agreement of the observed tsunami wave characteristics (heights, arrival times, and wave-train structure for this region) with those from the numerical computations of *Titov et al.* [2005]. The tide gauge records from Bermuda and the US Virgin Islands (Figure 2c) further confirm the second group as tsunami waves. No first group waves were recorded at these stations (the storm passed far to the west of these islands), while the second group waves arrived at the island stations about three hours earlier than at the main coast, close to the theoretically estimated time for tsunami wave propagation from the islands to the continental stations.

[9] At the southern tide gauge stations (e.g., Florida), the two wave groups were approximately two days apart (Figure 2b). The wave groups subsequently converged in the vicinity of Nova Scotia. Strong oscillations with heights of 40–65 cm were first observed at the Atlantic Canada stations of Saint John, Yarmouth, North Sydney, Port aux Basques, Argentia, and St. Johns at approximately 22:00 UTC on 26 December 2004 (10–12 hours before the theoretical arrival of the Sumatra tsunami waves at these sites) and lasted for about 30–40 hours. Although it proved

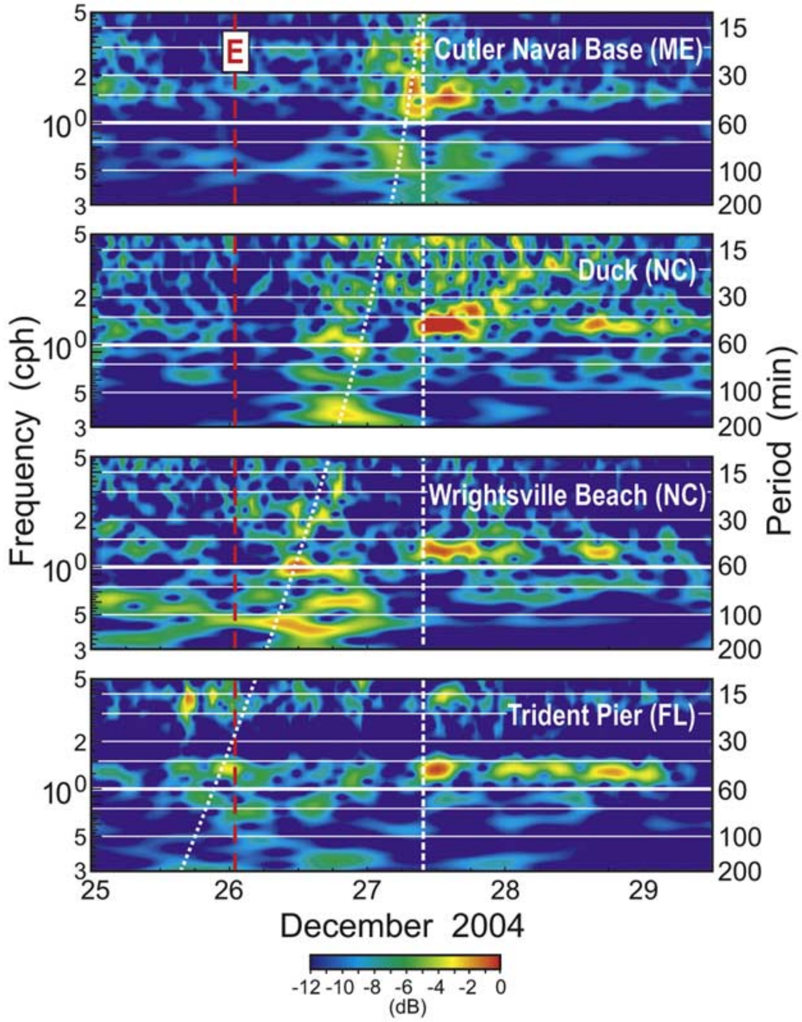

Figure 3. Frequency-time (*f-t*) diagrams for the 2004 Sumatra tsunami tide gauge records for four mainland stations. The dashed white lines indicate the times of storm-induced waves and tsunami arrival times; the solid vertical line "E" indicates the time of the 2004 Sumatra earthquake.

too difficult analytically to separate the storm- and earthquake generated waves at these locations, the incoming tsunami appears to have augmented both the amplitude and duration of the storm-forced waves by pumping additional energy directly into the long-wave field (cf. Figure 2b). This contrasts with *Geist and Zoback* [2002] who suggest that the tsunami generated during the 1906 San Francisco Earthquake may have disrupted self-organization of the surface waves off California.

3. Tsunami Versus Storm Waves

[10] As might be expected, we find major differences between the storm and tsunami wave groups. The storm waves were observed at almost all tide gauge stations, including those located deep inside Chesapeake and Delaware bays (upper inset Figure 1). In contrast, the tsunami waves were observed only at sites on the outer coast well exposed to the ocean (Figures 1 and 2b) and were much more regular and had more consistent periods (40–50 min) than the storm waves. This difference in frequency content between the two wave groups is best illustrated by a frequency-time (*f-t* or wavelet type) analysis of the residual (detided) tide gauge data (cf. *Rabinovich et al.* [2006] for details). As indicated in Figure 3 for four selected stations extending from Florida (FL) to Maine (ME), the wind-forced waves gradually amplified at the beginning and then became polychromatic, with several energetic bands (periods of 120–180 min, 80–90 min, 60 min, 30–40 min) causing the wave field to develop an irregular envelope. In contrast, arrival of the tsunami was marked by an abrupt onset of waves which were then generally monochromatic with typical periods of 40–50 min (in good agreement with those for the 2004 Sumatra waves observed in other oceans [*Rabinovich et al.*, 2006; *Rabinovich and Thomson*, 2007]).

[11] Our examination of the combined 107 NOAA and CHS tide gauge records for the east coast yielded reliable tsunami signals at 32 sites, including 22 additional sites to those found by *Rabinovich et al.* [2006]. All of the "new" tsunami records are for sites on the Atlantic seaboard of the US. The Canadian Atlantic stations, except Halifax, are not included in this updated list because the tsunami could not be reliably identified and separated from the storm-induced oscillations. The absence of a tsunami signal in the remain-

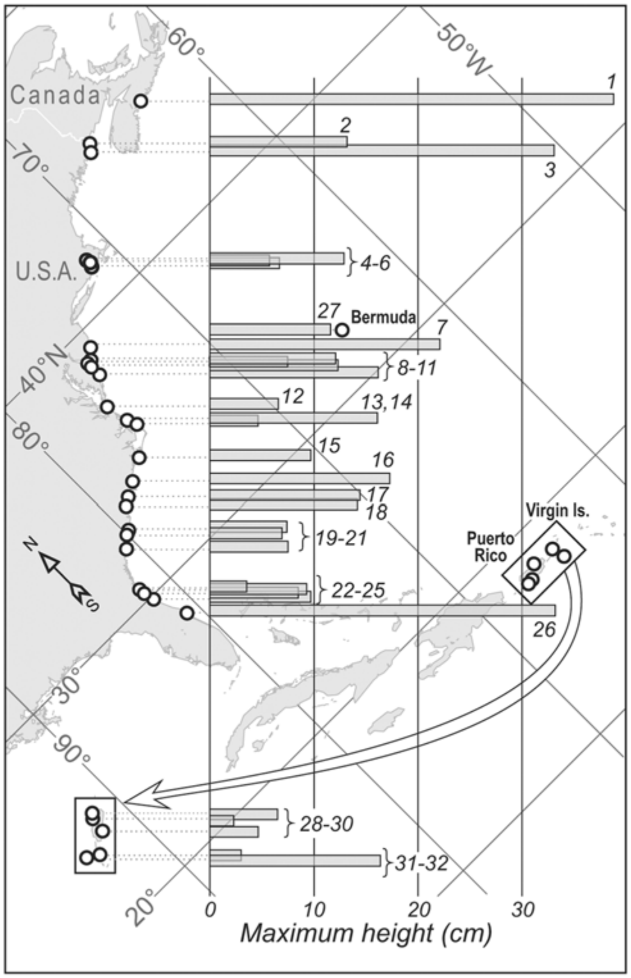

Figure 4. Estimates of maximum recorded heights for the 2004 Sumatra tsunami for the east coast of North America. Numbers on each horizontal bar denote the tide gauge sites listed in the caption to Figure 1.

ing 64 US sites is due to the placement of these gauges inside lagoons and bays where they are highly sheltered from the incoming tsunami. We note that the 32 tsunami records for this coast are several times more than the total number of historical tsunami records known for this entire coast before the 2004 event [*Lockridge et al.*, 2002].

[12] Figure 4 presents the tsunami heights along the Atlantic coastal sites and at the island stations. Maximum heights (39 cm) were observed at Halifax, which represents the maximum wave height recorded in the North Atlantic for the 2004 tsunami. However, because of the 15-min sampling interval of the Halifax gauge, this height is likely an underestimate of the true maximum tsunami height. To "correct" for sampling effects, we examined tide gauge records of the 2004 tsunami with similar frequency content to the Halifax record but with 1-min recording intervals. By artificially resampling these records, we found that the amplitude attenuation factor for 15 min observations is $\sim$ 0.50. This implies that the true recorded height of the tsunami at Halifax would have been close to 80 cm had the waves been recorded with 1-min sampling. Other sites with significant tsunami heights are Cutler Naval Base, ME (33 cm), Trident Pier, FL (33 cm) and Atlantic City, NJ (22 cm). Because these gauges sampled at 6-min intervals, sampling corrections are considerably smaller than for the Halifax gauge (attenuation factor $\sim$0.85). In general, the tsunami records show marked variations in height along the coast and significant differences in heights for even nearby stations. These variations appear to be related to the resonant characteristics of the shelf and coastline that profoundly affect tsunami waves in coastal regions. The large waves at Halifax are consistent with the numerical results of *Titov et al.* [2005], which show that this site was located at the terminus of the main path of the tsunami energy flux that had propagated northward along the Mid-Atlantic Ridge. The incoming waves from the 2004 event were further amplified by the broad Nova Scotia shelf (Figure 1). Superposition of the low-frequency storm-generated surge (Figure 2a) on the tsunami oscillations and storm-induced seiches (Figures 2b and 2c) produced waves with heights in excess of 1 m which were apparently responsible for the marked flooding observed in this region (C. O'Reilly, Canadian Hydrographic Service, Halifax, personal communication, 2005).

4. Discussion

[13] Considering the distance of more than 25,000 km and intervening land masses separating the Atlantic coast of North America from the coast of Sumatra, it is remarkable that 32 gauges in the NW Atlantic solely designed to measure tides and other low frequency oscillations were able to detect the much higher frequency waves associated with the 2004 tsunami. It is equally remarkable that the tsunami was recorded by almost every tide gauge on the outer coast. The observed tsunami arrival times for different stations are mutually consistent and closely match those in the numerical simulations [*Titov et al.*, 2005; *Kowalik et al.*, 2007]. This close agreement between oscillations observed at sites separated by thousands of kilometers with corresponding model results supports the validity of our tsunami wave interpretation. The tsunami records provide highly reliable statistics for this coast, where previously tsunamis had been almost unknown.

[14] The simultaneous arrival of the 2004 tsunami with storm-induced long waves (meteotsunamis) appears to be the first time that such a combined effect has been recorded in the ocean. Despite their different origins, observed wave properties for the two events are similar. Moreover, the superposition of these events at the northeastern US and southeastern Canadian tide gauge sites resulted in strongly amplified waves. After adjusting the maximum wave height in the Halifax record to compensate for the long (15 min) sampling time, we estimate that the storm surge and tsunami wave heights were roughly 50 and 80 cm, respectively, in this region of the Atlantic coast, for a combined contribution of over 1 m. Separation of these two types of wave oscillations presents an analytical challenge which will likely be repeated for future global tsunamis. However, as our analysis demonstrates, some of the problems can be circumvented through careful use of specific tsunami wave characteristics (such as wave group structure) and supporting numerical simulations.

[15] Prior to this analysis, we had expected to find little evidence for the 2004 tsunami in the tide gauge records for the western North Atlantic. The gauges are not only far from the source region but also have inadequate sampling intervals for accurate resolution of waves of tsunami period. The region also lacks a tsunami ''bell-weather'' site, such as Crescent City on the west coast of the US, which can be relied upon to record any tsunami impinging on the outer coast and therefore provide an incentive to examine other gauge data for the region. Contrary to expectation, we find that the 2004 tsunami was recorded in greater detail in the North Atlantic than in the North Pacific Ocean. Findings suggest establishment of an Atlantic international tsunami monitoring system responsible for the tsunami warning and sea level data dissemination. At present, locating tide gauge information is much more difficult for the Atlantic than the Pacific.

[16] **Acknowledgments.** Tide gauge data used in this study were made available by the U.S. National Atmospheric and Oceanic Administration (NOAA) and the Canadian Hydrographic Service (CHS). We thank Charles O'Reilly (CHS, Halifax, NS) for providing the CHS data, Vasily Titov (PMEL/NOAA, Seattle, WA) and Isaac Fine (IOS, Sidney, BC) for making available results of their numerical models, Patricia Kimber (Sidney, BC) for drafting the figures and Cynthia Wright for coordinating the electronic submissions. Partial support for ABR was provided by Russian Federation for Basic Research (RFBR) grants 05-05-64585 and 06-05-08108. The lead author dedicates this paper to the memory of his best friend, Rufus.

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