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Tsunami Heights along the Pacific Coast of Northern Honshu Recorded from the 2011 Tohoku and Previous Great Earthquakes

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Abstract—The 2011 Tohoku earthquake generated a huge, destructive tsunami with coastal heights of up to 40 m recorded along northern Honshu. The Sanriku coast experienced similar tsunamis and damage from the 1896 and 1933 Sanriku earthquakes, whereas the only damaging tsunamis on both the Ibaraki and Chiba coasts in the previous century were from the 1960 and 2010 Chile earthquakes. We summarized 12 field surveys in which the height of the 2011 tsunami was recorded at 296 points, along with descriptions of the survey method, reliability, and accuracy. We then compared them with the above-mentioned tsunamis at locations for which specific measurements were given in previous reports. On the Sanriku coast, the 2011 tsunami heights are positively correlated with the previous Sanriku tsunamis, indicating that local variations resulting from the irregular coastline were more dominant factors than the earthquake location, type, or magnitude for near-field tsunamis. The correlations with the Chilean tsunami heights are less significant due to the differences between the local and trans-Pacific tsunamis. On the Ibaraki and Chiba coasts, the 2011 Tohoku and the two Chilean tsunami heights are positively correlated, showing the general decrease toward the south with small local variations such as large heights near peninsulas.

Key words: 2011 Tohoku tsunami, 1896 Sanriku tsunami, 1933 Sanriku tsunami, 1960 Chilean tsunami, 2010 Chilean tsunami, Sanriku coast.

1. Introduction

On March 11, 2011, a giant earthquake, officially named the "2011 off the Pacific coast of Tohoku earthquake" by the Japan Meteorological Agency (JMA), occurred along the Japan Trench where the Pacific plate subducts beneath the Okhotsk plate (Fig. 1). This earthquake, which we refer to as the 2011 Tohoku earthquake in this paper, was the largest earthquake in Japan since the beginning of modern instrumental observations. It had a moment magnitude, M_w, of 9.0. It caused 15,883 fatalities and 2,656 people were reported missing (National Police Agency as of August 9, 2013); more than 90 % of the casualties were caused by the tsunami. The maximum tsunami height was nearly 40 m based on ~5,900 measurements compiled by the 2011 Tohoku Earthquake Tsunami Joint Survey Group (Mori *et al.* 2011, 2012). Such a gigantic earthquake (~M9) was unexpected in Japan, but was the huge tsunami also a surprise?

The Pacific coast of the Tohoku region has suffered from many large tsunamis generated by both near-field and far-field earthquakes. The 1896 Sanriku tsunami caused ~ 22,000 casualties, which is more than the 2011 Tohoku earthquake. The 1896 Sanriku earthquake was a "tsunami earthquake" (Kanamori 1972), that is, one that produces a tsunami that is much larger than that expected from the earthquake magnitude (surface wave magnitude M_s 7.2; Abe 1994). The 1933 Sanriku earthquake (M_s 8.5) also generated significant tsunami damage with ~3,000 fatalities. The 1960 Chile earthquake was the largest earthquake (M_w 9.5) of the last century and a transoceanic tsunami struck the Pacific coasts of Japan ~23 h after the earthquake, causing 142 fatalities. The 2010 Chile earthquake (M_w 8.8) also generated a trans-Pacific tsunami, which caused property damage to aquaculture facilities such as fishery rafts in Japan.

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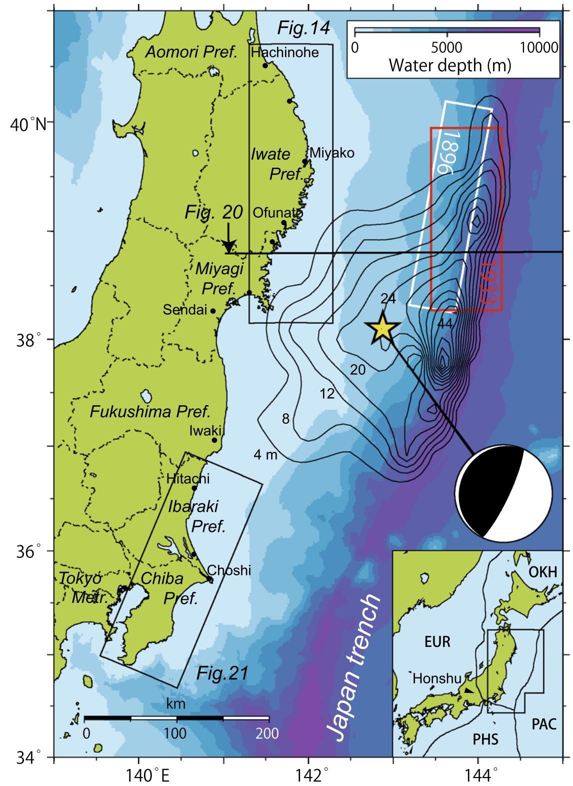

Figure 1
Map of northern Honshu where the 2011 Tohoku earthquake caused tsunami damage. Slip distribution of the 2011 Tohoku earthquake estimated from tsunami waveform inversion (Satake *et al.* 2013) is shown by contours with 4-m intervals. The *yellow star* indicates the epicenter of the mainshock, as determined by the JMA. The focal mechanism is provided by the Global Centroid Moment Tensor project. The *black rectangles* indicate regions shown in Figs. 14 and 21. The *white* and *red rectangles* indicate fault models of the 1896 (Tanioka and Seno 2001) and 1933 Sanriku (Aida 1977) earthquakes, respectively. *Dashed lines* indicate prefectural boundaries. The location of the profile in Fig. 20 is also shown. In the *inset*, OKH, EUR, PAC, and PHS indicate the Okhotsk, Eurasia, Pacific, and Philippine Sea Plates, respectively

This paper first summarizes our field surveys (Tsuji *et al.* 2011) in which the tsunami heights of the 2011 Tohoku earthquake were recorded, along with descriptions of the survey method, reliability, and accuracy. Then, we compare the tsunami heights with those from previous earthquakes both near Japan and across the Pacific Ocean. For the Sanriku coast, we compare the 2011 tsunami heights and inundation areas with two local tsunamis (i.e., the 1896 and 1933 Sanriku tsunamis) and two trans-Pacific tsunamis (i.e., 1960 and 2010 Chilean tsunamis) at selected sites where direct comparisons can be made. For the Pacific coasts of Ibaraki and Chiba prefectures, we similarly compare the 2011 tsunami heights with the 1960 and 2010 Chilean tsunami heights because no damaging tsunamis were recorded from near-field earthquakes in the last century. On the central Sanriku coast, the sawtooth coastal topography is a major factor that strongly affects tsunami heights more so than the earthquake location, type, or magnitude. On the other areas of the Sanriku coast, and the Ibaraki and Chiba coasts, local variations are smaller and the general pattern of tsunami heights reflects the location, slip distribution, and magnitude of the parent earthquake.

2. *Field Surveys of Tsunami Heights from the 2011 Tohoku Earthquake*

We conducted 12 field surveys between March 16 and October 24, 2011. Locations and tsunami heights above sea level were generally measured with handheld GPS receivers and auto-levels, laser rangefinders, or total stations. In the surveys, we first sought traces that indicate the tsunami heights, which were classified as inundation heights, runup heights, and tsunami heights in ports. For tsunami inundation, we measured flow depths above ground based on watermarks or other physical evidence. The highest inundation on a slope where the flow velocity is considered to have been zero is classified as the runup height. Runup heights were measured from debris carried by the tsunami, the absence of leaves, or similar evidence on a slope. However, as most physical evidence had disappeared by June 2011, later surveys mainly relied on eyewitness accounts. In ports where the tsunami did not inundate above the wharfs, we measured tsunami heights based on eyewitness accounts and classified them as tsunami heights in ports, as proposed by Tsuji *et al.* (2010).

The 2011 tsunami heights in this paper are heights that were above sea level at the time of the maximum tsunami arrival. The measured heights were corrected for differences in tide levels between the measurement time and the arrival time of the maximum tsunami. The arrival times of the maximum tsunami at Hachinohe, Miyako, Kamaishi, Ofunato, Ayukawa,

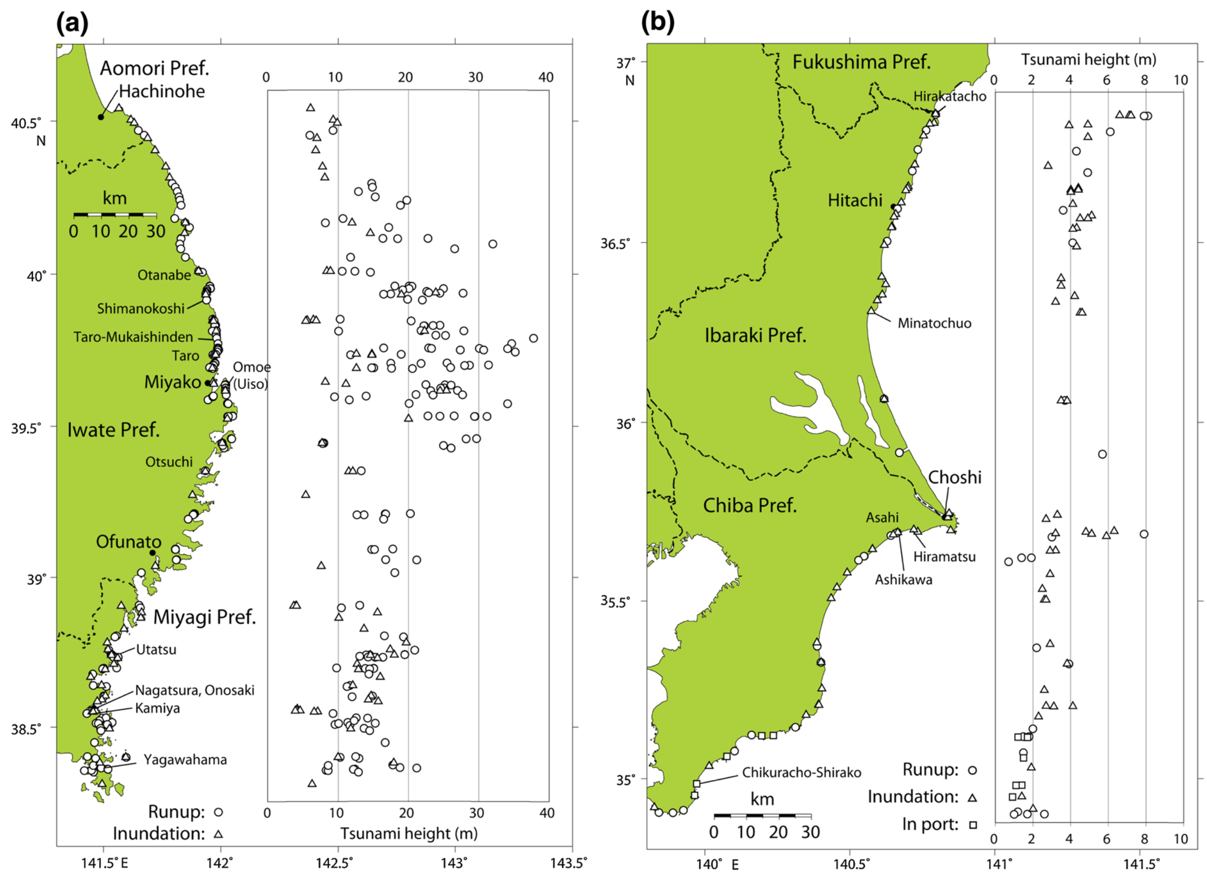

Figure 2

a Distribution of tsunami heights in Aomori, Iwate, and Miyagi prefectures (Tsuji *et al.* 2011). *Circles* and *triangles* indicate runup and inundation heights, respectively. The *dashed lines* indicate prefectural boundaries. **b** Distribution of tsunami heights in Ibaraki and Chiba prefectures. *Circles*, *triangles*, and *squares* indicate runup heights, inundation heights, and tsunami heights in ports, respectively

Onahama, Oarai, Choshi Fishing Port, and Mera (JMA 2011) were used for tide correction. At some locations where the measurement points were far from the sea, we measured altitudes above Tokyo Peil (TP), the leveling datum of Japan. In such cases, we considered land subsidence due to the mainshock, which was as large as 1 m, as recorded by continuous GPS data (Ozawa *et al.* 2011). The altitudes were converted to heights above mean sea level, then to heights above tide level at the time of the maximum tsunami arrival.

The reliability of the evidence was categorized into three classes (A, B, and C), as some tsunami heights were obtained from clear watermarks, whereas others were based on less objective eyewitness accounts (e.g., Shuto and Unohana 1984). Class A indicates the most reliable data, which are based on clear physical evidence or objective eyewitness accounts. Class B indicates evidence based mostly on natural traces such as leaves, grass roots, or debris; while class C indicates the least reliable data that are based on equivocal evidence such as fishing floats in trees or broken windowpanes. Other catalogs such as the NOAA/WDC Tsunami runup Database introduce another type of validity (doubtful), without classifying the reliability.

The measurement accuracy was also categorized into three classes (a, b, and c). Class a means measurement errors are considered to be <0.2 m. The error for class b ranges 0.2–0.5 m because repeated measurements were performed using an auto-level or the sea was rough at the time of measurement. Class c means the errors are > 0.5 m because the sea level could not be directly measured or laser measurements were performed without a reflector.

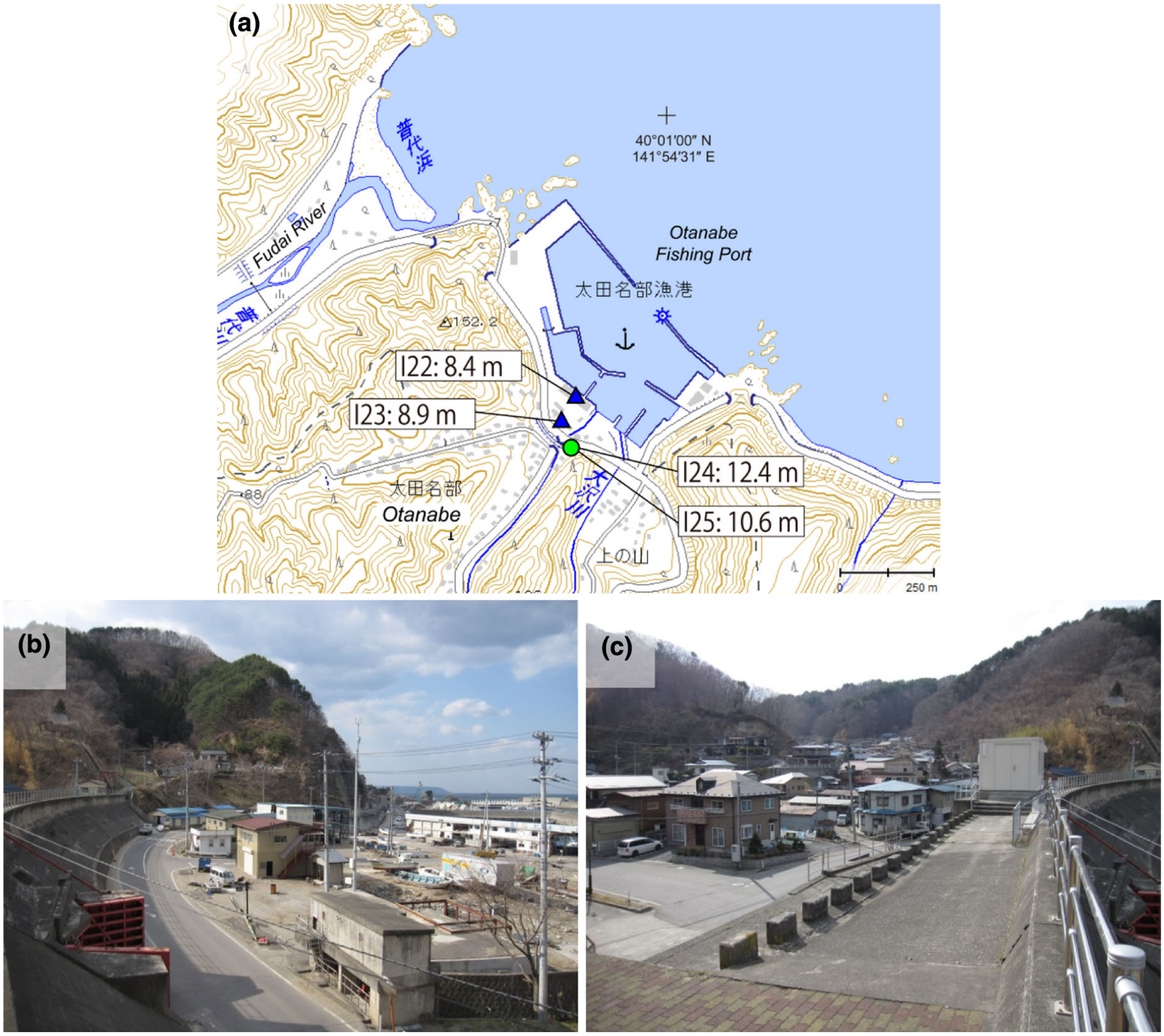

Figure 3

a Tsunami heights at Otanabe (Otanabe Fishing Port), Fudai Village, Iwate Prefecture (with 1:25,000 digital topographic map added from the Geospatial Information Authority of Japan). *Circles* and *triangles* indicate runup and inundation heights, respectively. *Closed circles* and *triangles* are *color* coded according to tsunami heights (i.e., 0–10 m *blue*; 10–20 m *green*, 20–30 m *yellow*, 30 m or above *red*). **b** Destructive damage outside the coastal levee (Otanabe Fishing Port). **c** Very minor damage inside the coastal levee (residential district)

3. Tsunami Heights from 2011 Tohoku Earthquake

Measurements of the 2011 tsunami were made at 296 points on the Sanriku coasts of Aomori (Northern Sanriku), Iwate (Central Sanriku), and Miyagi (Southern Sanriku) prefectures, and the Pacific coasts of Ibaraki and Chiba prefectures (Fig. 2a, b). While the details were reported by Tsuji *et al*. (2011) with the survey points shown on 1:25,000 maps from the Geospatial Information Authority of Japan and photographs of measured tsunami traces, we summarize the tsunami heights at some typical locations. In this paper, we employ the measurement numbers given by Tsuji *et al*. (2011), which start with a letter indicating the prefecture (i.e., A, I, M, B, and C for Aomori, Iwate, Miyagi, Ibaraki, and Chiba prefectures, respectively) and are followed by the sequence number in each prefecture.

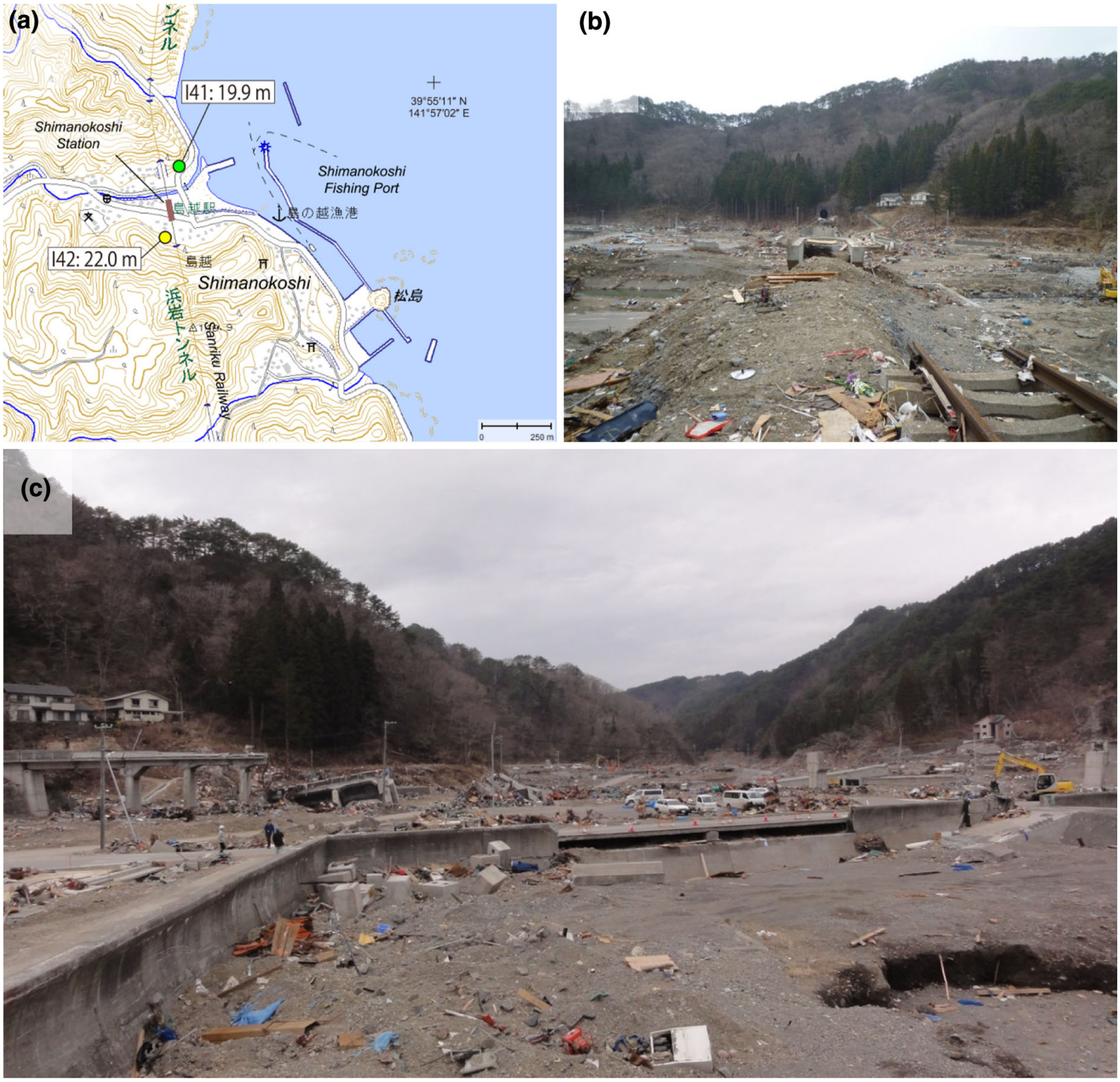

Figure 4
a Tsunami heights at Shimanokoshi, Tanohata Village, Iwate Prefecture. The *symbols* and their meanings are the same as in Fig. 3. **b**, **c** View of tsunami damage at Shimanokoshi

3.1. Sanriku Coast

Along the northern Sanriku coast of Aomori Prefecture, five tsunami heights ranging 6.0–9.9 were measured. Along the central Sanriku coast of Iwate Prefecture, 136 tsunami heights were measured. Tsunami heights were mostly over 10 m, while they were above 30 m at 10 measurement points. Along the southern Sanriku coast of Miyagi Prefecture, 76 tsunami heights were measured. The tsunami heights were mostly 10–20 m, slightly lower than those in Iwate Prefecture, indicating that the highest tsunami height was not recorded directly landward of the largest slip region near the Japan Trench (Figs. 1, 2a).

In the Otanabe district of Fudai Village, a 15-m-high coastal levee had been constructed between the fishing port area and residential area (Fig. 3). The inundation heights were measured as 8.4 and 8.9 m in the fishing port area, and two runup heights of 10.6 m

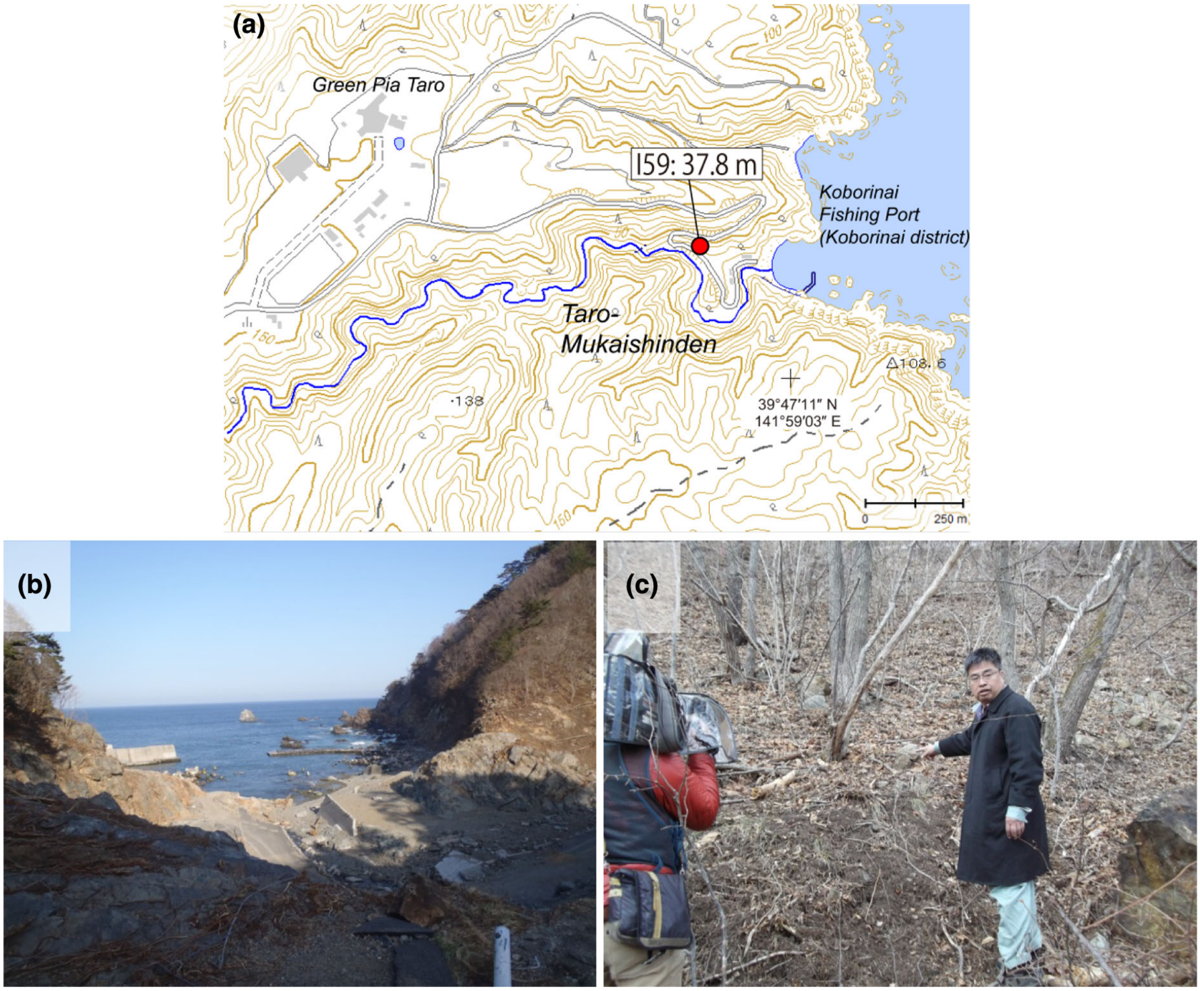

Figure 5

a Tsunami height at Taro-Mukaishinden, Miyako City, Iwate Prefecture. The *symbol* and its meaning are the same as in Fig. 3. **b** View of tsunami damage at Taro-Mukaishinden. The *white* pole in the *lower-right* of the picture was bent by the tsunami. **c** The survey point where the largest tsunami runup height of 37.8 m in our field surveys was measured

(class B) and 12.4 m (class C) were measured on the coastal levee (I22–I25). The floodgate, which was closed before the arrival of tsunami, completely protected the residential area from the devastating tsunami, while the outside fishing port area was severely damaged.

At Shimanokoshi in Tanohata Village, a bridge and Shimanokoshi Station of the Sanriku Railway were completely destroyed by the tsunami, and all the houses were swept away or leveled except for two that were located on a hill (Fig. 4). A runup height of 19.9 m was measured at the northern slope near the dai-ni (second) Shimanokoshi Tunnel (I41). A large amount of wood building materials and debris was deposited throughout the tunnel. The runup height of 22.0 m was measured at the front yard of one of the surviving houses (I42).

At Taro-Mukaishinden near Koborinai Fishing Port in Miyako City, a runup height of 37.8 m (I59), the maximum height in our field surveys, was measured on the basis of the upper limit of debris and absence of leaves (Fig. 5). Three firefighters, who were advising fishermen to evacuate, were killed at an elevation of about 30 m.

At Taro in Miyako City, coastal levees with a height of 10 m and a total length of ∼2.4 km had

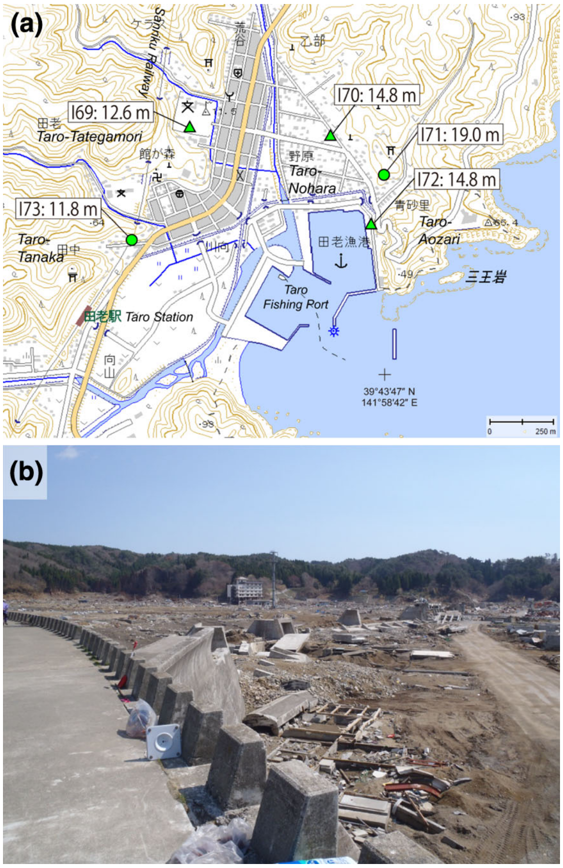

Figure 6

a Tsunami heights at Taro-Tategamori (I69), Taro-Nohara (I70), Taro-Aozari (I71 and I72), and Taro-Tanaka (I73), Miyako City, Iwate Prefecture. The *symbols* and their meanings are the same as in Fig. 3. **b** Part of the breakwater destroyed by the 2011 tsunami. The building in the background is a hotel that the tsunami damaged up to the third floor (14.8 m; I70)

Figure 7

a Tsunami heights at Omoe (Uiso), Miyako City, Iwate Prefecture. The *symbols* and their meanings are the same as in Fig. 3. **b** View of tsunami damage at Uiso Elementary School

been constructed; however, the 2011 tsunami destroyed a portion of these coastal levees, and transported blocks and other debris from the structure more than 100 m inland (Fig. 6). Almost all houses and fishing facilities were swept away or were completely leveled. The first three floors of a hotel were severely damaged, indicating an inundation height of 14.8 m (I70). Tsunami traces on the wall of a Japan Fisheries Cooperatives icehouse indicate the same inundation height (I72). Runup heights of 11.8 m (I73) and 19.0 m (I71) were measured at the western and eastern part of the residential area, respectively. Tsunami trace at a middle school indicates an inundation height of 12.6 m (I69).

At Omoe (Uiso), which is located on the east coast of Miyako City on the Omoe Peninsula, the tsunami arrived at Uiso Elementary School, which is sited on a hill having an altitude of >20 m (Fig. 7). Panes of glass on the first floor were broken and a large amount of debris was scattered over the school playground. The measured inundation heights were 25.4 and 24.5 m, while the runup heights were 27.0 and 23.2 m (I96–I99).

At Utatsu-Namiita and Utatsu-Minato in Minamisanriku Town, most houses in the lowlands were leveled or swept away (Fig. 8). It was found from eyewitness accounts that the second tsunami arrival was the largest. At the northern settlement, one inundation height of 18.0 m and two runup heights of 19.4 and 19.5 m were measured (M15–M17). Although the southern settlement is located nearby, a lower inundation height of 14.6 m and runup heights of 14.5 and 14.0 m were measured (M18–M20).

Figure 8
a Tsunami heights at Utatsu-Namiita (M15, M16, and M17) and Utatsu-Minato (M18, M19, and M20), Minamisanriku Town, Miyagi Prefecture. The *symbols* and their meanings are the same as in Fig. 3. **b**, **c** Tsunami damage at Utatsu-Namiita (*left*) and Utatsu-Minato (*right*)

Around Nagazuraura, which is a brackish lake connected to Oppa Bay in Ishinomaki City, almost all the houses were inundated by the 2011 tsunami (Fig. 9). Japanese black pines and houses at the mouth of the Kitakami River were swept away. Many houses and rice paddies were submerged due to significant ground subsidence, and sand was deposited all over the residential district. In Onosaki district, which is located eastward of Nagazuraura, inundation heights of 4.2 and 3.9 m were measured (M43, M46). In Nagatsura district to the west of Nagazuraura, four inundation heights ranging 4.1–7.1 m were obtained (M44, M45, M47 and M48). Some residents drowned at the temple to which they had evacuated, erroneously assuming it was at a safe elevation.

At Okawa Elementary School in Kamaya, Ishinomaki City, 10 teachers and 74 of the 108 students

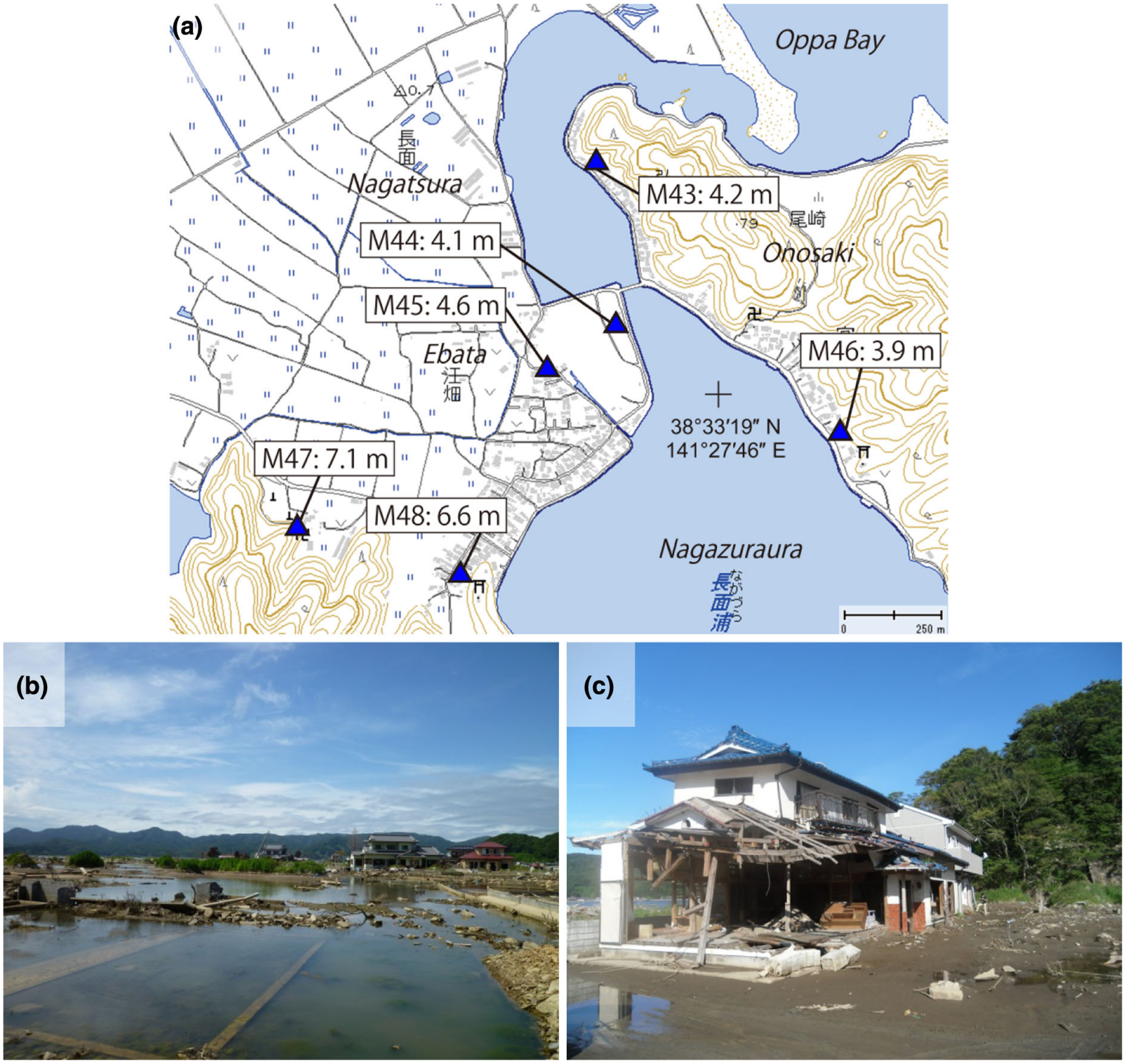

Figure 9

a Tsunami heights at Onosaki (M43, M46) and Nagatsura (M44, M45, M47, and M48), Ishinomaki City, Miyagi Prefecture. The *symbols* and their meanings are the same as in Fig. 3. **b**, **c** View of tsunami damage and ground subsidence at Onosaki and Nagatsura

died on the way to an evacuation site. It was found that the tsunami, which had run up the Kitakami River, inundated to a height above the ceiling of the second floor of the school (Fig. 10). A runup height of 9.3 m was measured at a slope behind the school (M49).

At Yagawahama in Ishinomaki City, almost all the houses were swept away by the tsunami, and farmland was covered by tsunami sediment deposits that included sand, shell fragments and gravel (Fig. 11). A large amount of debris, which was caught in trees on the side of a road, indicate an inundation height of 18.7 m (M67). The maximum runup height of 21.2 m in the Miyagi Prefecture was measured at the cemetery behind Tofuku-ji Temple (M68).

3.2. Ibaraki and Chiba Coasts

On the Ibaraki coast (between 35.7° and 36.9°N), 36 measurements of the 2011 Tohoku tsunami ranged 2.8–8.1 m, and the heights generally decreased

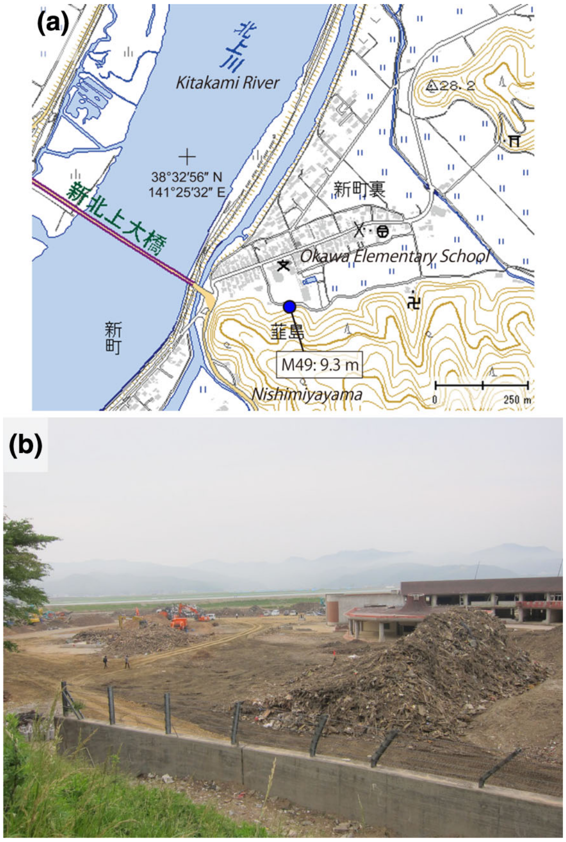

Figure 10
a Tsunami height at Kamaya in Ishinomaki City, Miyagi Prefecture. The *symbol* and its meaning are the same as in Fig. 3. **b** View of tsunami damage at the Okawa Elementary School

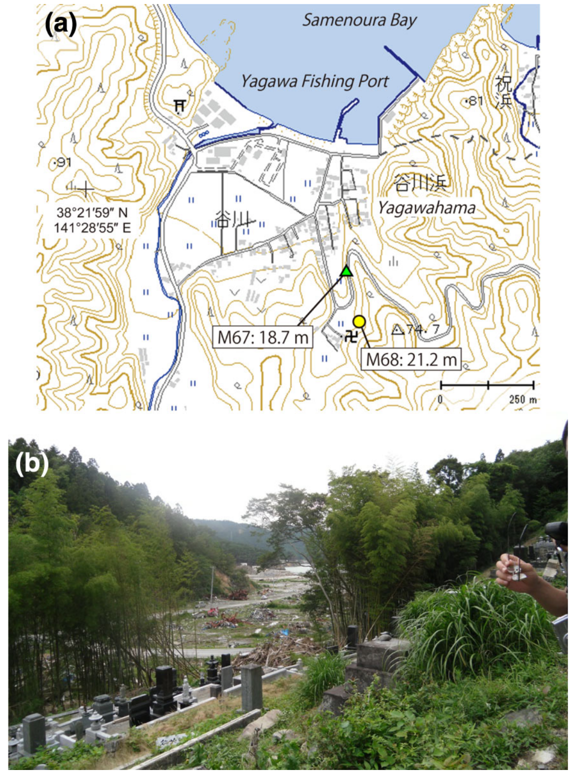

Figure 11
a Tsunami heights at Yagawahama, Ishinomaki City, Miyagi Prefecture. The *symbols* and their meanings are the same as in Fig. 3. **b** View from the survey point with a runup height of 21.2 m (M68)

toward the south (Fig. 2b). The typical tsunami height was 4 m and the local variations were significantly smaller than those along the Sanriku coast. Along the coast of Chiba Prefecture (between 34.9° and 35.7°N), 43 measurements of the 2011 tsunami heights were generally <4.0 m. They gradually decreased toward the south, and most tsunami heights were <2 m along the coast of southern Chiba Prefecture. However, tsunami heights were locally high (5.1–7.9 m) around Asahi City.

At Hirakatacho in Kitaibaraki City, the fishing port and residential area were severely damaged (Fig. 12). The first floors of many houses were destroyed by the tsunami and some houses collapsed completely. Watermarks on buildings indicated inundation heights ranging 6.6–7.2 m, while debris indicated runup heights of 7.9 and 8.1 m (B1–B5). At Minatochuo in Oarai Town, which is located in the central part of Ibaraki Prefecture, inundation heights of 4.5 and 4.6 m were measured from the watermarks on the ferry terminal building (B30, B31).

At Asahi City, the tsunami heights were locally high. Residential areas along the Pacific coast were badly damaged and 13 people were killed (Fig. 13). In the Hiramatsu district where buildings were densely distributed, a clear watermark on the windows of a store indicated the inundation height as 6.3 m (C4). In the Ashikawa district, an inundation height of 5.1 m and a runup height of 7.9 m were measured (C5, C6). At the Shirako Fishing Port in Chikuracho-Shirako in Minamiboso City, according to eyewitness accounts, the first tsunami arrived at 15:15–15:30 and the seawater rose to near the top of the quay. The measured tsunami heights in this port ranged 1.0–1.4 m (C35, C36). The eyewitnesses also

Figure 12
a Tsunami heights at Hirakatacho, Kitaibaraki City, Ibaraki Prefecture. The *symbols* and their meanings are the same as in Fig. 3. **b** View of tsunami damage at Hirakatacho. **c** Watermarks on windowpanes of entrance doors of the guesthouse Yanagiya (0.89 m above ground level, B3)

reported that the second tsunami arrival was one hour after the first arrival and that the height was similar.

4. Tsunami Height Data from Past Earthquakes

4.1. 1896 and 1933 Sanriku Earthquakes

A number of field surveys and investigations have been conducted for the tsunamis caused by the June 15, 1896 and March 3, 1933 Sanriku earthquakes to determine the heights and inundation areas (e.g., Imamura 1934; Shuto and Goto 1985a, b; Imamura and Watanabe 1990; Hatori 1995). In this study, we examined the reports of the original surveys published soon after the earthquakes (i.e., in the 1890s and 1930s), rather than secondary or recent papers. We briefly describe these original reports below.

Yamana (1896; reproduced by Unohana and Ota 1988) reported that his survey was conducted between July 28 and September 9, 1896, in all the

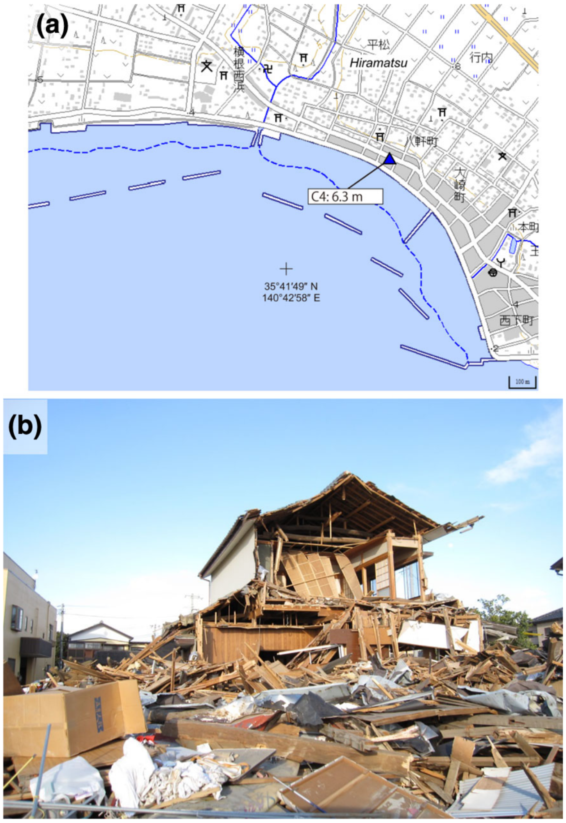

Figure 13
a Tsunami height at Hiramatsu, Asahi City, Chiba Prefecture. The *symbol* and its meanings are the same as in Fig. 3. **b** A damaged house in Hiramatsu district

villages along the Sanriku coast. He reported not only tsunami heights, but also casualty numbers and property damage for each village, along with providing 168 maps illustrating the disaster. The largest heights of 180 shaku, or 55 m (1 shaku = 0.303 m) were reported at Kosode (I12, I13) and Ryori-Shirahama (I133). However, the accuracy of Yamana's measurements varies at different locations. For example, the reported runup height is 132 shaku (40.0 m) at Shimanokoshi (I41, I42), whereas the height is 130–180 shaku (39–55 m) at Ryori–Shirahama (I133).

Iki (1897) surveyed the Sanriku coast from June 20 to July 21, 1896, and his report contains list of locations and tsunami heights. However, it contains very few figures, making it difficult to identify the exact measurement locations. The reported tsunami heights in feet (1 foot = 0.305 m) were from sea level at the time of measurement. He measured tsunami heights from changes in vegetation color or watermarks due to tsunami inundation, which are considered to be highly reliable, or from debris or scratches on trees. He also distinguished heights measured by himself and those based on eyewitness accounts.

Matsuo (1933) reported tsunami heights from the 1896 and 1933 Sanriku tsunamis based on surveys he conducted during March 3–10 and May 19–June 4, 1933, with the support of the Iwate and Miyagi prefectural governments. The tsunami heights from the 1896 Sanriku tsunami were measured 37 years after the event, based on eyewitness accounts. The often quoted maximum height of 38 m at Ryori–Shirahama (I133) from the 1896 Sanriku tsunami was based on this report. Matsuo (1934) also reported the 1933 tsunami heights and inundation areas of the 1896 and 1933 tsunamis along the coasts of Hokkaido and Aomori prefectures.

Kunitomi (1933) reported tsunami heights together with arrival times from both eyewitness accounts and tide gauge records, the number of tsunami waves, and periods from the 1933 Sanriku tsunami in Hokkaido, along the Sanriku coasts of Aomori, Iwate, Miyagi prefectures, and along the Pacific coast of Fukushima Prefecture, based on field surveys from meteorological observatories. Tsunami heights were measured on the basis of traces left at the coast and/or eyewitness accounts. Appendix figures indicating tsunami heights and inundation areas on maps with a scale of 1:200,000, and photographs recording severe damage are also shown. Kunitomi (1933) also compared the 1933 heights with the 1896 heights from Iki (1897) and surveys from the Civil Engineering Division of the Iwate prefectural government.

The Earthquake Research Institute (1934) reported the survey results for the Pacific coasts from Hokkaido to Ibaraki Prefecture. It reported tsunami heights with maps showing estimated inundation limits, damage to houses and other structures, relations between the severity of tsunami effects and topographic conditions, photographs, and tide gauge records. In addition, Otuka (1934) discussed the relationship between tsunami heights and the topography of the Sanriku coast.

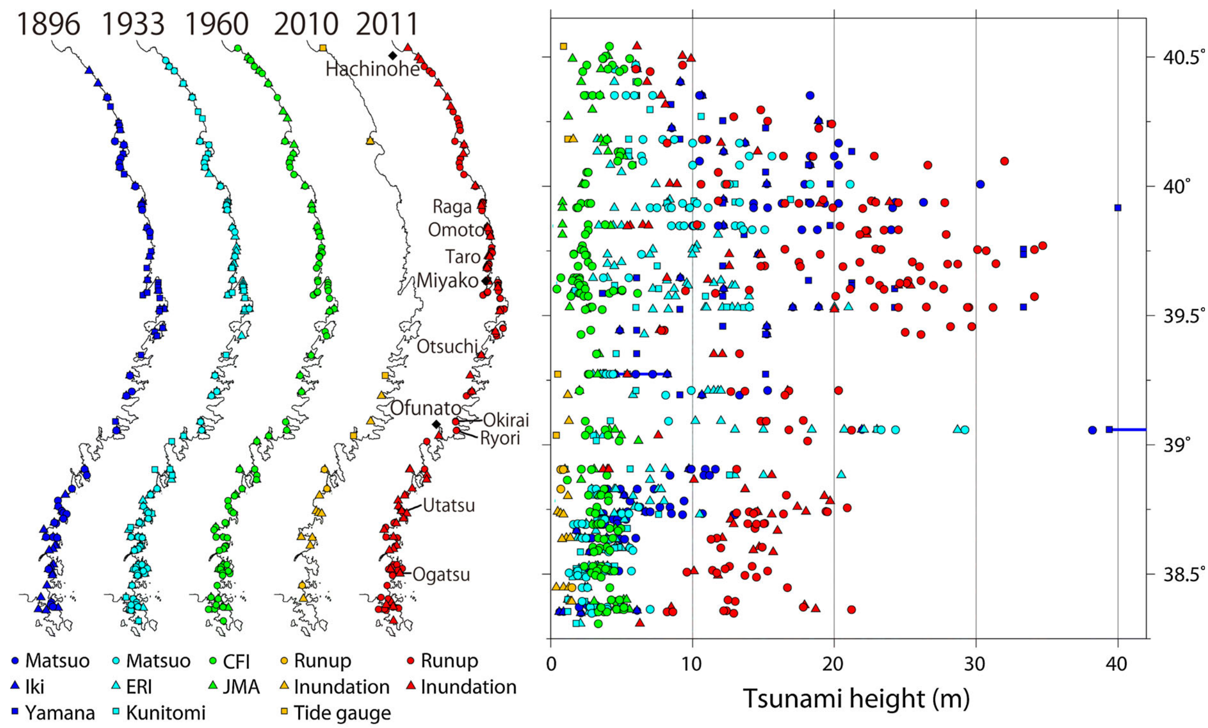

Figure 14
Comparison of 1896 and 1933 Sanriku tsunami heights, 1960 and 2010 Chilean tsunami heights with 2011 tsunami heights. *Bars* indicate the range of measured heights. The measurement locations are indicated on the maps on the *left*. Only data measured at the same locations for two or more tsunamis are shown. *Blue circles*, *triangles*, and *squares*, respectively, indicate the 1896 tsunami heights given by Matsuo (1933), Iki (1897), and Yamana (1896), which were reproduced by Unohana and Ota (1988). *Light blue circles*, *triangles*, and *squares*, respectively indicate the 1933 heights from Matsuo (1933, 1934), the Earthquake Research Institute (1934), and Kunitomi (1933). *Green circles* and *triangles* indicate the 1960 Chilean tsunami heights from CFI (1961), and JMA (1961), respectively. *Orange circles*, *triangles*, and *squares*, respectively, indicate the 2010 runup, inundation heights, and heights from tide gauges by Tsuji *et al*. (2010). *Red circles* and *triangles*, respectively, indicate the 2011 runup and inundation heights from Tsuji *et al*. (2011)

4.2. 1960 and 2010 Chile Earthquakes

The Committee for Field Investigation of the Chilean Tsunami of 1960 (CFI, 1961) consisted of 100 investigators who conducted surveys along the entire Pacific coast of Japan from Hokkaido to Kyushu. They compiled measured tsunami heights above TP (nearly equal to mean sea level), reliability (1–5), and arrival time of the maximum tsunami. The report contains detailed maps showing the exact measurement locations.

Japan Meteorological Agency (JMA, 1961) contains field survey results made by the agency. The reported tsunami heights were either measured on tide gauges or were based on eyewitness accounts. The definition of tsunami heights and datum varies according to location; and detailed maps indicate measurement locations.

Imai *et al*. (2010) reported tsunami heights from the 2010 Chile earthquake along the coasts of the Kanto and Tokai districts measured from field surveys or tide gauges. Tsuji *et al*. (2010) reported the 2010 tsunami heights along the Sanriku coast measured from field surveys or tide gauges. The tsunami heights were above sea level at the time of maximum tsunami and were classified as inundation heights, runup heights, and tsunami heights in ports. The survey locations were measured using handheld GPS devices showing latitudes and longitudes.

4.3. Selection of Locations for Comparison

We selected locations for which measurements for the 2011 tsunami and at least one of the previous tsunamis were available in order to enable a direct comparison. While the precise measurement points of the 1896 and 1933 Sanriku tsunamis are unknown, comparisons were made at locations (village or smallest bay). We attempted to reduce the local variability in tsunami heights as much as possible. For the 1960 and 2010 Chilean tsunamis, we selected tsunami height data measured in the same ports or similar coastal locations by examining maps of the measurement points. For the comparison of tsunami heights between the 2011 and previous tsunamis, we use the median height of multiple measurements in each report. For an example, three tsunami heights (by the Earthquake Research Institute, median of five heights by Matsuo, and by Kunitomi) were compared with the 2011 height (7.8 m) at I3 (Taneichi, Hirono Town). For another example, the median height of three measurements of the 2011 tsunami (I16–I18) was compared with the previous tsunamis at the Noda Fishing Port in Noda Village.

5. *Comparison of Tsunami Heights on the Sanriku Coast*

Along the Sanriku coasts of Aomori, Iwate, and Miyagi prefectures, Tsuji *et al*. (2011) measured 217 tsunami heights at 120 locations. Of these, the 1896 and 1933 heights were reported at 80 and 94 locations, respectively (Fig. 14; Table 1). The 1896 tsunami heights are smaller than the 2011 tsunami heights (median ratio is 0.69; Table 3), and the 1933 heights are even smaller (median ratio 0.33). The 1960 and 2010 Chilean tsunami heights can be compared with the 2011 tsunami heights at 98 and 19 locations, respectively (Table 2). The 1960 tsunami heights are also smaller than the 2011 tsunami heights (median ratio 0.25), and the 2010 heights are much smaller (median ratio 0.07).

5.1. *Central Sanriku Coast*

Along the central Sanriku coast with latitudes between 39.0° and 40.2°N, the 2011 tsunami heights ranged from 5 to 40 m (Fig. 14). In this region, the 1896 heights were approximately similar (median ratio is 0.85; Table 3) to the 2011 heights, whereas the 1933 heights were smaller (median ratio 0.47). The 1960 and 2010 Chilean tsunami heights were much smaller than the 2011 heights (median ratio is 0.16 and 0.09, respectively).

At Raga in Tanohata Village, the 1896 and 2011 tsunami heights were much larger than the 1933 tsunami height. The measured 2011 tsunami heights ranged from 23 to 28 m (I34–I37), while the reported 1896 tsunami heights varied from 60 shaku (18 m; Yamana 1896), 75 feet (23 m; Iki 1897), and 24–26 m (Matsuo 1933). During our survey, a local resident testified that the 1896 Sanriku tsunami washed away their former family house, which was at the same location as the current one, whereas the 2011 tsunami did not. Furthermore, the 2011 tsunami inundation limit is located just below the tsunami stone transported by the 1896 tsunami (Fig. 15). Takeda (1987) measured the level of the tsunami stone as 28.2 ± 1.2 m above TP and concluded that the maximum runup height of the 1896 Sanriku tsunami at Raga may have been higher than 30 m. The 1933 tsunami height was reported to be 13 m, while the 1960 tsunami height was 1 m.

At Omoto in Iwaizumi Town, the 1896, 1933, and 2011 tsunamis had similar inundation areas (Fig. 16). The 1960 Chilean tsunami reportedly inundated about 1 km from the river mouth and raised the water level by 1 m (CFI 1961). The 2011 tsunami topped the coastal levee and floodgate, which was constructed in 1990. The measured inundation height was 5 m in the residential area east of the Omoto River (I48). West of the Omoto River, the tsunami inundated farmland and the tsunami heights ranged from 6 to 10 m (I43–I46). Seaward of the Omoto floodgate, the measured runup height was 20 m (I47). The 1896 tsunami heights were between 10 and 20 m. The reported 1933 tsunami heights were between 3 and 13 m. The 1960 tsunami heights were reported as 4 m near I47, 3–4 m at the river mouth by CFI (1961), and 1 m by JMA (1961).

At Taro in Miyako City, the 2011 tsunami was larger than the 1933 tsunami, but it is unclear whether it was larger than the 1896 tsunami. Tsunami heights from the 2011 event ranged from 12 to 19 m (I69–I73). The 1896 heights were reported as being 110 shaku (33 m; Yamana 1896) or 48 feet (15 m; Iki 1897), while the heights from the 1933 tsunami ranged from 4 to 10 m. The damage to an icehouse of the Japan Fisheries Cooperatives indicates that the

Table 1

Tsunami heights for Sanriku coasts of Aomori, Iwate, and Miyagi prefectures from the 1896, 1933, and 2011 earthquakes

No.	Location Name	Latitude		Longitude		2011 height[a]	rel.[b]	acc.[c]	type	1896 height[d]			1933 height[e]		
		deg	min	deg	min.	(m)				Iki (feet)	Yamana	Matsuo (m)	ERI (m)	Matsuo (m)	Kunitomi (m)
A3	Daisakutai, Samemachi, Hachinohe City (Okuki Fishing Port)	40	30	141	38	9.9	A	a	I					3.7	
A4	Oja, Dobutsu, Hashikami Town (Oja Fishing Port)	40	28	141	39	9.3	A	a	R				6.0	6.0	6.0
A5	Kominato, Dobutsu, Hashikami Town (Kominato Fishing Port)	40	27	141	40	6.0	A	a	R	20				4.5	4.5
I2	Taneichi, Hirono Town (Taneichi Fishing Port)	40	24	141	43	6.8	B	a	I	30			4.5		6.0
I3	Taneichi, Hirono Town (Yagi Port)	40	21	141	46	7.8	B	b	I	Δ35	20	10.5 18.3	3.5	2.5 4.5 5.3 5.9 7.2	6.0
I4	Uge, Hirono Town (Uge Fishing Port)	40	19	141	47	8.1	A	a	I		28				
I5	Nakano, Hirono Town (Koge Fishing Port, Koge District)	40	18	141	48	14.8	B	a	R						7.0
I7	Samuraihamacho-Mukaicho, Kuji City (Kawatsunai Fishing Port, Kawatsunai District)	40	16	141	49	12.9	B	a	R						10.6
I8	Samuraihamacho-Shiromae, Kuji City (Shiromae Fishing Port, Shiromae District)	40	15	141	49	15.3	A	a	R	62	40				
I9	Samuraihamacho-Honnami, Kuji City (Shiromae Fishing Port, Honnami District)	40	14	141	50	19.8	B	a	R		65				
I10	Samuraihamacho-Mugyo, Kuji City (Mugyo Fishing Port)	40	13	141	50	18.9	B	a	R	28	50				
I11	Osanaicho (Tamanowaki), Kuji City (Tamanowaki Fishing Port)	40	11	141	48	10.7	A	a	R		30	11.0	3.3 4.0	6.5 7.9 8.7	5.5
I12	Ubecho (Kosode), Kuji City (Kosode Fishing Port, Kosode District)	40	10	141	51	12.0	B	a	I	45	180	20.3 20.3		10.0 13.3	8.2
I13	Ubecho (Kosode), Kuji City	40	10	141	51	8.2	A	a	R						
I15	Ubecho (Kuki), Kuji City (Kuki Fishing Port)	40	8	141	51	14.6	A	b	I	40	70		3.3		5.5
I16	Noda, Noda Village (Noda Fishing Port)	40	7	141	50	22.8	C	a	R			18.3	5.5	6.4	5.5
I17		40	7	141	50	16.4	B	a	R			20.0		14.0	
I18		40	7	141	50	18.5	B	a	R					15.6	
I19	Noda (Maita), Noda Village	40	6	141	50	32.0	B	b	R			10.5		6.5	
I20	Tamagawa, Noda Village (Noda Tamagawa Station)	40	5	141	50	26.6	B	a	R	60	60	20.3 20.3	4.2	10.0 13.3	5.8
I21	Tamagawa (Shimoakka), Noda Village	40	3	141	51	11.8	B	a	R		50		5.0		
I22	Otanabe, Fudai Village (Otanabe Fishing Port)	40	1	141	54	8.4	A	c	I	50	65	17.9	7.4	12.3	13.0
I23		40	1	141	54	8.9	A	a	I			30.3		12.6	
I24		40	1	141	54	12.4	C	a	R					18.3	
I25		40	1	141	54	10.6	B	a	R					21.1	
I32	Aketo, Tanohata Village	39	57	141	57	19.2	B	a	R	Δ40			8.4		16.9
I33		39	57	141	57	22.6	B	a	R				8.4		
I34	Raga, Tanohata Village	39	56	141	56	23.9	A	a	I	75	60	24.3		13.3	13.0
I35		39	56	141	56	22.9	A	a	R			24.3		13.3	
I36		39	56	141	56	27.8	B	a	R			26.3		13.3	
I37		39	56	141	56	24.5	B	a	R						
I38	Raga (Hiraiga), Tanohata Village	39	56	141	56	17.5	B	a	R		40	14.3 16.3	8.2 8.3	9.3 10.3	8.2
I39		39	56	141	56	16.5	B	a	R			18.3		10.3	
I40	Wano, Tanohata Village	39	56	141	56	19.0	B	a	I			19.3 20.3		10.3	
I41	Shimanokoshi, Tanohata Village	39	55	141	56	19.9	B	a	R		132	14.3 14.3 15.3	4.5 4.5 6.0	7.0 7.5 8.3	9.7
I42		39	55	141	56	22.0	A	a	R			19.9 24.1		8.5 9.8 11.1	
I43	Omoto, Iwaizumi Town	39	51	141	58	10.3	B	a	R	40	65	10.0	3.4–4.4	8.5	
I44		39	51	141	58	6.5	A	a	I			11.8	5.0	9.1	
I45		39	51	141	58	5.6	A	a	I					9.4	
I46		39	51	141	58	6.9	A	a	I					10.1 10.4	
I47		39	51	141	58	20.4	B	a	R					10.6	13.0
I48		39	51	141	58	5.4	A	a	I					13.0 13.4	
I49	Moshi, Omoto, Iwaizumi Town (Moshi Fishing Port)	39	50	141	59	24.5	B	a	R			17.7		13.6	
I50		39	50	141	59	23.5	B	a	R			18.8		14.2	
I51	Moshi, Omoto, Iwaizumi Town	39	50	141	58	22.3	B	a	R			24.0		15.1	
I52		39	50	141	58	22.2	B	a	R					15.1	

Table 1

continued

No.	Location Name	Latitude		Longitude		2011 height[a]	rel.[b]	acc.[c]	type	1896 height[d]			1933 height[e]		
		deg	min	deg	min.	(m)				Iki (feet)	Yamana	Matsuo (m)	ERI (m)	Matsuo (m)	Kunitomi (m)
I53	Taro-Shimosettai, Miyako City	39	49	141	59	21.8	B	a	R		45		11.8		
I54		39	49	141	59	27.9	B	a	R						
I55		39	49	141	59	22.3	A	a	I						
I60	Taro-Aonotakiminami, Miyako City (Aonotaki Fishing Port)	39	46	141	59	34.7	B	b	R				10.3		
I61	Taro-Otobeno, Miyako City	39	45	141	59	22.9	B	a	R		110		7.2		
I62		39	45	141	59	16.5	B	a	R				10		
I63		39	45	141	59	23.3	B	a	R				10.2		
I64		39	45	141	59	30.1	B	a	R						
I65		39	45	141	59	34.1	B	a	R						
I69	Taro-Tategamori, Miyako City	39	44	141	58	12.6	A	a	I	48	110		4	6.4	
I70	Taro-Nohara, Miyako City	39	44	141	59	14.8	A	c	I				7		
I71	Taro-Aozari, Miyako City	39	44	141	59	19.0	B	b	R				10		
I72		39	44	141	59	14.8	A	c	I						
I73	Taro-Tanaka, Miyako City	39	44	141	58	11.8	B	a	R						10.1
I74	Taro-Nishimukaiyama, Miyako City (Kashinai Fishing Port)	39	43	141	58	25.5	B	a	R				5		
I75		39	42	141	59	17.5	B	a	R						
I76	Taro-Kashinai, Miyako City (Kashinai Fishing Port)	39	42	141	58	21.8	B	a	R						
I77	Sakiyama (Mattsuki), Miyako City	39	42	141	58	31.4	B	a	R				4		
I78		39	42	141	58	28.7	B	a	R						
I79		39	42	141	58	28.0	B	a	R						
I80	Sakiyama (Onappe), Miyako City	39	42	141	58	15.1	A	a	R		40		4.5		7.5
I81		39	42	141	58	14.8	B	a	R						
I82		39	41	141	58	12.6	B	a	I						
I83		39	41	141	58	17.6	B	a	R						
I84		39	41	141	58	20.6	B	a	R						
I85		39	41	141	58	26.0	B	a	R						
I86	Kuwagasaki (Nakamachi), Miyako City	39	39	141	58	8.2	A	a	I	Δ30	20		3 4	3.7 5.5	
I88	Tsugaruishi (Norinowaki), Miyako City	39	35	141	57	11.6	B	a	R		12		1.5		1.6
I89	Akamae, Miyako City	39	36	141	58	9.5	B	a	R		15				1.7
I90		39	36	141	58	14.0	B	a	R						
I91	Omoe (Tatehama), Miyako City	39	38	142	1	22.5	B	a	R		60		8.2		
I92		39	38	142	1	25.2	B	a	R				12		
I93		39	38	142	1	26.1	B	a	R						
I94	Omoe (Shukuhama), Miyako City	39	38	142	1	25.1	B	a	R		70		9.6-		
I95		39	38	142	1	24.6	B	a	R				11.5		
I96	Omoe (Uiso), Miyako City	39	37	142	1	27.0	B	a	R		70		9.7		4.5
I97		39	37	142	1	25.4	A	a	I				12.8		
I98		39	37	142	1	23.2	B	a	R				13		
I99		39	37	142	1	24.5	A	a	I						
I100	Omoe (Aramaki), Miyako City	39	36	142	1	21.1	B	a	R	Δ40	80		7.2		7.6
I101		39	36	142	1	27.7	B	a	R				8.7		
I102		39	36	142	1	23.5	B	a	R						
I103	Omoe (Sato), Miyako City (Omoe Fishing Port)	39	34	142	2	20.1	B	a	R		40		8.3		10.9
I104		39	34	142	2	34.1	C	a	R				8.8 14		
I105	Omoe (Aneyoshi), Miyako City	39	32	142	3	26.5	B	a	R	62	110		12.8	14.0	12.4
I106		39	32	142	3	22.8	B	a	R				14.0		
I107		39	32	142	3	24.5	B	c	R				20 21.0		
I108	Omoe (Chikei), Miyako City	39	32	142	2	29.5	A	a	R	56	80		10.9		6.0
I109		39	32	142	2	31.2	A	a	R				11.0		13.6
I110		39	32	142	2	29.4	A	a	R				12.1 13.2		
I111	Omoe (Ishihama), Miyako City	39	31	142	2	20.0	A	a	I		30		7.2 8.7		12.0
I112	Funakoshi (Ohura), Yamada Town	39	27	142	0	8.0	B	a	R	16	20				
I113		39	27	142	0	7.7	A	a	I						
I114		39	27	142	0	8.0	B	a	R						
I115		39	27	142	0	7.8	B	a	R						
I116	Funakoshi (Sukuiso), Yamada Town	39	27	142	3	29.7	B	a	R	50	40				
I117		39	27	142	3	28.2	B	a	R						
I118	Funakoshi (Koyadori), Yamada Town	39	26	142	1	26.1	A	a	R	50	50		6.6		
I119		39	26	142	1	25.0	B	a	R						
I120	Akahama, Otsuchi Town	39	21	141	56	13.3	B	a	R		20				4.6
I121	Akahama, Otsuchi Town	39	21	141	56	11.5	A	a	I						
I122	(International Coastal Research Center, Atmosphere and Ocean Research Institute, the University of Tokyo)	39	21	141	56	12.1	A	a	I						

Table 1

continued

No.	Location Name	Latitude deg	Latitude min	Longitude deg	Longitude min.	2011 height[a] (m)	rel.[b]	acc.[c]	type	1896 height[d] Iki (feet)	1896 height[d] Yamana	1896 height[d] Matsuo (m)	1933 height[e] ERI (m)	1933 height[e] Matsuo (m)	1933 height[e] Kunitomi (m)
I123	Omachi, Kamaishi City	39	16	141	53	5.4	A	b	I	15–27	50	6.0 6.0 7.2	3.0 3.5 3.7 3.8 3.9	2.7 3.6 3.9 4.2 4.2 4.4 4.4	5.4
I124	Osone, Tonicho,	39	13	141	53	20.3	A	a	R			15.3	11.1	9.9	6.0
I125	Kamaishi City	39	13	141	53	16.7	C	a	I			15.3	11.5	9.9	
I126		39	13	141	53	16.8	B	a	R				11.8		
I127	Sakuratoge, Tonicho,	39	12	141	53	13.7	B	a	R				12.0		
I128	Kamaishi City	39	12	141	53	12.7	B	a	R						
I129	Arakawa, Tonicho, Kamaishi City	39	12	141	52	16.5	B	a	R	Δ35	30	13.3 13.3	5.8	8.1 8.1	
I130	Horei, Sanrikucho-Okirai, Ofunato City	39	6	141	48	17.8	B	a	R		50		12	8.3	4.2
I131		39	6	141	48	14.8	B	a	R				10.2		
I132		39	6	141	48	15.2	B	a	R						
I133	Shirahama, Sanrikucho-Ryori, Ofunato City	39	4	141	49	16.8	B	a	R	72	130–180	38.2	13 15	23.3 23.3	23.0
I134	Okubo, Sanrikucho-Ryori, Ofunato City	39	3	141	49	21.2	B	a	R				18.4 20.7 22.1 23.0 28.7	24.3 29.2	
I135	Miyanomae, Ofunatocho, Ofunato City	39	2	141	43	7.6	A	a	I				3.2 3.7 4.1		3.0
I136	Yonesakicho, Rikuzentakata City	39	1	141	40	18.1	B	b	R						3.2
M1	Karakuwacho-Baba, Kesennuma City	38	54	141	39	13.1	A	a	R	32		9.9 10.9 11.6	7 8.1		5.6
M3	Karakuwacho-Kakehama, Kesennuma City	38	53	141	40	15.6	A	a	I			8.4 10.8 11.2	13 15 20.5		12.6
M4	Karakuwacho-Tsumoto, Kesennuma City	38	52	141	40	10.1	A	a	I				7.0		
M5	Minamimachikaigan, Kesennuma City	38	54	141	34	4.0	A	a	I						1.0
M6	(Kesennuma Port)	38	54	141	34	3.7	A	a	I						
M7		38	54	141	34	4.1	A	a	I						
M8		38	54	141	35	4.1	A	a	I						
M9	Hajikamisuginoshita, Kesennuma City	38	50	141	35	13.7	A	b	I			4.0 4.9 6.1 7.3	2.9 4.5 4.6 7.6 7.8	2.9 3.2 3.8	
M10	Motoyoshicho-Amagasawa, Kesennuma City (Hikado Fishing Port)	38	48	141	33	16.6	A	a	R	17			3.3 4.0 4.0	3.3	3.0
M11	Motoyoshicho-Maehama, Kesennuma City	38	48	141	33	19.3	B	a	I			9.3 9.5	5.8		
M12	Motoyoshicho-Toyomazawa, Kesennuma City	38	47	141	31	19.7	A	a	I			5.6 9.4	7-8		
M13	Motoyoshicho-Nijuichihama, Kesennuma City	38	46	141	31	17.4	A	a	I	20		6.3 7.7 8.4	5.9	6.2	
M14		38	45	141	31	20.9	B	a	R						
M15	Utatsu-Namiita, Minamisanriku Town	38	45	141	32	19.4	A	a	R	22		5.4 6.7 7.0	3.5	3.2	
M16		38	45	141	32	18.0	A	a	I						
M17		38	45	141	32	19.5	A	a	R						
M18	Utatsu-Minato, Minamisanriku Town	38	44	141	32	14.5	A	a	R						
M19		38	44	141	32	14.0	A	a	R						
M20		38	44	141	32	14.6	A	a	I						
M21	Utatsu-Tanoura, Minamisanriku Town	38	44	141	33	13.1	B	a	R	16		3.7 8.5 10.7	4.5 5.1	5.0 5.5	
M22	Utatsu-Kaminoyama, Minamisanriku Town	38	44	141	33	14.3	A	a	R						
M23		38	44	141	33	16.4	B	a	R						
M25	Utatsu-Ishihama, Minamisanriku Town	38	44	141	34	15.6	B	a	I			9.3 12.9 13.0	10.5		7.6
M27	Utatsu-Tatehama, Minamisanriku Town	38	43	141	33	12.7	A	a	I			3.9 4.4 4.7 5.3	3.9 5.2	3.3 3.6 3.7 3.8	

Table 1

continued

No.	Location Name	Latitude deg	Latitude min	Longitude deg	Longitude min.	2011 height[a] (m)	rel.[b]	acc.[c]	type	1896 height[d] Iki (feet)	1896 height[d] Yamana	1896 height[d] Matsuo (m)	1933 height[e] ERI (m)	1933 height[e] Matsuo (m)	1933 height[e] Kunitomi (m)
M28	Utatsu-Niranohama, Minamisanriku Town	38	42	141	30	12.9	A	a	I			3.5 3.6 3.7	2.9	1.6 2.4 2.5	
M29	Shizugawa-Nishida, Minamisanriku Town	38	42	141	30	15.1	B	a	R	12		3.8 4.7 4.7	2.5	1.9 1.9 2.2	3.6
M30		38	42	141	30	15.0	B	a	R						
M31	Shizugawa-Hosoura, Minamisanriku Town	38	42	141	30	13.9	B	a	R						
M32		38	42	141	30	14.5	A	a	R						
M33	Shizugawa-Omori, Minamisanriku Town	38	41	141	27	14.4	C	a	R						5.4
M34	Shizugawa-Hayashi, Minamisanriku Town	38	40	141	27	16.0	A	a	I	6			3.2		
M35	Mitobe, Tokura, Minamisanriku Town	38	38	141	27	11.7	B	a	R	Δ8		2.7 2.9	1.9 2.1	2.2 2.2	
M36	Takihama, Tokura, Minamisanriku Town	38	38	141	30	12.1	B	a	I	13		4.7 6.0	2.4	2.5 2.5	2.4
M37	Nagashizu, Tokura, Minamisanriku Town	38	38	141	31	11.3	B	a	R	16		4.9 5.2	4.6	4.0 4.2	2.4
M38	Kozashi, Kitakamicho-Jusanhama, Ishinomaki City	38	36	141	30	14.7	A	a	I	15			4.6		4.8
M39	Aikawa, Kitakamicho-Jusanhama, Ishinomaki City	38	36	141	30	14.9	A	a	R	15			5.5		4.8
M40	Kodomari, Kitakamicho-Jusanhama, Ishinomaki City	38	36	141	30	12.0	A	a	R				5.0	5.6	4.5
M41	Omuro, Kitakamicho-Jusanhama, Ishinomaki City	38	36	141	30	14.3	C	a	I	13			3.5 3.7	5.8 5.8	3.0
M42	Shirahama, Kitakamicho-Jusanhama, Ishinomaki City	38	35	141	28	15.7	A	a	I	9			3.2	4.1	2.1
M50	Ogatsucho-Naburi, Ishinomaki City	38	32	141	30	14.2	B	a	R	11			2.7 3.3	4.0	4.2
M51	Ogatsucho-Funakoshi, Ishinomaki City	38	32	141	31	12.6	B	a	R				3.7 4	4.0	4.5
M52	Ogatsucho-Osu, Ishinomaki City	38	31	141	32	11.4	B	a	R				3.8	4.2	
M53	Ogatsucho-Kuwanohama, Ishinomaki City	38	30	141	32	11.8	A	a	I				2.3	1.9 1.9 1.9	1.5
M54	Ogatsucho-Tachihama, Ishinomaki City	38	30	141	31	11.7	B	a	R				2.0	1.3 1.8 1.9 2.2 2.2	1.8
M55		38	31	141	31	9.6	B	a	R						
M56	Ogatsucho-Myojin, Ishinomaki City	38	31	141	29	12.3	B	a	R	8			2.0	2.2 2.2	1.8
M57	Funatoshinmei, Ogatsucho-Ogatsu, Ishinomaki City	38	31	141	28	15.3	A	a	R	10		2.9 3.0 3.1 3.2 3.6 3.8 4.8	3.5 3.65 3.90 3.98	3.3 3.4 3.4 3.7 3.8 4.2 4.3 4.5 5.7	
M58	Karakuwa, Ogatsucho-Ogatsu, Ishinomaki City	38	31	141	29	10.1	C	a	I	6			2.1	1.9 1.9	1.8
M59	Wakehama, Ogatsucho-Wakehama, Ishinomaki City	38	30	141	29	13.7	B	a	R	7			1.8	1.9 1.9	1.5
M60	Namiita, Ogatsucho-Wakehama, Ishinomaki City	38	29	141	29	14.5	A	a	R	8			2.1	2.5 2.5	1.5
M61	Ishihama, Onagawa Town	38	27	141	28	16.7	A	a	R	8			2.6	2.2 2.6	2.4
M62	Oishiharahama, Onagawa Town	38	24	141	28	13.0	B	a	R					2.2 2.2	2.4
M65	Samenoura, Ishinomaki City	38	23	141	29	17.9	C	a	I	10		2.6	5.0	3.2	4.8
M66	Oyagawahama, Ishinomaki City	38	22	141	29	17.8	B	a	R			2.0		2.8 4.0	5.2
M67	Yagawahama, Ishinomaki City	38	22	141	29	18.7	C	a	I	11		3.0	5.2	4.0	4.8
M68		38	22	141	29	21.2	B	a	R					7.0	

Table 1

continued

No.	Location Name	Latitude		Longitude		2011 height[a]	rel.[b]	acc.[c]	type	1896 height[d]			1933 height[e]		
		deg	min	deg	min.	(m)				Iki (feet)	Yamana	Matsuo (m)	ERI (m)	Matsuo (m)	Kunitomi (m)
M69	Tomarihama, Ishinomaki City	38	22	141	31	12.4	A	a	R	x20			3.7		
M70		38	22	141	31	12.2	A	a	R						
M71	Kugunarihama, Ishinomaki City	38	19	141	30	6.3	A	a	I				2.1		1.8
M72	Koamikurahama, Ishinomaki City	38	21	141	27	12.9	B	a	R	7			3.0	2.9	3.0
M73	Fukkiura, Ishinomaki City	38	21	141	27	8.2	B	a	R				2.7		1.2
M74	Kitsunezakihama, Ishinomaki City	38	21	141	25	8.6	B	a	R	x2–3					
M75	Kozumihama, Ishinomaki City	38	22	141	27	8.5	B	a	I				2.9	3.5	2.7
M76	Momonoura, Ishinomaki City	38	24	141	26	12.5	B	a	R	4			1.2		1.2

R runup height; *I* inundation height; *P* tsunami height in ports

[a] 2011 heights above sea level at time of maximum tsunami

[b] Rel.: reliability, A: most reliable based on clear physical evidence or eyewitness account; B: mostly based on natural traces; C: least reliable based on equivocal evidence

[c] Acc.: accuracy, a: measurement error <0.2 m; b 0.2 ≤ error ≤ 0.5 m; c error >0.5 m

[d] Iki: runup heights taken from Iki (1897). 1 foot = 0.305 m. Δ: visual measurements; *x* eyewitness accounts; Yamana: measured by Yamana (1896) reproduced by Unohana and Ota (1988). 1 shaku = 0.303 m, Matsuo: taken from Matsuo (1933, 1934) measured with 1933 heights based on eyewitness accounts

[e] ERI: taken from Earthquake Research Institute (1934), Matsuo: taken from Matsuo (1933, 1934), Kunitomi: taken from Kunitomi (1933)

2011 inundation tsunami height was 15 m (I72). On the back cliff behind the icehouse, two white markers indicate the heights of the 1896 (15 m; Iki 1897) and 1933 (10 m; Earthquake Research Institute 1934) Sanriku tsunamis (Fig. 17). These show that the 2011 tsunami was larger than the 1933 tsunami, but similar to the 1896 tsunami. According to Yamashita (2003), 1,867 of 2,248 residents in the affected area were killed by the 1896 tsunami (fatality rate 83 %), and 911 among 2,773 residents died during the 1933 tsunami (fatality rate 32 %). The 2011 tsunami killed ~200 of 4,434 (fatality rate ~5 %). The 1960 tsunami heights were 2–3 m as reported by CFI (1961), and 2 m as reported by JMA (1961), and the coastal levee completely protected the residential area from the 1960 and 2010 Chilean tsunamis.

At Akahama in Otsuchi Town, the 2011 tsunami was larger than the other historical tsunamis. Most of the houses were swept away by the 2011 tsunami. The International Coastal Research Center, Atmosphere and Ocean Research Institute of the University of Tokyo was severely damaged up to the third floor, indicating inundation heights of ~12 m (I121, I122). The runup height behind of the building was measured as 13 m (I120). During the 1896 tsunami, a tsunami height of 6 m, reportedly caused two houses to collapse, 16 to be washed away, and 26 fatalities. The 1933 tsunami height was 5 m, while the 1960 tsunami height was 3 m.

At Sanrikucho-Okirai in Ofunato City, the 2011, 1896, and 1933 tsunamis caused similar inundations and runup heights; however, 1960 tsunami height was much smaller. The 2011 tsunami inundated areas up to ~150 m from the coast near Horei Station of the Sanriku Railway. Tsunami inundation would have been larger if the railway track had not been raised to a height of ~15 m. The 2011 runup heights ranged from 15 to 18 m (I130–I132). The 1896 tsunami completely destroyed a coastal levee with a height of 15 shaku (~5 m), inundating areas up to 500 ken (~900 m; 1 ken = 1.818 m) from the coast with a reported tsunami height of 15 m. At the time of the 1933 tsunami, the inundation distance was 300–400 m with reported tsunami heights of 4–12 m. The 1960 tsunami height was 2 m (CFI 1961).

At Sanrikucho-Ryori in Ofunato City, the 2011 tsunami height was lower than the 1896 and 1933 Sanriku tsunami heights, but higher than the 1960 tsunami. The 1896 tsunami height was reported as 130–180 shaku (approximately 39–55 m; Yamana 1896), 72 feet (22 m; Iki 1897), or 38 m (Matsuo 1933) (Fig. 18), and it killed 204 of 240 residents. According to Matsuo (1933), the maximum heights of the 1896 Sanriku tsunami (38 m) and 1933 Sanriku tsunami (29 m) were recorded here. The 2011 runup

Table 2

Tsunami heights for Sanriku coasts of Aomori, Iwate, and Miyagi prefectures and Pacific coasts of Ibaraki and Chiba prefectures from the 1960, 2010, and 2011 earthquakes

No.	Location Name	Latitude		Longitude		2011 height[a]	rel.[b]	acc.[c]	type	1960 height						2010 height	
		deg	min	deg	min	(m)				CFI[d] (m)	CFI Corrected[e] (m)	CFI acc.[f]	JMA[g] (m)	JMA datum	JMA Corrected[e] (m)	Tsuji/Imai[h] (m)	type
A1	Shimomekurakubo, Samemachi, Hachinohe City (Hachinohe Fishing Port, Ebisuhama District)	40	32	141	34	6.1	A	a	I	4.2	4.2	4				0.9	T
A2	Yoboishi, Samemachi, Hachinohe City (Tanesashi Fishing Port)	40	30	141	37	9.3	A	a	I	3.9	3.9	3	4.1	tp	4.1		
A3	Daisakutai, Samemachi, Hachinohe City (Okuki Fishing Port)	40	30	141	38	9.9	A	a	I	3.7 5.6	3.7 5.6	4 4	1.6	tp	1.6		
A4	Oja, Dobutsu, Hashikami Town (Oja Fishing Port)	40	28	141	39	9.3	A	a	R	4.4	4.4	4	2.6	tp	2.6		
A5	Kominato, Dobutsu, Hashikami Town (Kominato Fishing Port)	40	27	141	40	6.0	A	a	R	4.1–5.2	4.1 –5.2	2	3.6	tp	3.6		
I1	Taneichi (Kadonohama), Hirono Town (Kadonohama Fishing Port)	40	27	141	41	7.0	B	a	R	4.9	4.9	2	2.3	tp	2.3		
I2	Taneichi, Hirono Town (Taneichi Fishing Port)	40	24	141	43	6.8	B	a	I	6.2	6.2	2	2.2	tp	2.2		
I3	Taneichi, Hirono Town (Yagi Port)	40	21	141	46	7.8	B	b	I	3.0 3.5	3.0 3.5	4 4	2.4	tp	2.4		
I5	Nakano, Hirono Town (Koge Fishing Port, Koge District)	40	18	141	48	14.8	B	a	R				3.0	tp	3.0		
I7	Samuraihamacho-Mukaicho, Kuji City (Kawatsunai Fishing Port, Kawatsunai District)	40	16	141	49	12.9	B	a	R				1.3	tp	1.3		
I11	Osanaicho (Tamanowaki), Kuji City (Tamanowaki Fishing Port)	40	11	141	48	10.7	A	a	R	4.0	4.0	4	3.6	tp	3.6	1.2 1.2	T I
I12	Ubecho (Kosode), Kuji City (Kosode Fishing Port, Kosode District)	40	10	141	51	12.0	B	a	I				3.8	tp	3.8		
I13	Ubecho (Kosode), Kuji City	40	10	141	51	8.2	A	a	R								
I15	Ubecho (Kuki), Kuji City (Kuki Fishing Port)	40	8	141	51	14.6	A	b	I	4.8 5.0	4.8 5.0	3 3	4.1	tp	4.1		
I16	Noda, Noda Village (Noda Fishing Port)	40	7	141	50	22.8	C	a	R	4.9	4.9	1	5.2	tp	5.2		
I17		40	7	141	50	16.4	B	a	R								
I18		40	7	141	50	18.5	B	a	R								
I19	Noda (Maita), Noda Village	40	6	141	50	32.0	B	b	R	4.9	4.7	4					
I20	Tamagawa, Noda Village (Noda Tamagawa Station)	40	5	141	50	26.6	B	a	R	5.9 5.9	5.7 5.7	4 4	8.1	tp	7.9		
I21	Tamagawa (Shimoakka), Noda Village	40	3	141	51	11.8	B	a	R	2.7 2.7 2.8	2.5 2.5 2.6	4 4 4					
I22	Otanabe, Fudai Village (Otanabe Fishing Port)	40	1	141	54	8.4	A	c	I	2.5	2.3	4	2.4	tp	2.2		
I23		40	1	141	54	8.9	A	a	I	2.6	2.4	3					
I24		40	1	141	54	12.4	C	a	R								
I25		40	1	141	54	10.6	B	a	R								
I34	Raga, Tanohata Village	39	56	141	56	23.9	A	a	I				x 1.0	tp	0.8		
I35		39	56	141	56	22.9	A	a	R								
I36		39	56	141	56	27.8	B	a	R								
I37		39	56	141	56	24.5	B	a	R								
I38	Raga (Hiraiga), Tanohata Village	39	56	141	56	17.5	B	a	R	2.3	2.1	3	x 1.0	tp	0.8		
I39		39	56	141	56	16.5	B	a	R	2.3	2.1	4					
I40	Wano, Tanohata Village	39	56	141	56	19.0	B	a	I	2.8 3.0	2.6 2.8	4 3					
I41	Shimanokoshi, Tanohata Village	39	55	141	56	19.9	B	a	R	2.0	1.8	4	x 1.0	tp	0.8		
I42		39	55	141	56	22.0	A	a	R	2.1	1.9	4					
I43	Omoto, Iwaizumi Town	39	51	141	58	10.3	B	a	R	2.8 4.0	2.6 3.8	4 4	x 1.0	tp	0.8		
I47		39	51	141	58	20.4	B	a	R	4.4	4.2	4					
I51	Moshi, Omoto, Iwaizumi Town	39	50	141	58	22.3	B	a	R	2.8	2.6	4					
I52		39	50	141	58	22.2	B	a	R								
I53	Taro-Shimosettai, Miyako City	39	49	141	59	21.8	B	a	R	2.6	2.4	4	x 1.0	tp	0.8		
I54		39	49	141	59	27.9	B	a	R								
I55		39	49	141	59	22.3	A	a	I								
I60	Taro-Aonotakiminami, Miyako City (Aonotaki Fishing Port)	39	46	141	59	34.7	B	b	R	2.4	2.2	4					
I61	Taro-Otobeno, Miyako City	39	45	141	59	22.9	B	a	R	2.3	2.1	4					
I62		39	45	141	59	16.5	B	a	R								
I63		39	45	141	59	23.3	B	a	R								
I64		39	45	141	59	30.1	B	a	R								
I65		39	45	141	59	34.1	B	a	R								
I66	Taro-Wano, Miyako City	39	45	142	0	30.7	B	a	R	2.5	2.3	4					
I67		39	45	141	59	27.4	B	a	R								
I70	Taro-Nohara, Miyako City	39	44	141	59	14.8	A	c	I	1.8	1.6	4					

Table 2

continued

No.	Location Name	Latitude		Longitude		2011 height[a]	rel.[b]	acc.[c]	type	1960 height						2010 height	
		deg	min	deg	min	(m)				CFI[d] (m)	CFI Corrected[e] (m)	CFI acc.[f]	JMA[g] (m)	JMA datum	JMA Corrected[e] (m)	Tsuji/Imai[h] (m)	type
I71	Taro-Aozari, Miyako City	39	44	141	59	19.0	B	b	R	1.8	1.6	4					
I72		39	44	141	59	14.8	A	c	I	2.6 2.7	2.4 2.5	4 4	2.6	tp	2.4		
I74	Taro-Nishimukaiyama, Miyako City	39	43	141	58	25.5	B	a	R	2.8	2.6	3					
I75	(Kashinai Fishing Port)	39	42	141	59	17.5	B	a	R								
I76	Taro-Kashinai, Miyako City (Kashinai Fishing Port)	39	42	141	58	21.8	B	a	R								
I80	Sakiyama (Onappe), Miyako City	39	42	141	58	15.1	A	a	R	2.1	1.9	4					
I81		39	42	141	58	14.8	B	a	R	3.1	2.9	4					
I82		39	41	141	58	12.6	B	a	I								
I83		39	41	141	58	17.6	B	a	R								
I84		39	41	141	58	20.6	B	a	R								
I85		39	41	141	58	26.0	B	a	R								
I86	Kuwagasaki (Nakamachi), Miyako City	39	39	141	58	8.2	A	a	I	1.8	1.6	4	2.0 2.2	tp	1.8 2.0	0.7	T
I87	Rinkodori, Miyako City	39	38	141	58	11.1	C	a	I	2.1	1.9	4	2.2	tp	2.0		
I88	Tsugaruishi (Norinowaki), Miyako City	39	35	141	57	11.6	B	a	R	6.3	6.1	4	4.3	tp	4.1	2.0 2.1	I I
I89	Akamae, Miyako City	39	36	141	58	9.5	B	a	R	4.6	4.4	4	5.2	tp	5.0		
I90		39	36	141	58	14.0	B	a	R	5.2	5.0	2					
I91	Omoe (Tatehama), Miyako City	39	38	142	1	22.5	B	a	R				1.7	tp	1.5		
I92		39	38	142	1	25.2	B	a	R								
I93		39	38	142	1	26.1	B	a	R								
I94	Omoe (Shukuhama), Miyako City	39	38	142	1	25.1	B	a	R	2.1	1.9	3					
I95		39	38	142	1	24.6	B	a	R								
I96	Omoe (Uiso), Miyako City	39	37	142	1	27.0	B	a	R	2.5	2.3	3	2.2	tp	2.0		
I97		39	37	142	1	25.4	A	a	I								
I98		39	37	142	1	23.2	B	a	R								
I99		39	37	142	1	24.5	A	a	I								
I100	Omoe (Aramaki), Miyako City	39	36	142	1	21.1	B	a	R	2.6	2.4	4	0.6	tp	0.4		
I101		39	36	142	1	27.7	B	a	R								
I102		39	36	142	1	23.5	B	a	R								
I103	Omoe (Sato), Miyako City (Omoe Fishing Port)	39	34	142	2	20.1	B	a	R	2.5	2.3	3	1.6	tp	1.4		
I104		39	34	142	2	34.1	C	a	R	2.8	2.6	4					
I105	Omoe (Aneyoshi), Miyako City	39	32	142	3	26.5	B	a	R	3.0	2.8	4	1.5	tp	1.3		
I106		39	32	142	3	22.8	B	a	R	3.1	2.9	4					
I107		39	32	142	3	24.5	B	c	R								
I108	Omoe (Chikei), Miyako City	39	32	142	2	29.5	A	a	R	3.1	2.9	4	3.0	tp	2.8		
I109		39	32	142	2	31.2	A	a	R								
I110		39	32	142	2	29.4	A	a	R								
I111	Omoe (Ishihama), Miyako City	39	31	142	2	20.0	A	a	I	2.6 3.8	2.4 3.6	4 4	2.7	tp	2.5		
I112	Funakoshi (Ohura), Yamada Town	39	27	142	0	8.0	B	a	R	3.0	2.8	4					
I113		39	27	142	0	7.7	A	a	I								
I114		39	27	142	0	8.0	B	a	R								
I115		39	27	142	0	7.8	B	a	R								
I118	Funakoshi (Koyadori), Yamada Town	39	26	142	1	26.1	A	a	R	2.3	2.1	4					
I119		39	26	142	1	25.0	B	a	R								
I120	Akahama, Otsuchi Town	39	21	141	56	13.3	B	a	R	3.4	3.2	4	3.6	tp	3.4		
I121	Akahama, Otsuchi Town	39	21	141	56	11.5	A	a	I								
I122	(International Coastal Research Center, Atmosphere and Ocean Research Institute, the University of Tokyo)	39	21	141	56	12.1	A	a	I								
I123	Omachi, Kamaishi City	39	16	141	53	5.4	A	b	I	2.8 2.9 2.9	2.6 2.7 2.7	4 4 4	3.5	tp	3.3	0.5	T
I124	Osone, Tonicho, Kamaishi City	39	13	141	53	20.3	A	a	R	2.2	2.0	4	2.2	tp	2.0		
I125		39	13	141	53	16.7	C	a	I								
I126		39	13	141	53	16.8	B	a	R								
I127	Sakuratoge, Tonicho, Kamaishi City	39	12	141	53	13.7	B	a	R								
I128		39	12	141	53	12.7	B	a	R								
I129	Arakawa, Tonicho, Kamaishi City	39	12	141	52	16.5	B	a	R							1.2	I
I130	Horei, Sanrikucho-Okirai, Ofunato City	39	6	141	48	17.8	B	a	R	2.6	2.4	4					
I131		39	6	141	48	14.8	B	a	R								
I132		39	6	141	48	15.2	B	a	R								
I133	Shirahama, Sanrikucho-Ryori, Ofunato City	39	4	141	49	16.8	B	a	R	2.9 4.0	2.7 3.8	3 4	4.3 4.7	tp tp	4.1 4.5		
I134	Okubo, Sanrikucho-Ryori, Ofunato City	39	3	141	49	21.2	B	a	R								
I135	Miyanomae, Ofunatocho, Ofunato City	39	2	141	43	7.6	A	a	I	2.6 4.2	2.4 4.0	4 4	5.13	tp	5.0	0.4	T
I136	Yonesakicho, Rikuzentakata City	39	1	141	40	18.1	B	b	R	5.0	4.8	4	6.36	tp	6.2		
M1	Karakuwacho-Baba, Kesennuma City	38	54	141	39	13.1	A	a	R	2.0	2.2	2					
M3	Karakuwacho-Kakehama, Kesennuma City	38	53	141	40	15.6	A	a	I	3.8	4.0	2					
M4	Karakuwacho-Tsumoto, Kesennuma City	38	52	141	40	10.1	A	a	I	1.0	1.2	3	2.0	tp	2.2		
M5	Minamimachikaigan, Kesennuma City (Kesennuma Port)	38	54	141	34	4.0	A	a	I	2.7	2.9	4	2.9	tp	3.1	0.7	R
M6		38	54	141	34	3.7	A	a	I							0.9	R
M7		38	54	141	34	4.1	A	a	I							1.0	I
M8		38	54	141	35	4.1	A	a	I							1.2 1.2	I I
M9	Hajikamisuginoshita, Kesennuma City	38	50	141	35	13.7	A	b	I	3.6	3.8	4				0.3 0.7	I R

Table 2

continued

No.	Location Name	Latitude		Longitude		2011 height[a]	rel.[b]	acc.[c]	type	1960 height						2010 height	
		deg	min	deg	min	(m)				CFI[d] (m)	CFI Corrected[e] (m)	CFI acc.[f]	JMA[g] (m)	JMA datum	JMA Corrected[e] (m)	Tsuji/Imai[h] (m)	type
M10	Motoyoshicho-Amagasawa, Kesennuma City (Hikado Fishing Port)	38	48	141	33	16.6	A	a	R	2.5 3.4	2.7 3.6	4 4	3.2	tp	3.4		
M11	Motoyoshicho-Maehama, Kesennuma City	38	48	141	33	19.3	B	a	I	3.9	4.1	4				1.2	I
M12	Motoyoshicho-Toyomazawa, Kesennuma City	38	47	141	31	19.7	A	a	I	3.9	4.1	4					
M13	Motoyoshicho-Nijuichihama, Kesennuma City	38	46	141	31	17.4	A	a	I	3.1	3.3	4					
M14		38	45	141	31	20.9	B	a	R								
M15	Utatsu-Namiita, Minamisanriku Town	38	45	141	32	19.4	A	a	R	2.6	2.8	4				0.5	I
M16		38	45	141	32	18.0	A	a	I								
M17		38	45	141	32	19.5	A	a	R								
M18	Utatsu-Minato, Minamisanriku Town	38	44	141	32	14.5	A	a	R								
M19		38	44	141	32	14.0	A	a	R								
M20		38	44	141	32	14.6	A	a	I								
M21	Utatsu-Tanoura, Minamisanriku Town	38	44	141	33	13.1	B	a	R	3.0	3.2	4				0.7	I
M22	Utatsu-Kaminoyama, Minamisanriku Town	38	44	141	33	14.3	A	a	R								
M23		38	44	141	33	16.4	B	a	R								
M28	Utatsu-Niranohama, Minamisanriku Town	38	42	141	30	12.9	A	a	I	2.8 3.1	3.0 3.3	4 4					
M29	Shizugawa-Nishida, Minamisanriku Town	38	42	141	30	15.1	B	a	R	3.2 3.4	3.4 3.6	4 4					
M30		38	42	141	30	15.0	B	a	R								
M31	Shizugawa-Hosoura, Minamisanriku Town	38	42	141	30	13.9	B	a	R								
M32		38	42	141	30	14.5	A	a	R								
M33	Shizugawa-Omori, Minamisanriku Town	38	41	141	27	14.4	C	a	R	4.0 4.8	4.2 5.0	4 4	x 4.4	tp	4.6		
M34	Shizugawa-Hayashi, Minamisanriku Town	38	40	141	27	16.0	A	a	I	4.6	4.8	4					
M35	Mitobe, Tokura, Minamisanriku Town	38	38	141	27	11.7	B	a	R	4.2	4.4	4				1.1 1.4	I I
M36	Takihama, Tokura, Minamisanriku Town	38	38	141	30	12.1	B	a	I	3.2	3.4	4					
M37	Nagashizu, Tokura, Minamisanriku Town	38	38	141	31	11.3	B	a	R	3.6	3.8	4				0.8	I
M38	Kozashi, Kitakamicho-Jusanhama, Ishinomaki City	38	36	141	30	14.7	A	a	I	2.8 2.8	3.0 3.0	4 4					
M39	Aikawa, Kitakamicho-Jusanhama, Ishinomaki City	38	36	141	30	14.9	A	a	R	3.8	4.0	4				0.7	I
M40	Kodomari, Kitakamicho-Jusanhama, Ishinomaki City	38	36	141	30	12.0	A	a	R	3.3	3.5	4					
M41	Omuro, Kitakamicho-Jusanhama, Ishinomaki City	38	36	141	30	14.3	C	a	I	3.2 4.0	3.4 4.2	4 4	3.2	tp	3.4		
M42	Shirahama, Kitakamicho-Jusanhama, Ishinomaki City	38	35	141	28	15.7	A	a	I	2.9	3.1	4					
M50	Ogatsucho-Naburi, Ishinomaki City	38	32	141	30	14.2	B	a	R	2.6 2.8	2.8 3.0	4 4	3.0	tp	3.2		
M51	Ogatsucho-Funakoshi, Ishinomaki City	38	32	141	31	12.6	B	a	R	3.4	3.6	4				0.7	P
M53	Ogatsucho-Kuwanohama, Ishinomaki City	38	30	141	32	11.8	A	a	I	3.2	3.4	4					
M54	Ogatsucho-Tachihama, Ishinomaki City	38	30	141	31	11.7	B	a	R	2.7	2.9	4					
M55		38	31	141	31	9.6	B	a	R								
M56	Ogatsucho-Myojin, Ishinomaki City	38	31	141	29	12.3	B	a	R	3.3 3.7	3.5 3.9	4 4	3.6	tp	3.8		
M57	Funatoshinmei, Ogatsucho-Ogatsu, Ishinomaki City	38	31	141	28	15.3	A	a	R	4.3	4.5	4	4.0	tp	4.2		
M58	Karakuwa, Ogatsucho-Ogatsu, Ishinomaki City	38	31	141	29	10.1	C	a	I	3.1	3.3	4					
M59	Wakehama, Ogatsucho-Wakehama, Ishinomaki City	38	30	141	29	13.7	B	a	R	3.0	3.2	4					
M60	Namiita, Ogatsucho-Wakehama, Ishinomaki City	38	29	141	29	14.5	A	a	R	3.4	3.6	4					
M61	Ishihama, Onagawa Town	38	27	141	28	16.7	A	a	R	4.0	4.2	4				0.3 0.4 0.9 1.3 1.3 1.5	I I I I I R
M62	Oishiharahama, Onagawa Town	38	24	141	28	13.0	B	a	R	4.4	4.6	4	2.9	tp	3.1	1.4 1.4 1.5	I I I
M65	Samenoura, Ishinomaki City	38	23	141	29	17.9	C	a	I	4.5	4.7	4					

Table 2

continued

No.	Location Name	Latitude		Longitude		2011 height[a]	rel.[b]	acc.[c]	type	1960 height						2010 height	
		deg	min	deg	min	(m)				CFI[d] (m)	CFI Corrected[e] (m)	CFI acc.[f]	JMA[g] (m)	JMA datum	JMA Corrected[e] (m)	Tsuji/Imai[h] (m)	type
M66	Oyagawahama, Ishinomaki City	38	22	141	29	17.8	B	a	R	5.0	5.2	2	5.4	tp	5.6		
M67	Yagawahama, Ishinomaki City	38	22	141	29	18.7	C	a	I	4.0	4.2	4					
M68		38	22	141	29	21.2	B	a	R	4.6 4.7	4.8 4.9	4 4					
M69	Tomarihama, Ishinomaki City	38	22	141	31	12.4	A	a	R	3.2	3.4	4				0.8	T
M70		38	22	141	31	12.2	A	a	R								
M71	Kugunarihama, Ishinomaki City	38	19	141	30	6.3	A	a	I	3.6 3.8	3.8 4.0	4 2					
M72	Koamikurahama, Ishinomaki City	38	21	141	27	12.9	B	a	R	3.2 3.8	3.4 4.0	4 4					
M73	Fukkiura, Ishinomaki City	38	21	141	27	8.2	B	a	R	3.4	3.6	4					
M75	Kozumihama, Ishinomaki City	38	22	141	27	8.5	B	a	I	5.0	5.2	4	4.4 x 5.0	tp tp	4.6 5.2		
M76	Momonoura, Ishinomaki City	38	24	141	26	12.5	B	a	R	4.1 4.7	4.3 4.9	4	5.0 x 5.2	tp tp	5.2 5.4		
B1	Hirakatacho, Kitaibaraki City	36	51	140	48	6.6	A	a	I				5	da	2.5		
B2		36	51	140	48	7.1	A	a	I								
B3		36	51	140	48	7.2	A	a	I								
B4		36	51	140	48	8.1	B	b	R								
B5		36	51	140	48	7.9	B	b	R								
B6	Otsucho, Kitaibaraki City (Otsu Fishing Port)	36	50	140	47	4.9	A	a	I	1.5	1.4	3	5.7	da	2.9	1.0	I
B19	Osecho, Hitachi City (Ose Fishing Port)	36	35	140	39	5.1	A	a	I				3	msl	3.0	0.8 1.3 1.5 1.5 1.5 1.5 1.6 1.8 1.8	P R R R R R R R R
B24	Kujicho, Hitachi City (Kuji Fishing Port)	36	30	140	38	4.1	B	b	R	2.3	2.2	3	3	un			
B27	Isozakicho, Hitachinaka City (Isozaki Fishing Port)	36	23	140	37	3.5	A	a	I				3	da	1.5		
B28	Hiraisocho, Hitachinaka City (Hiraiso Fishing Port)	36	21	140	37	4.2	A	a	I				2.5	da	1.3		
B29	Kaimoncho, Hitachinaka City (Nakaminato Fishing Port)	36	20	140	36	3.2	A	a	I	1.25 2.1	1.41 2.2	1 5	2	da	1.0		
B30	Minatochuo, Oarai Town (Ibaraki Port, Oarai Port District)	36	19	140	34	4.5	A	a	I							1.2 1.2	P P
B31		36	19	140	34	4.6	A	a	I								
B32	Takeigama, Kashima City	36	4	140	37	3.5	A	b	I				2	un		1.5	R
B33		36	4	140	37	3.7	A	b	R								
B34	Hamatsuga, Kashima City	36	4	140	37	3.8	B	b	I								
B35	Higashifukashiba, Kamisu City (Kashima Port)	35	55	140	40	5.7	B	a	R							0.8 1.6	T I
B36	Hasakishinko, Kamisu City (Shin Fishing Port)	35	45	140	51	3.3	A	a	I							0.4 0.5	P P
C1	Araoicho, Choshi City (Choshi Fishing Port)	35	44	140	50	2.7	A	a	I	0.6 0.95	0.7 1.05	5 5				0.5 0.5 0.6	P P T
C2	Inuwaka, Choshi City (Inuwaka Fishing Port)	35	42	140	51	4.8	A	a	I	2.09	2.19	5	2.14	msl (Togawa)	2.2	1.0 1.2	I I
C3	Shimonagai, Asahi City (Iioka Fishing Port)	35	42	140	44	3.2	A	a	I				3.5	tp	3.5	0.9 1.5	R R
C4	Hiramatsu, Asahi City	35	42	140	43	6.3	A	a	I	3.7	3.8	2					
C5	Ashikawa, Asahi City	35	42	140	40	5.1	A	a	I							0.3	P
C6		35	42	140	40	7.9	B	a	R								
C15	Koseki, Kujukuri Town (Katakai Fishing Port)	35	32	140	27	2.5	A	a	I	1.4	1.5	3				0.6 0.7 0.7 0.7 0.7	R R R R I
C18	Sendokyu, Ichinomiya Town	35	23	140	23	2.9	A	c	I	1.0	1.1	3	2	nt	2.0		
C22	Ohara, Isumi City (Ohara Fishing Port)	35	15	140	24	2.6	B	a	I	1.8 1.8	1.6 1.6	1 1	2-3	un		0.8	I
C26	Hama, Onjuku Town (Onjuku Fishing Port)	35	11	140	21	2.3	A	a	I	1.7	1.5	3				0.5 0.7 1.1	R P R
C27	Hamakatsuura, Katsuura City (Katsuura Fishing Port)	35	9	140	19	2.0	B	a	R	1.9 2.2	1.7 2.0	3 2	2.0-2.5	msl	1.8-2.3	0.6 0.8	P P

Table 2

continued

No.	Location Name	Latitude		Longitude		2011 height[a] (m)	rel.[b]	acc.[c]	type	1960 height						2010 height	
		deg	min	deg	min					CFI[d] (m)	CFI Corrected[e] (m)	CFI acc.[f]	JMA[g] (m)	JMA datum	JMA Corrected[e] (m)	Tsuji/Imai[h] (m)	type
C29	Kominato, Kamogawa City (Kominato Fishing Port)	35	7	140	12	1.7	B	a	P	1.5	1.3	3					
C30	Amatsu, Kamogawa City (Amatsu Fishing Port)	35	7	140	10	1.8	B	a	R	1.3	1.1	2					
C31		35	7	140	10	1.5	B	a	R								
C34	Wadacho-Wada, Minamiboso City (Wada Fishing Port)	35	2	140	1	1.9	A	a	I	1.0	0.8	2	0.7	ht	0.9		
C37	Chikuracho-Hedate, Minamiboso City (Chikura Fishing Port)	34	57	139	58	1.4	B	a	I	1.3 1.2	1.0 1.1	3 3	0.9	ht	1.1		
C38		34	57	139	58	0.9	B	a	P								
C39	Shirahamacho-Otohama, Minamiboso City (Otohama Fishing Port)	34	55	139	56	1.2	B	a	R	1.3	1.1	3					
C40	Shirahamacho-Shirahama, Minamiboso City (Nojimahigashi Fishing Port)	34	54	139	53	1.0	B	a	R	1.0	0.8	3[i]	2.0	da	1.0		
C43	Mera, Tateyama City (Tomisaki Fishing Port)	34	55	139	50	2.0	A	a	I	1.32	1.11	5	1.73	nt	1.7	0.7 0.8	P T

R runup height, *I* inundation height, *P* tsunami height in ports, *T* tide gauge, *da* double amplitude, *msl* tsunami heights above mean sea level, *dl* datum line, *tp* tsunami heights above TP, *nt* tsunami heights above sea level at time of maximum tsunami, *ht* tsunami heights above high tide level of the tsunami arrival date, *un* unknown, *x* eyewitness accounts

[a] 2011 heights above sea level at time of maximum tsunami

[b] Rel.: reliability, A: most reliable based on clear physical evidence or eyewitness account; B: mostly based on natural traces; C: least reliable based on equivocal evidence

[c] Acc.: accuracy; a: measurement error <0.2 m; b 0.2 ≤ error ≤ 0.5 m; c error >0.5 m

[d] Tsunami heights above Tokyo Peil (TP) taken from the Committee of Field Investigation of the Chilean Tsunami of 1960 (CFI 1961). The numbers in parentheses indicate questionable data

[e] Tsunami heights above sea level at time of maximum tsunami

[f] 5: Values observed by tide gauges; 4: values with highest accuracy; 3: values with moderate accuracy; 2: values with fair accuracy; 1: values obtained by other sources

[g] Tsunami heights from JMA (1961)

[h] Tsunami heights above sea level at the time of maximum tsunami taken from Tsuji *et al*. (2010) or Imai *et al*. (2010)

[i] Nojimanishi

heights were measured as 17 and 21 m (I133–I134). The 1960 tsunami heights were 3 and 4 m by CFI (1961), and 4 and 5 m by the JMA (1961), respectively.

5.2. Northern and Southern Sanriku Coasts

Along the northern Sanriku coast (north of latitude 40.2°N), the 2011 tsunami heights drastically decrease toward the north from 20 to 5 m. The two preceding Sanriku tsunami heights also become smaller toward the north (Fig. 14). The 1896 heights are similar to the 2011 heights (median ratio is 1.01; Table 3), while the 1933 heights are smaller (median ratio 0.66). The 1960 and 2010 Chilean tsunami heights are more uniform throughout the Sanriku coast, and are smaller than the three Sanriku tsunamis (median ratio of 1960/2011 heights is 0.42, while one 2010 height is 0.15 of the 2011 height).

Along the southern Sanriku coast (south of latitudes 39.0°N), the 2011 tsunami heights range mostly from 10 to 20 m, and larger than all the previous tsunamis (median ratio is 0.29, 0.24, 0.28, 0.06 for 1896, 1933, 1960, and 2010 tsunami, respectively). The 1960 and 2010 tsunami heights are more uniformly distributed. The 1896 and 1933 tsunami heights drastically decrease toward the south

Table 3

Median ratios and correlation coefficients of the previous tsunami heights and the 2011 tsunami heights

Coast	1896/2011			1933/2011			1960/2011			2010/2011		
	Ratio (median)	Correlation	Number[a]	Ratio (median)	Correlation	Number[a]	Ratio (median)	Correlation	Number[a]	Ratio (median)	Correlation	Number[a]
N. Sanriku	1.01	0.63	11	0.66	0.65	13	0.42	−0.38	17	0.15	–	1
C. Sanriku	0.85	0.24	66	0.47	0.36	81	0.16	0.21	71	0.09	0.60	6
S. Sanriku	0.29	0.22	46	0.24	0.39	105	0.28	0.33	58	0.06	−0.12	12
All Sanriku	0.69	0.34	123	0.33	0.47	199	0.25	0.17	146	0.07	0.14	19
Ibaraki–Chiba	–	–	–	–	–	–	0.62	0.63	37	0.28	0.41	15

[a] Number of comparison; if multiple measurements are reported at one location, the median height is used for each report

and become smaller than the 1960 Chilean tsunami heights at the southernmost Sanriku coast.

At Utatsu-Tanoura in Minamisanriku Town, the 2011 tsunami was evidently much higher than the other historical tsunamis. Almost all the houses in low-lying areas were washed away, and large amounts of rubble, fishing boats, and equipment were transported by the tsunami. The 2011 runup heights were between 13 and 16 m (M21–M23), while the 1896 tsunami heights were 16 feet (5 m; Iki 1897) or 4–11 m (Matsuo 1933). The 1933 tsunami heights were 5–6 m (Matsuo 1933; Earthquake Research Institute 1934). The 1960 tsunami height was 3 m by CFI (1961) and the 2010 height was 1 m by Tsuji *et al.* (2010), respectively.

At Ogatsucho-Wakehama in Ishinomaki City, the 2011 tsunami height was the largest, followed by the 1960 Chilean tsunami height, which was larger than the 1896 and 1933 Sanriku tsunamis. The 2011 tsunami inundated areas up to a temple ~250 m from the coast, and almost all houses were swept away. The 2011 runup height was 14 m (M59), while the reported 1896 and 1933 tsunami heights were ~2 m and the 1960 tsunami height was reported as 3 m by CFI (1961).

5.3. Correlation of Tsunami Heights

The tsunami heights from the 1896 and 1933 Sanriku tsunamis and the 1960 and 2010 Chilean tsunamis were compared with the 2011 tsunami heights at the same locations (Fig. 19; Table 3). Along the Sanriku coasts, the 2011 tsunami heights are positively correlated with those from the 1896 and 1933 Sanriku tsunamis. The correlation coefficient of the 2011 and 1896 tsunamis is 0.34, and that for the 2011 and 1933 tsunamis is 0.47 for the entire Sanriku coasts. The correlation coefficients are much larger on the northern Sanriku coast (0.63 and 0.65 for 2011–1896 and 2011–1933, respectively), but smaller on the central coast (0.24 and 0.36) and southern coast (0.22 and 0.39). The positive correlation coefficients indicate that the tsunami height variation is similar for local tsunamis. On the other hand, the 2011 tsunami heights are weakly correlated with those from the Chilean tsunami heights; the correlation coefficients are 0.17 for the 2011 and

Figure 15
Tsunami stone transported by the 1896 Sanriku tsunami at Raga, Tanohata Village, Iwate Prefecture. The 2011 tsunami inundation limit (24.5 m; I37) is just below this stone

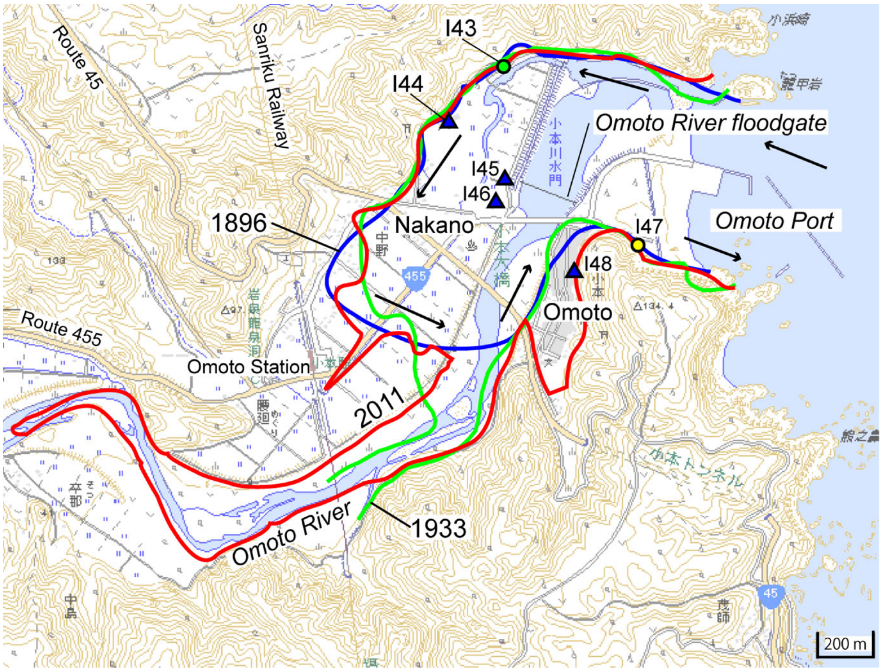

Figure 16
Inundation areas from the 1896, 1933, and 2011 tsunamis at Omoto, Iwaizumi Town, Iwate prefecture. The *blue curve* indicates the area severely damaged by the 1896 tsunami from Iki (1897). The *black arrows* show the direction of the 1896 tsunami reported by the Fudai Village chief in those days. The *green curves* show the inundation limits of the 1933 tsunami from the Earthquake Research Institute (1934). The *red curve* indicates the inundation limit of the 2011 tsunami by Haraguchi and Iwamatsu (2011). The *circles* and *triangles* indicate the measurement points of runup and inundation heights, respectively, with the same *color* code as Fig. 3

1960 tsunamis and 0.14 for the 2011 and 2010 tsunamis for the entire Sanriku coastline. They are negatively correlated on the northern Sanriku coast for the 1960 tsunami and on the southern coast for the 2010 tsunami. These indicate that tsunami height distribution of local tsunamis is different from that of trans-Pacific tsunamis.

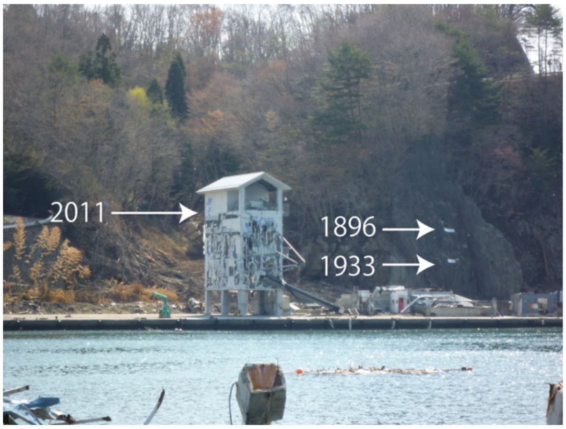

Figure 17
Icehouse of the Japan Fisheries Cooperatives at Taro Fishing Port, which was severely damaged by the 2011 tsunami (14.8 m; I72). The two *white* markers on the back cliff show the heights of the 1896 (14.6 m; Iki 1897) and 1933 (10 m; Earthquake Research Institute 1934) Sanriku tsunamis. The tsunami height of 10 m for the 1933 tsunami was measured at a slightly different location; the tsunami heights at this location measured by Earthquake Research Institute (1934) and Matsuo (1933) were 7.0 and 6.4 m, respectively

Figure 18
Maximum tsunami height of 38.2 m from the 1896 Sanriku tsunami shown on a pole near the border of Okubo and Shirahama, Sanrikucho-Ryori, Ofunato City, Iwate Prefecture (labeled Ryori in Fig. 14). The 2011 tsunami with heights of 16.8 m (I133) and 21.2 m (I134) did not reach this location

5.4. *Controlling Factors of Tsunami Heights and their Variations*

The type, location, and magnitude of the 1896, 1933, and 2011 earthquakes are all different. The 1896 Sanriku earthquake (M_s 7.2) was an example of a "tsunami earthquake" (Kanamori 1972) that produces weak ground shaking, but a very large tsunami. The 1896 tsunami source was estimated to be near the trench axis with a 210 km fault length and ~50 km fault width (Fig. 1; Tanioka and Satake 1996; Tanioka and Seno 2001). The seafloor deformation, landward subsidence, and seaward uplift were limited near the trench axis (Fig. 20). The 1933 Sanriku earthquake (M_s 8.5) was an outer-rise earthquake with a normal faulting mechanism (Kanamori 1971). The seafloor deformation was dominantly subsidence (Aida 1977). The 2011 Tohoku earthquake was the largest (M_w 9.0). The seafloor deformation extended much further than the above-mentioned Sanriku earthquakes. The largest slip occurred at around 38.3°N, 143.3°E, to the east of the epicenter, but the maximum tsunami heights were recorded on the central Sanriku coast ~100 km north of the largest slip. The 2011 Tohoku earthquake can be considered a combination of a great interplate earthquake and a "tsunami earthquake" (Fig. 1; Fujii *et al*. 2011; Satake *et al.* 2013), while Okal (2013) argued that there is no evidence of 'slowness' in the earthquake source, and Grilli *et al*. (2013) suggested additional tsunami generation mechanisms not represented in the coseismic sources (e.g., splay faults, sub-marine mass failure).

The tsunami heights from the three Sanriku tsunamis exhibit a large variation on the central Sanriku coast (between 39.0° and 40.2°N) regardless of the type, location, and magnitude of the earthquakes. The tsunami heights from the 1896 and 2011 earthquakes ranging 5–40 m are approximately similar on the central Sanriku coast, whereas the seismologically determined earthquake magnitudes of M_s 7.2 for the 1896 were much smaller than the 2011 earthquake (M_w 9.0). While the source region of the 2011 earthquake includes the rupture area of the 1896 earthquake, the 1896 tsunami heights are higher than the 2011 tsunami heights at some locations. These facts demonstrate that the coastal tsunami heights on the central Sanriku coast are not necessarily controlled by the location, type, or the magnitude of earthquake, and that the huge tsunami was not a surprise.

The Sanriku coast consists of numerous bays of various sizes and depths; it is called a ria coast, as it

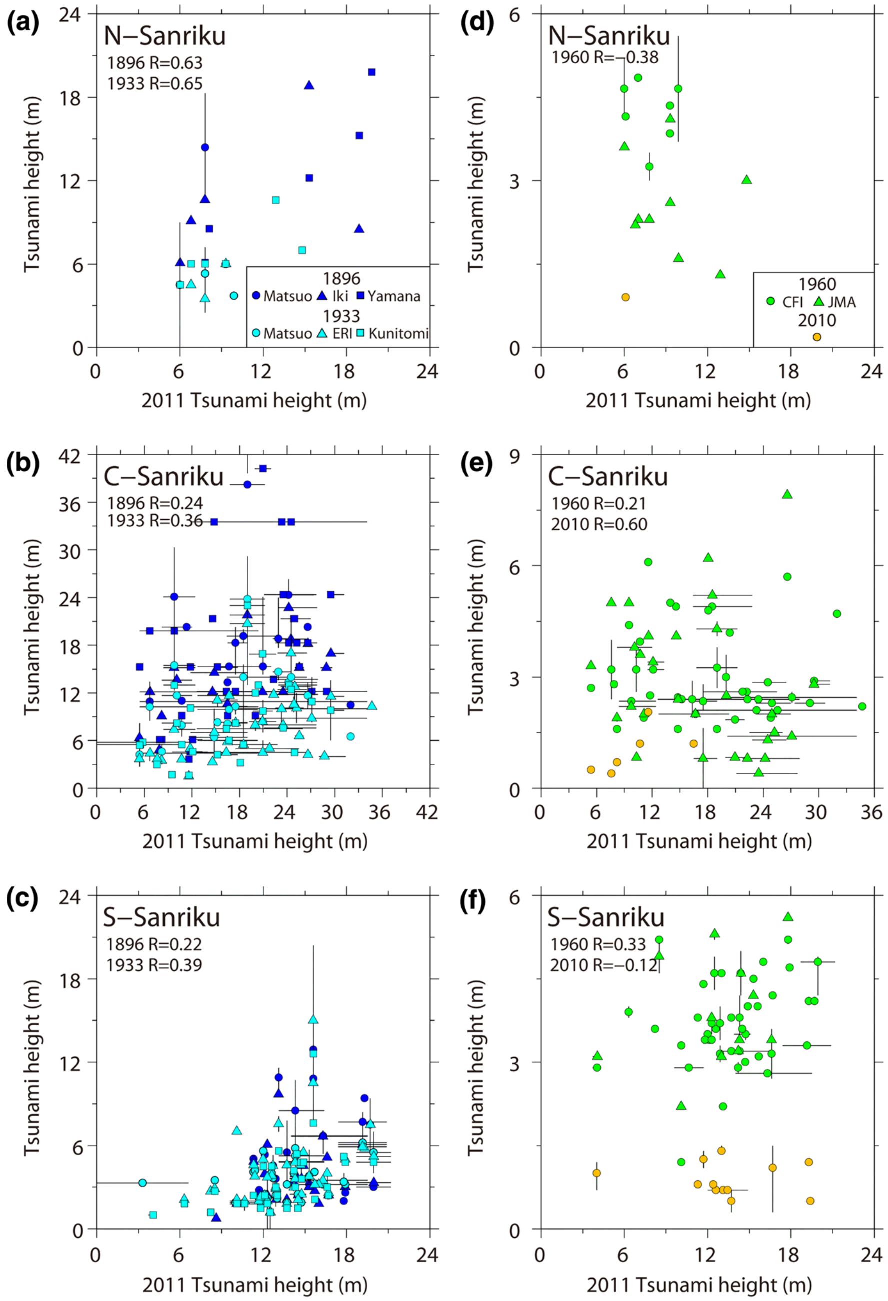

Figure 19

Comparison between the 2011 tsunami and the 1896 and 1933 Sanriku tsunamis for the northern (**a**), central (**b**), and southern Sanriku coasts (**c**). The similar comparison between the 2011 tsunami and the 1960 and 2010 Chilean tsunamis are shown in **d**–**f**. *Orange circles* indicate the 2010 tsunami heights from Tsuji *et al*. (2010). Other *symbols* are the same as in Fig. 14. Multiple height data at the same locations are represented as median values with ranges (shown as *bars*). The correlation coefficients of the previous tsunami heights and the 2011 tsunami heights are also shown

was created by the submergence and subsequent flooding of mountainous terrain (e.g., Otuka 1934; Koike *et al*. 2005). The characteristic periods of sea level oscillations in bays are also variable; 55.2 min for Miyako Bay, the largest bay on the Sanriku coast, while 27.0 min for Otsuchi (Honda *et al*. 1908).

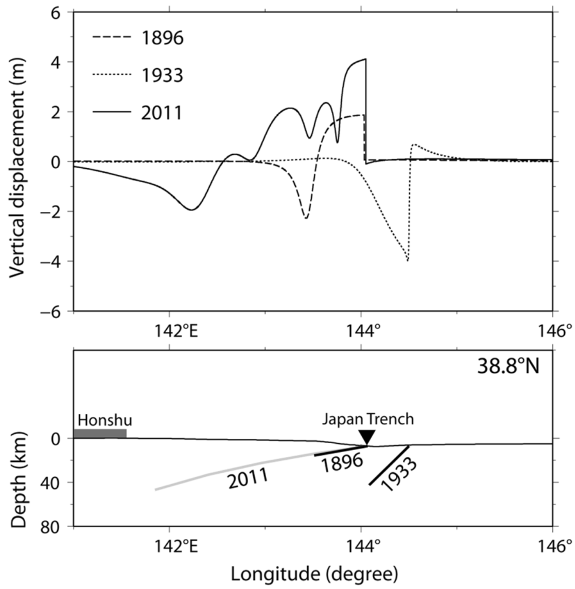

Figure 20
Seafloor deformation along the latitude of 38.8°N caused by the 1896 Sanriku (*dashed curve*), 1933 Sanriku (*dotted curve*), and 2011 Tohoku (*solid curve*) earthquakes. Cross sections of fault models for the 1896 Sanriku (Tanioka and Seno 2001), 1933 Sanriku (Aida 1977), and 2011 Tohoku (Satake *et al.* 2013) earthquakes are shown below. Locations of trench axis and land area are also shown

The period of an incoming tsunami wave is also a controlling factor. The dominant period for the 2011 event was estimated to be ~45 min at DART 21418 and 33–66 min at DART 21413 (Borrero and Greer 2013), while Heidarzadeh and Satake (2013) estimated the two dominant periods of 37 and 67.4 min from multiple DART records. The dominant periods of the preceding two Sanriku tsunamis are expected to be shorter because their source dimensions were much smaller than that of the 2011 event (i.e., 210 km × 50 km for the 1896 tsunami; Tanioka and Satake 1996, and 185 km × 50 km for the 1933 Sanriku tsunami; Aida 1977). However, the dominant period of the 2010 Chilean tsunami was much longer (~110 min) at DART 21413 (Borrero and Greer 2013). The dominant period becomes longer after a tsunami propagates the Pacific Ocean because of the dispersion effect (Watada *et al.* 2013).

For local tsunamis, the large variation of tsunami heights along the Sanriku coast are probably caused by matching the periods of incoming waves and the characteristic periods of some bays. On the other hand, tsunami heights are less sensitive to the coastal topography and show a more uniform distribution for trans-Pacific Chilean tsunamis, resulting from longer periods than the characteristic periods of bays along the Sanriku coast.

On the northern (north of 40.2°N) and southern (south of 39.0°N) Sanriku coasts, the local variations in tsunami height are much smaller. The tsunami heights from the three earthquakes were similar on the northern Sanriku coast, while the 2011 heights were much larger than those of the 1896 or 1933 Sanriku tsunamis on the southern Sanriku coast. The distance from the tsunami source and the earthquake magnitude control the tsunami heights on these coasts. The distances to the northern Sanriku coasts from the three sources were similar, while the 2011 tsunami source is much closer to the southern Sanriku coast (Fig. 1).

Suppasri *et al.* (2013) performed regression analyses between the earthquake magnitude and the maximum tsunami heights based on the historical tsunami trace database and the field survey of the 2011 Tohoku earthquake in each tsunami-affected location. They claimed that the earthquake magnitude is a major controlling factor in determining the maximum tsunami heights. However, the examples of the 1896 and 2011 tsunami heights are clear counterevidence for magnitude dependence. Choi *et al.* (2012) approximated the distribution of tsunami heights along the coast by simple log-normal distributions, suggesting that the tsunami heights are controlled only by the distance from the source. However, the distribution of tsunami heights along the Sanriku coast clearly demonstrates a significant contribution by other factors such as irregular coastal topography.

6. *Comparison of Tsunami Heights on Ibaraki and Chiba Coasts*

For the Pacific coasts of Ibaraki and Chiba prefectures (between 34.9° and 36.9°N), Tsuji *et al.* (2011) measured 79 tsunami heights at 35 locations. Of these, tsunami heights from the 1960 and 2010 Chile earthquakes were also reported at 24 and 15 locations, respectively (Fig. 21; Table 2). The 1960

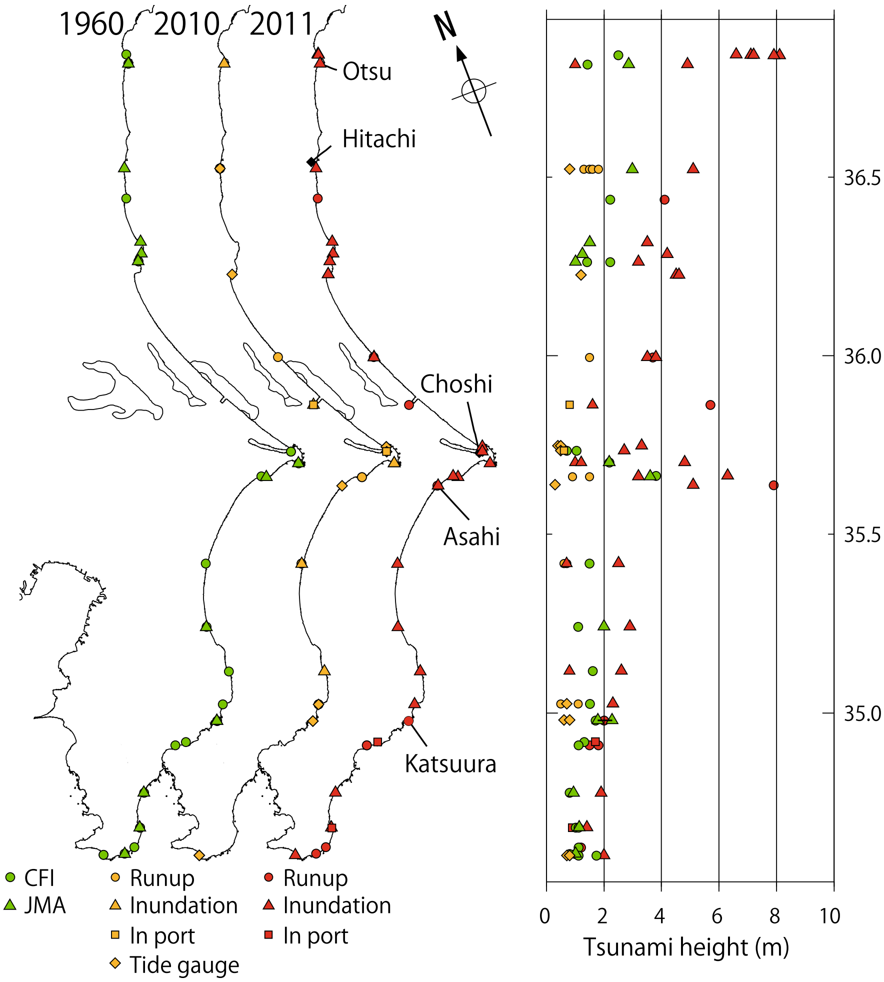

Figure 21

Comparison of 1960 and 2010 Chilean tsunami heights with 2011 Tohoku tsunami heights along the coasts of Ibaraki and Chiba prefectures. *Green circles* and *triangles* indicate 1960 heights from CFI (1961) and JMA (1961), respectively. *Orange circles*, *triangles*, *squares*, and *diamonds*, respectively, indicate runup heights, inundation heights, tsunami heights in ports, and tsunami heights from tide gauges from the 2010 Chile earthquake (Tsuji *et al*. 2010; Imai *et al*. 2010). *Red circles*, *triangles*, and *squares*, respectively, indicate 2011 runup heights, inundation heights, and tsunami heights in ports from Tsuji *et al*. (2011). The measurement locations are indicated on the maps on the *left*. Only data measured at the same locations for two or more tsunami are shown

tsunami heights are smaller than the 2011 tsunami heights (median ratio is 0.62; Table 3), and the 2010 heights are much smaller (median ratio 0.28).

6.1. *Tsunami Heights*

At Otsu in Kitaibaraki City, the measured inundation height from the 2011 Tohoku tsunami was ∼5 m (B6). The 1960 tsunami heights were 1 m (CFI 1961) or 3 m (JMA 1961), while the 2010 tsunami caused only a minor inundation with a height of 1 m.

Along the coast of Ibaraki and Chiba prefectures, the 2011 tsunami heights gradually decreased toward the south. The two Chilean tsunamis also showed similar tendencies, though the change is smaller. These similar variations are reflected in the positive correlation of tsunami heights (Table 3; Fig. 22). The correlation coefficient between the 2011 and 1960 tsunami heights is 0.63, and that for the 2011 and 2010 tsunamis is 0.41.

Local amplifications of tsunami heights around Asahi City were found for the 2011, 2010, and 1960

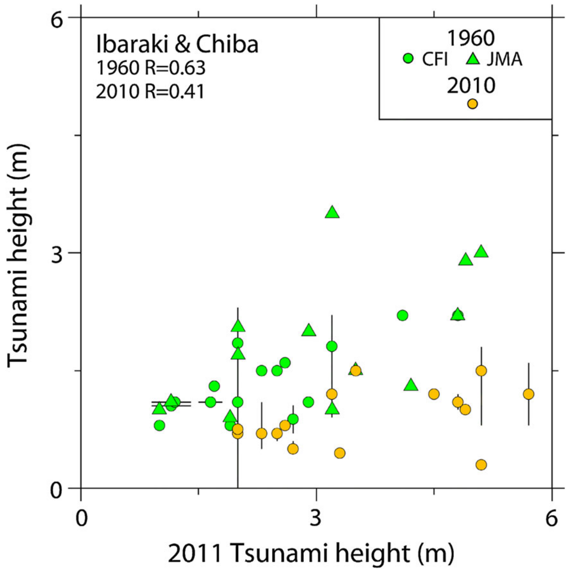

Figure 22
Comparison between the 2011 tsunami and the 1960 and 2010 Chilean tsunamis along the Ibaraki and Chiba coasts. *Green circles* and *triangles* indicate the 1960 Chilean tsunami heights from CFI (1961), and JMA (1961), respectively. *Orange circles* indicate the 2010 tsunami heights from Tsuji *et al*. (2010) or Imai *et al*. (2010). Multiple height data at the same locations are represented as median values with ranges (shown as *bars*)

tsunamis: tsunami heights were locally high (5–8 m) around Asahi City in 2011, while the 1960 and 2010 Chilean tsunami heights were 4 and 2 m, respectively. This local peak may be due to the local topography (the peninsula around Choshi and the local bathymetry off Asahi). The tsunami heights were also locally large around Katsuura, another gentle peninsula (Fig. 21). These common local variations also contributed to the large correlation coefficients.

6.2. *Factors Controlling Tsunami Heights and their Variability*

The 2011 tsunami heights generally decreased toward the south, away from the tsunami source. The 1960 and 2010 tsunamis, which were generated by the earthquakes in Chile (M_w 9.5 and 8.8, respectively) and propagated across the Pacific Ocean, show more uniform heights along the coasts, although they also decreased toward the south. Of the two Chilean tsunamis, the 2010 tsunami heights are consistently lower than the 1960 heights because of the smaller earthquake magnitude.

On a smaller scale, both near-field and transoceanic tsunamis show similar local variations. Local peaks around Choshi and Asahi, and near Katsuura were found for all the tsunamis, possibly as a result of the local topography, which consists of a number of small peninsulas. The peninsula is more distinct around Choshi and the tsunami heights show a more significant peak, while the peninsula near Katsuura is gentler and the peak in tsunami heights is less pronounced. This indicates that the local topography also affects local variation in tsunami height, although the main controlling factor is the source location, slip distribution, and the earthquake magnitude.

7. *Conclusions*

We summarized our 12 field surveys in which 296 tsunami heights accompanying the 2011 Tohoku earthquake were measured. The data and detailed locations of survey points and photographs (this paper and Tsuji *et al*. 2011) will be useful for modeling the 2011 tsunami source (e.g., Satake *et al*. 2013). We then compared tsunami heights for the 2011 Tohoku earthquake with those from past earthquakes: the 1896 and 1933 Sanriku earthquakes in Japan, and the 1960 and 2010 Chile earthquakes. Along the central Sanriku coast (between 39.0° and 40.2°N), the 2011 and 1896 tsunami heights ranged from 5 to 40 m, showing significant local variation. This may be due to the rugged and irregular coastline, indicating that local topography is a major factor in controlling tsunami height, together with the location, type, or magnitude of the earthquake. This is evident from the fact that the largest tsunami height was recorded at around 40.0°N for the 1896 and 2011 tsunamis, despite these tsunamis having different source locations. The local variations are much smaller on the northern and southern Sanriku coasts and the Ibaraki and Chiba coasts. The 2011 tsunami heights generally decrease toward the north and south, and also show local variations probably due to local topography. The 1960 and 2010 Chilean tsunami heights are more uniform. Both near-field and transoceanic tsunamis exhibit local peaks in their heights near peninsulas. Such local variations of tsunami heights may be helpful for educating coastal residents to reduce future tsunami disasters.

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