EERI Preliminary Notes on Tsunami Damage and Response:
Tsunami Generated by $M_{\text{JMA}} 7.4$ ($M_{\text{W}} 6.9$) Fukushima, Japan, Earthquake on November 22, 2016

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1 PURPOSE

The Earthquake Engineering Research Institute (EERI) supports gathering and sharing information about the effects and damage caused by tsunamis as well as the lessons learned about tsunami notification, evacuation and response activities. This report summarizes the damage and response outcomes of the tsunami which was generated by the M\textsubscript{JMA}7.4 (M\textsubscript{w}6.9)\textsuperscript{1} Fukushima, Japan earthquake on November 22, 2016 (November 21, 2016 for U.S.) (Figure 1). Although EERI-related field teams were not deployed for the tsunami, the report provides information compiled by the authors from various references, colleagues, and their own personal experiences during and after the event. The information presented should be considered preliminary; for updates, the authors recommend readers visit the scientific and emergency management websites discussed herein.

![Figure 1 Map showing the epicentral area of the M6.9 Fukushima Earthquake as well as the epicenter and general fault rupture area of the March 11, 2011 M9.1 Tohoku-oki Earthquake. The moment tensor diagram, showing a NE – SW oriented normal fault dipping to the northeast or southwest, for the event from the USGS earthquake page.](image)

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\textsuperscript{1} The magnitude estimated by Japan Meteorological Agency, M\textsubscript{JMA}, is generally utilized in Japan and is determined from maximum displacement amplitudes of the total seismic wave traces. These relations were designed to give almost the same magnitude value as that of Gutenberg and Richter. Moment magnitude, M\textsubscript{w}, is calculated from the centroid moment tensor solutions.
The authors’ objectives for this paper include:

1. Summarizing the physical tsunami effects and damage from the event.
2. Documenting tsunami notification and response activities both in Japan and elsewhere.
3. Discussing potential lessons learned and future improvements for tsunami-related scientific research, engineering, notification and response (NOTE: discussion about lessons learned represent the opinions of the authors).

## 2 EARTHQUAKE RUPTURE PATTERN AND TSUNAMI EFFECTS

### 2.1 Event Description

According to the Japan Meteorological Agency (JMA) and the U.S. Geological Survey (USGS), the $M_{\text{JMA}}7.4$ ($M_w6.9$) earthquake occurred at 20:59 UTC on Monday, November 21, 2016 (05:59 local Japan time on Tuesday, November 22, 2016). The earthquake hypocenter was located just offshore from Fukushima Prefecture approximately 37km east-southeast of Namie, Japan, at a depth of 11km (Figure 1). The earthquake occurred in a tectonic region where the North American Plate overrides the Pacific Plate towards the east along the Japan trench subduction zone. Based on information from the USGS earthquake webpage for the event, the earthquake was a shallow, normal-fault event within the overriding North American Plate, and not along the actual subduction zone. A number of aftershocks of 2011 aftershocks were on shallow NE to SE trending normal faults and have been interpreted as a response to over slip or overshooting of the main event (Ide et al., 2011). Based on the moment tensor and related information, the fault rupture was along a normal fault dipping to the northwest or southeast which indicates that the primary tsunami energy would likely also be focused in those directions.

According to the Japanese National Research Institute for Earth Science and Disaster Resilience (NIED) website, this event was similar to other aftershocks from the $M_w9.1$ March 11, 2011 Tohoku-Oki Earthquake, which ruptured the subduction zone to the north of this event (Figure 1). The tsunami generated by the 2011 earthquake caused widespread inundation along the coasts of Fukushima, Miyagi, and Iwate prefectures leaving over 18,000 people either dead or missing. The cooling system for spent fuel rods at Fukushima Nuclear Power Plant, which was heavily damaged during the 2011 event, shutdown at the moment of the November 22, 2016 earthquake but a backup cooling system initiated and no serious incident was reported.

The 2011 earthquake produced a vigorous aftershock sequence that continues to the present time. Figure 2 shows the number of earthquakes of $M\geq4.5$ per year recorded in the eventual Tohoku-oki aftershock zone. Prior to the 2011 sequence, the background level of activity averaged about 35 earthquakes per year, jumping to over 2100 in 2011. Since then, aftershock frequency has declined but remains nearly four times the pre-2011 rate. Four of these aftershocks produced measureable tsunamis (Table 1). In addition to the event described in this paper, the July 2014 $M\ 6.5$ was also on a normal fault.
A small- to moderate-sized tsunami was generated by the November 22, 2016 earthquake, occurring along Pacific coasts of Fukushima, Miyagi, Iwate, and Ibaraki prefectures. According to the U.S. National Tsunami Warning Center (NTWC) website, the tsunami was recorded on a number of tide gauges in Japan and at Midway Island, Hawaii (see Table 1). Based on this information, the time of peak tsunami amplitude occurred close to or within the first hour of the observed arrival times at each tide gauge.

Table 1 Rupture source, magnitude, and tsunami height of four large aftershocks of the 2011 Tohoku-Oki Earthquake; compiled from NOAA NCEI Tsunami Database.

<table>
<thead>
<tr>
<th>Date of Aftershock</th>
<th>Mw</th>
<th>Rupture Source</th>
<th>Peak Tsunami Amplitude Measured or Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/7/11</td>
<td>7.1</td>
<td>thrust</td>
<td>0.08</td>
</tr>
<tr>
<td>7/10/11</td>
<td>7</td>
<td>strike-slip</td>
<td>0.09</td>
</tr>
<tr>
<td>7/11/14</td>
<td>6.5</td>
<td>normal</td>
<td>0.2</td>
</tr>
<tr>
<td>11/21/16</td>
<td>6.9</td>
<td>normal</td>
<td>1.4</td>
</tr>
</tbody>
</table>
Table 2 Tsunami information from tide gauges in the region and Midway Island, Hawaii (summarized from National Tsunami Warning Center event website).

<table>
<thead>
<tr>
<th>Tide Gauge Measurement Location</th>
<th>Observed Arrival Time (UTC)</th>
<th>Peak Amplitude (above sea level in meters)</th>
<th>Time of Peak Amplitude (UTC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boso, Japan</td>
<td>2138</td>
<td>0.08</td>
<td>2148</td>
</tr>
<tr>
<td>Ofunato, Japan</td>
<td>2155</td>
<td>0.35</td>
<td>2256</td>
</tr>
<tr>
<td>Mera, Japan</td>
<td>2201</td>
<td>0.27</td>
<td>2213</td>
</tr>
<tr>
<td>Midway Island, Hawaii</td>
<td>0208</td>
<td>0.09</td>
<td>0247</td>
</tr>
</tbody>
</table>

Figure 2 from the Japan Coast Guard and Imamura et al. (2016) shows the de-tided marigrams for these and other tide gauges in Japan that measured the tsunami. The largest measured tsunami amplitude was 0.8m at the Souma (also spelled Soma), Japan, tide gauge. Based on these marigrams, it appears the first tsunami arrival was a negative wave which would have exhibited a withdrawal of water along the coast. Based on the northwest or southeast dip of the fault, the directionality of tsunami energy would have been focused towards Soma and the Sendai coast north of Soma.

There were many eyewitness accounts and videos of the tsunami propogating up rivers channels and flooding land adjacent to harbors and other waterfront areas but there was limited inundation of residential and business areas and no tsunami-related injuries were reported. According to the Earthquake-Report website, TEPCO recorded a tsunami amplitude of one meter off shore from the Fukushima NPP. According to JMA, the largest tsunami amplitude observed was 1.4m within the
Port of Sendai. This is likely an effect of directionality from the tsunami source to the northwest as well as amplification of the tsunami within or around the port.

2.2 Geotechnical Setting and Effects

To date, there have been reports of minor damage isolated to harbors and waterfront areas. Tsunami bores traveled up some of the coastal rivers, as shown in the Sunaoshikawa River at Tagajo, Miyagi Prefecture, in Figure 4a. According to an article in The Japan Times dated November 22, 2016, the Japan Coast Guard reported there were sixteen small boats overturned off the coast of Miyagi Prefecture but no one was believed to be on board. From a report in The Asahi Shimbun dated November 22, 2016, included photos showing damage to small fishing boats and flooding that impacted cars parked near a harbor in Miyagi Prefecture (Figure 4b and c). In Ibaraki Prefecture, there were reports of inundation in some harbors, and twelve cars were reported to have been washed away.

There were reports of minor damage to fisheries in the Tohoku region. According to an article in The Japan Times dated December 4, 2016, sixteen fishing boats were overturned and ten rafts for seaweed farming were damaged near Miyato at a cost of about $75,000. Oyster farms and salmon-breeding facilities also sustained minor damage.

Figure 4 Various photos showing tsunami activity and damage during the 2016 tsunami: a) still from video showing the tsunami surge and bores travel up the Sunaoshikawa River in Tagajo, Miyagi Prefecture (https://www.youtube.com/watch?v=syEbtvIlyHeo&list=PlqlToVLZLg-Gjcy_Zs9MbuQ-Bs_ZTVbQ&index=2); b) and c) photos of damage to boats and cars. (source: The Asahi Shimbun article, November 22, 2016).
At the Port of Sendai, minor impacts to coastal protection structures and a river mouth were captured by pre- and post-
tsunami videos from unmanned aerial vehicles (UAV; also known as aerial drones). The videos were captured and several
observations were made by Dr. Volker Roeber, an engineering professor at Tohoku University, who took the pre-tsunami
video on November 14, 2016 as part of a post-typhoon coastal recovery survey (https://www.youtube.com/watch?v=VmFNwi0bA-A),
and the post-tsunami video on November 23, 2016 (https://www.youtube.com/watch?v=OuOQsPUvkWo). Figure 5 are pre-
and post-tsunami still frames showing that the tsunami overtopped and partially damaged the coastal seawall protecting an earthen berm at the base of an elevated parking lot. Erosion was apparently significant enough that local authorities closed the parking lot for several days. Figure
6 shows pre- and post-tsunami still frames from the mouth of the Nanakita River. It appears that a significant amount of
sediment was deposited at the mouth of the river, partially burying the breakwater at the river mouth.

As previously mentioned, JMA reported that the maximum tsunami amplitude of 1.4m was observed at the Port of Sendai.
For this area south of the port breakwater, there may have been reflection of the tsunami off the breakwater and amplification
of the surges which impacted this coastline. This may help explain the erosion and sedimentation observed this area.

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**Figure 5** Still images from UAV video taken by Volker Roeber of (a) pre-tsunami taken on November 14, 2016, and (b)
post-tsunami taken on November 23, 2016. This areas is just south of the breakwater for the Port of Sendai. Dark areas within the coastal seawall indicated saturation from tsunami inundation. Parts of the seawall were damaged and minor coastal erosion was observed.

**Figure 6** Still images from UAV video taken by Volker Roeber of (a) pre-tsunami taken on November 14, 2016, and (b)
post-tsunami taken on November 23, 2016. The red circle shows the area of significant sedimentation around the breakwater at the mouth of the Nanakita River, south of the Port of Sendai.
3 EMERGENCY NOTIFICATION AND RESPONSE

3.1 Local Tsunami Warning System, Emergency Notifications, and Response Activities

JMA is responsible for real-time tsunami forecasts and dissemination of official tsunami notifications in Japan. JMA works with a number of universities and related research centers (like NEID and Tohoku University) specializing in earthquake and tsunami analysis that can help with real-time forecasts. According to JMA’s website, earthquake activity and tsunami generation are monitored around the clock.

An example of the real-time data collected and available to JMA includes the NEID’s High Sensitivity Seismograph Network (Hi-net) which includes an ocean bottom cable system of seismic and water pressure sensors; an example of the data captured during the event is shown in Figure 7. According to the NEID’s website:

“Visualization of strong motions (left) and tsunamis (right) propagation using (the Hi-net system) data. Strong motions, represented by the real-time seismic intensity, were first detected by (Hi-net) and propagated through both sea and land areas. Tsunamis, represented by water pressure changes, propagated from off Fukushima-ken prefecture to the north and south approximately 15 minutes after the earthquake.”

![Figure 7 Hi-net seismic intensity and tsunami pressure data captured shortly after the start of the November 22, 2016, Fukushima earthquake (modified from http://www.hinet.bosai.go.jp/topics/off-fukushima161122/). This information can help with real-time forecasting.](image)
For tsunamis, JMA uses three categories of actionable tsunami alert levels provided in Table 2 below; the equivalent tsunami alert categories for the U.S. tsunami warning centers (National and Pacific Tsunami Warning Centers, NTWC and PTWC respectively) are included for comparison.

**Table 3** Tsunami alert categories from JMA and U.S. tsunami warning centers.

<table>
<thead>
<tr>
<th>JMA Tsunami Alert Categories for Japan</th>
<th>Equivalent NTWC and PTWC Tsunami Alert Categories for U.S.</th>
<th>Estimated maximum forecast tsunami heights</th>
<th>Expected damage and action (bolded) to be taken, from JMA website for Japan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Tsunami Warning</td>
<td>Tsunami Warning</td>
<td>Greater than 3 m</td>
<td>Damage: Wooden structures are expected to be completely destroyed and/or washed away; anybody exposed will be caught in tsunami currents. <strong>Action</strong>: Evacuate from coastal or river areas immediately to safer places such as high ground or a tsunami evacuation building.</td>
</tr>
<tr>
<td>Tsunami Warning</td>
<td></td>
<td>1-3 m</td>
<td>Damage: Tsunami waves will hit, causing damage to low-lying areas. Buildings will be flooded and anybody exposed will be caught in tsunami currents. <strong>Action</strong>: Evacuate from coastal or river areas immediately to safer places such as high ground or a tsunami evacuation building.</td>
</tr>
<tr>
<td>Tsunami Advisory</td>
<td>Tsunami Advisory</td>
<td>&lt;1 m (0.3 to 1m for NTWC/PTWC)</td>
<td>Damage: Anybody exposed will be caught in strong tsunami currents in the sea. Fish farming facilities will be washed away and small vessels may capsize. <strong>Action</strong>: Get out of the water and leave coastal areas immediately.</td>
</tr>
</tbody>
</table>

According to the JMA, the tsunami forecasting system was triggered immediately and effectively. The only potential issues which arose were uncertainties in the earthquake source because the earthquake was not along the subduction zone, and bathymetric and topographic data that needs to be updated. According to the JMA tsunami website, the Earthquake Report’s website, a Reuters article dated November 22, 2016, and an article in The Telegraph dated November 22, 2016, the following provides a timeline of the emergency notification activities and relevant earthquake and tsunami information flow after the start of the earthquake at 5:59AM:

6:02AM – Within three minute of the start of the earthquake, JMA’s automated earthquake monitoring system generated an initial magnitude of M\textsubscript{JMA}7.3; the preliminary magnitude generated by the U.S. tsunami warning centers was M\textsubscript{w}7.3. JMA also releases a tsunami forecast map and information for the areas of tsunami “Warning” and “Advisory” (Figure 8). A tsunami Warning was forecasted for Fukushima Prefecture and a tsunami Advisory was issued for coastal prefectures to the north and south of Fukushima, including Aomori, Iwate, Miyagi, Ibaraki, and parts of Chiba prefectures. Notification systems, including sirens and public address speakers, television and radio alerts, and social media messaging, were triggered and sent out to over 500,000 residents. Coastal populations within Fukushima Prefecture were informed to evacuate and expect tsunamis up to 3m high. However, the general message from emergency managers has been to evacuate to the highest ground possible, a product of the under-evacuations from the 2011 tsunami. Residents evacuated by foot as well as by car based on the earthquake ground shaking and the emergency notification system. Many residents noted their memory of the 2011 tsunami and their fear of another large tsunami prompted their immediate evacuation. People also indicated their fear of another incident or accident at the Fukushima NPP.
6:30AM – Based on post-event modeling results from Tohoku University (Imamura et al., 2016), this is about the time that the first surge arrives along the Fukushima coast.

6:32AM – The USGS lowers its initial magnitude from Mw7.3 to Mw6.9. This reassures tsunami warning centers and emergency operation centers outside of the country of Japan that a damaging trans-Pacific tsunami is unlikely to occur. In Japan during this time, many ships were observed moving out to sea from the harbors near Fukushima despite the fact that tsunami activity had likely started in this area.

6:50AM – The first tsunami surge is measured on the Soma tide gauge (Figure 3). The first surge has a negative wave which indicates that tsunami drawdown occurred in this area first. For the Soma tide gauge, the largest negative surge amplitude of -0.8m occurred at about 7AM and the largest positive amplitude +0.8m occurred at 7:10AM. During this time, emergency broadcasts start to transmit observed tsunami height information to the public. Although they indicate that the observed heights are below or slightly above one meter, they warn people that larger tsunami surges may occur and that the public should stay at evacuation sites and not return to the coast.

Figure 8 Tsunami warning maps and alert levels provided by JMA several minutes after the earthquake.
7:26AM – JMA expanded the tsunami Advisory area to the Izu Islands and additional parts of Chiba Prefecture.

7:48AM – Emergency broadcasts continued during this time on local Japanese television stations as well as in English translation on NHK World (Figure 9). Live video feeds from the coastal ports accompany information about emergency alerts and response activities, and observed tsunami heights along the coast. According to a Reuters article dated November 22, 2016 (author unknown), the broadcast announcers were instructed to use more emphatic words and messages to prompt coastal residents to immediately evacuate. The broadcast also discussed the impacts to the Fukushima NPP where the cooling system for the stored fuel rods has stopped. Reporters discussed the temperature of the water cooling the fuel rods in real time and indicate that temperature had not reached a critical point for concern. This all occurs prior to the indication that a backup cooling system had been initiated.

![Figure 9](https://www.youtube.com/watch?v=aR3Q9PtGUgU)

8:09AM – JMA upgraded the magnitude to $M_{\text{JMA}}7.4$, reset the earthquake depth to 30km, and increased the tsunami Warning area to include Miyagi Prefecture. This was based partly on tsunami forecast models which showed a direct focusing effect to the north into Miyagi Prefecture. Some residents questioned this action though the tsunami appeared to exceed the 1m threshold in this area based on eyewitness accounts and post-tsunami field observations. The post-tsunami field observations by Dr. Roeber’s UAV showed erosion to a coastal protection structure and inundation several hundred meters inland into a coastal marsh (Figure 5 and 6).

9:46AM – JMA downgraded the tsunami Warnings in the Fukushima and Miyagi prefectures to tsunami Advisories. JMA also cancelled the tsunami Advisories for Aomori and Chiba prefectures and the Izu Islands; the remaining prefectures to remain in the Advisory alert level were Iwate, Miyagi, Fukushima, and Ibaraki.

12:50AM – Almost seven hours after the earthquake, JMA cancelled all tsunami Advisories and Warnings for Japan.

According to Reuters article dated November 22, 2016 (author unknown), most coastal residents who felt the earthquake immediately evacuated to high ground. Others evacuated following the messaging coming from the government via multiple
3.2 Emergency Notifications and Response for Distant Coastal Areas – Example from the State of California

The U.S. Pacific and National Tsunami Warning Centers (PTWC and NTWC) provided tsunami notification information to U.S. and other regions around the Pacific Ocean after the earthquake. For example, the NTWC provided a number of “Tsunami Information Bulletins” about the tsunami threat to the west coast of the U.S. For the west coast of the U.S. (Pacific time), the earthquake occurred at 12:59PM on November 21, 2016. Table 3 summarizes the content of the messages sent by the two warning centers:

Table 4 Summary of tsunami information statements from the PTWC and NTWC.

<table>
<thead>
<tr>
<th>Tsunami Warning Center and Related Information Statements</th>
<th>Time Message Sent (Pacific time)</th>
<th>Information about Earthquake</th>
<th>Primary Emergency Response Message about Tsunami</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTWC Statement #1</td>
<td>1:08PM</td>
<td>event time 12:59PM….Mw7.3</td>
<td>Hazardous tsunami conditions possible within 300km of the epicenter along the coast of Japan</td>
</tr>
<tr>
<td>NTWC Statement #1</td>
<td>1:10PM</td>
<td>event time 12:59PM….Mw7.3</td>
<td>Tsunami NOT expected for U.S. west coast and Alaska</td>
</tr>
<tr>
<td>PTWC Statement #2</td>
<td>1:28PM</td>
<td>event time 12:59PM….Mw7.3</td>
<td>Tsunami amplitudes could be 0.3m and 1m along the Japan coast. Estimated times of first tsunami arrival for Japan were also provided.</td>
</tr>
</tbody>
</table>

The State of California is within the area of responsibility of the NTWC. The California Governor’s Office of Emergency Services (CalOES) is responsible for statewide tsunami response, including advising local counties and communities about the tsunami threat. The CalOES Earthquake and Tsunami Program duty officer contacted the tsunami scientist from the California Geological Survey (CGS) at 1:22PM in order to discuss the “no threat” message from the NTWC. During the November 13, 2016, earthquake and tsunami in New Zealand, the NTWC changed the initial “no threat” message to “the threat is being evaluated” once the earthquake magnitude was upgraded to the Mw7.9 threshold (Wilson and Johnson, 2017). Considering this change during the previous event, the CalOES duty officer wanted to confirm that there would be no hazard. The CGS tsunami scientist indicated that the magnitude had actually been downgraded by the USGS to Mw6.9 and earthquake source was not along the subduction zone, both sets of information helping to confirm a “no tsunami threat” for California.

4 LESSONS LEARNED

The 2016 Fukushima earthquake and tsunami provides an opportunity for scientists, engineers, planners, and emergency managers to review the event outcomes and develop a list of potential improvements to their ongoing work. There are a number of “lessons” that the authors would like to note. These lessons and recommendations are the opinion of the authors based on this and other recent events.

4.1 Tsunami Science and Engineering

Potential lessons about tsunami science from this event:

1. The fault rupture during this earthquake was along a southeast or northwest dipping normal fault, and not along the Japan subduction zone. This is the second large earthquake/aftershock to occur on a normal fault since the 2011 Tohoku-Oki Earthquake. This complicates the tsunami forecast since forecast methods and pre-event modeling are primarily associated with subduction zone earthquakes where the most significant tsunamis are generated.
Having said that, dangerous tsunamis can still occur along non-subduction zone sources like reverse and normal faults as well as submarine and subaerial landslides. This event presents a case for developing and using alternative tsunami detection and forecast systems, such as seafloor cable detection system run by the Japan NIED or coastal radar detection systems, in areas where non-subduction tsunami sources exist, as long as they are cost effective. Likewise, non-subduction zone source modeling should also be considered in conventional warning systems like those run by the U.S.

2. **Video from repeated UAV (drone) overflights near the Port of Sendai** proved useful in providing information for recognizing subtle coastal changes and damage related to the tsunami. Use of UAV overflights in key coastal locations on a quarterly to annual basis can help identify coastal change after tsunamis as well as other coastal hazards.

3. The **UAV overflights** showed both minor damage to new seawalls as well as significant sediment movement from this relatively small tsunami, which is typically more common than a large, local subduction zone source tsunami. Coastal engineers should consider developing and using a performance-based approach for design and construction of coastal structures to defend against tsunamis of various sizes through a probabilistic tsunami hazard analysis.

4. Based on evaluation of the UAV data, it appears that the long breakwater outside the Port of Sendai may have caused focusing of tsunami surges, amplifying tsunamis locally. Breakwaters are generally constructed to protect harbors from wave activity but they do not always consider amplification and other impacts outside or near the harbor. Coastal engineers should consider the influences and impacts to beaches, structures, and other facilities outside the harbors from extreme events like tsunamis when they create breakwaters and other structures.

### 4.2 Tsunami Warning Notifications

Potential lessons locally within Japan:

1. The earthquake magnitude and tsunami alert messages from JMA were provided to the public within three minutes after the earthquake and they turned out to be very accurate. Timely magnitude prediction and tsunami forecasting can be essential for sending the initial messaging out to communities near the source region to confirm there is a tsunami threat and evacuation should occur. However, forecasting agencies should also make it clear to the public that many times the magnitude and tsunami threat can increase because preliminary magnitudes and related tsunami forecasts can be underestimated in the first few minutes if the earthquake and fault rupture.

2. After reassessing the initial tsunami forecast during the event, JMA enlarged the tsunami Warning area to include the Miyagi Prefecture about two hours after the earthquake. This change caused confusion for many residents in the area, especially as the tsunami had already arrived along the coast within the first hour after the earthquake. More thoroughly explaining the reason for upgrading this area to a Warning would help reduce uncertainty with the public.

3. The tsunami alert messaging in Japan used multiple formats (sirens, television/radio, social media) for public notifications. Announcers on television and radio used more emphatic language to motivate people to evacuate/respond. Other countries should look more closely at the methods used by Japan to notify and motivate their coastal population to evacuate, especially in regions with large local sources (subduction zones).

4. Because of the Fukushima disaster following the March 11, 2011 tsunami, many residents in Fukushima and Miyagi prefectures were fearful of potential earthquake or tsunami damage to the NPP during the 2016 event. Knowing this, governmental and media provided reports on the status of the Fukushima and other NPPs to the public through their tsunami alert messaging. Other countries and communities with vulnerable coastal facilities like NPPs should evaluate the methods and effectiveness of this messaging from this event and consider including similar messaging in their tsunami alerts.

Potential lesson for distant areas, specifically lessons from the California experience:

1. The PTWC and NTWC were accurate with their forecasts and recommendations that there was no tsunami threat for U.S. regions. State of California emergency managers worked with tsunami scientists at CGS to confirm the NTWC forecasts. Continued consulting with state and university tsunami scientists about the tsunami hazard before, during, and after events helps emergency managers with their decision making, even confirming that there is no tsunami threat.
4.3 Tsunami Response

Potential lessons about tsunami response activities in Japan:

1. Most people who felt the earthquake shaking evacuated to high ground immediately as they were educated to do. Others evacuated after being instructed to by one of the many notification methods discussed previously. Evacuees went to high ground or inland by foot and by car. In many cases, however, road congestion and traffic prevented evacuees getting to safe areas in a timely manner. Vehicular evacuations are not recommended because traffic jams and/or injuries can occur. In most cases, pedestrian evacuations can be executed more quickly. The Japanese government is aware of this problem and vows to continue to address this issue.

2. Many residents discussed that memories of the 2011 tsunami caused them to evacuate more quickly to high ground. This demonstrates that past events can be effective for motivating evacuees and improving response in the future. However, small events like the 2016 tsunami might cause the opposite effect. It is important to continue to educate the public that full immediate evacuations or following the recommendations of emergency managers and responders should be done for all Warning-level tsunami forecasts.

3. Emergency managers in Japan recommend that when a large earthquake is felt or official notifications indicated a large tsunami is imminent, coastal populations in evacuation zones should go as far away from the coast or to the highest ground possible. This is a result from the 2011 tsunami where many evacuation sites were inundated because of underestimations of the tsunami threat. Although tsunami hazard analyses and evacuation planning has greatly improved over the past decade, taking a conservative approach and going beyond established evacuation sites may be appropriate where there is a large, imminent tsunami threat.

4. Reports and video indicated that many boat captains took their boats offshore after feeling the earthquake or getting the notification that a tsunami might be coming. Taking a boat out of a harbor just before or during a tsunami can be very dangerous and possibly fatal for the ship’s crew. This was the experience during the 2011 Tohoku tsunami where many ships which tried to go offshore before the tsunami arrived were sunk or heavily damaged (Wilson, 2011). In addition, boats and crews which do survive getting offshore might be stranded for more than 24 hours or may not have a harbor to return to. The U.S. National Tsunami Hazard Mitigation Program has developed draft guidance (2016) which recommends that any ship crew on the docks or on a boat still attached to the dock should not try to take their ship offshore, but instead evacuate by foot to high ground or inland. Harbor and port safety officers should consider this guidance where life safety is more important than attempting to save a ship.

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Japan Coast Guard website: http://www.kaiho.mlit.go.jp/index.html