

Chapter 5

NOAA's Historical Tsunami Event Database, Raw and Processed Water Level Data, and Model Output Relevant to the 11 March 2011 Tohoku, Japan Earthquake and Tsunami

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Abstract On 11 March 2011, a magnitude 9.0 M_w earthquake occurred near the east coast of Honshu Island, Japan. The earthquake generated a tsunami with wave heights up to 40 m triggering a response from the National Oceanic and Atmospheric Administration (NOAA). NOAA is the lead federal agency responsible for tsunami warnings issuance, technology innovation, research, and mitigation for the United States. These activities are matrixed across several closely integrated bureaus, including the National Weather Service National Data Buoy Center, Tsunami Warning Centers, and UNESCO/IOC – NOAA International Tsunami Information Center; the National Ocean Service Center for Operational Oceanographic Products and Services, the Pacific Marine Environmental Laboratory; and the National Environmental Satellite, Data, and Information Service National Geophysical Data Center (NGDC). Each of these bureaus work together to improve tsunami forecasting and thereby protect lives. Immediately following the March 2011 Japan earthquake and tsunami, all NOAA offices were involved in complimentary tsunami activities. In this paper, we describe the status of data associated with this tsunami event, review the processing and availability of tide gauge and tsunameter data, including Deep-ocean Assessment and Reporting of Tsunamis (DART®) and discuss the uses of these data in tsunami models. The basic data in the NGDC historical event databases include: date, time, event location, magnitude of the phenomenon, and socio-economic information such as the total number of

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fatalities and dollar damage estimates. The tsunami database includes additional information on runups (locations where tsunami waves were observed by eyewitnesses, post-tsunami field surveys, tide gauges, or deep ocean sensors). Therefore, an introduction and summary of the effects of the earthquake and tsunami is also included.

Keywords Damage • Earthquake • Runup • Tide gauge • Tsunameter • Tsunami • 2011 Tohoku Japan Tsunami

5.1 Introduction

The National Oceanic and Atmospheric Administration (NOAA) is the lead federal agency responsible for tsunami warnings issuance, technology innovation, research, and mitigation for the United States. These activities are matrixed across several closely integrated bureaus:

- National Weather Service (NWS) line offices have several responsibilities. The NWS Global Telecommunication System (GTS) provides real-time data flow of all observation data including Deep-ocean Assessment and Reporting of Tsunamis (DART®) observations from the network managed by the NWS National Data Buoy Center (NDBC). The NWS Tsunami Warning Centers (TWC) operationally forecast tsunami impact along U.S. coastlines and issue warnings. The International Tsunami Information Center (ITIC) is a United Nations Educational, Scientific and Cultural Organization (UNESCO)/Intergovernmental Oceanographic Commission (IOC) – NOAA partnership that assists Member States in establishing warning systems and serves as a clearinghouse for educational and preparedness materials.
- National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) maintains the U.S. coastal sea level tide-gauge network and distributes all data, including 1-min, for operations and research.
- Office of Atmospheric Research (OAR) Pacific Marine Environmental Laboratory (PMEL) works to address technology obsolescence and conducts tsunami research to improve observation and forecasting technologies. PMEL designed and developed the DART® system that is now the international tsunameter standard.
- National Environmental Satellite, Data, and Information Service (NESDIS) National Geophysical Data Center (NGDC) maintains the global tsunami archive, providing integrated access to tsunami event observational, instrumental, and socio-economic impact data. This includes the historical tsunami and significant earthquake databases, imagery, raw and processed coastal tide gauge and DART® data relevant to a tsunami event. NGDC also hosts the World Data Service (WDS) for Geophysics.

Each of the above mentioned bureaus work together to improve tsunami forecasting and thereby protect lives. CO-OPS tide gauge data and NDBC DART® and other tsunameter data are transmitted to the TWCs in real-time to verify tsunami arrival time and amplitude at ocean and coastal locations. NGDC processed tide gauge data are used to calibrate forecast models and determine tidal characteristics for tsunami isolation in any given signal. NDBC DART® and international tsunameter observations are used in real-time to estimate a tsunami source via inversion techniques and post-event to improve both the inversion process and the models. The work of NGDC to minimize background noise and all tidal contribution to the signal is essential to the forecasting effort.

Immediately following the March 2011 Japan earthquake and tsunami, all NOAA offices were involved in complimentary tsunami activities. In this paper, we describe the status of data associated with this tsunami event, review the processing and availability of tide gauge and tsunameter data, and discuss the uses of these data in tsunami models. The basic data in the NGDC historical event databases include: date, time, event location, magnitude of the phenomenon (tsunami or earthquake magnitude and/or intensity), and socio-economic information such as the total number of fatalities, injuries, houses damaged or destroyed, and dollar damage estimates. The tsunami database includes additional information on runups (locations where tsunami waves were observed by eyewitnesses, post-tsunami field surveys, tide gauges, or deep ocean sensors). Therefore, an introduction and summary of the effects of the earthquake and tsunami follows.

5.2 11 March 2011 Tohoku, Japan Earthquake and Tsunami

On 11 March 2011, at 05:46:24 UTC, a magnitude M_w 9.0 earthquake occurred at 38.297° N, 142.373° E, depth 29 km, near the east coast of Honshu Island, Japan (USGS 1971 to present). The earthquake generated a tsunami with wave heights up to 40 m in the near field at Aneyoshi Bay south of Miyako City (Mori et al. 2011). The tsunami, not the earthquake, was responsible for the majority of casualties and a large portion of the physical damage and loss of life (PEER/EERI/GEER/Tsunami Field Investigation Team 2011). The National Police Agency of Japan (2012) reported that as of 3 October 2012 there were 15,870 deaths, 2,813 missing and presumed deaths, and 6,111 injuries in 20 Japanese prefectures. More than 90 % of the deaths were due to drowning and 65 % of the dead were older than 60 years of age (UNESCO 2012). The earthquake and tsunami also caused a nuclear disaster with an International Atomic Energy Agency (IAEA) rating of 7 that included equipment failures, explosions, fires, nuclear core meltdowns, and radiation release (Strickland 2011). The damage costs resulting from the earthquake and tsunami in Japan are estimated at 16.9 trillion yen (approximately \$220 billion) (UNESCO 2012). A review of the NGDC historical tsunami databases reveals that this is the

deadliest tsunami since the 2004 magnitude 9.1 Sumatra earthquake and tsunami that caused nearly 230,000 deaths and \$10 billion in damage and the most costly tsunami that has ever occurred.

5.2.1 Damage in Japan from the 2011 Tohoku Event

Mori et al. (2011) determined from field surveys that the tsunami affected a 2,000 km stretch of Japan's Pacific coast and inundated more than 400 km² of land. The earthquake and tsunami resulted in the complete collapse and wash out of 129,549 houses and partially damaged 265,781 houses (NPA of Japan 2012). After the earthquake, there were 345 fires in 12 prefectures, including some cases where the tsunami triggered the fire (Mimura et al. 2011). The damage to infrastructure was also widespread including damage to 4,200 areas along roads, 77 bridges, and 29 parts of the railway system (NPA of Japan 2012). Lifeline infrastructure was also damaged (Mimura et al. 2011).

This event caused explosions and leaks in three reactors at the Fukushima I (Daiichi) Nuclear Power station, located approximately 150 km from the epicenter. When the earthquake occurred the reactors that were in operation at Daiichi shut down as they were designed. Although the local power grid had been knocked out, the plant had its own generators. Approximately 1 h after the earthquake, the generators shut down as a result of the tsunami waves (Sanger and Wald 2011). The Tokyo Electric Power Company (TEPCO) estimated the tsunami at 10 m at Daiichi and 12 m at Daiini (World Nuclear News 2011). The Fukushima power plants were required to withstand a certain height from tsunamis: 5.7 m at Daiichi and 5.2 m at Daiini (World Nuclear News 2011). As of 30 September 2011 Japan lifted evacuation advisories for an area spanning five towns and cities around the nuclear power plant (Tabuchi 2011). A 12-mile exclusion zone will remain in place around the nuclear power plant and the worst contaminated areas close to the plant are likely to remain uninhabitable for decades. On 16 December the Government of Japan announced that all reactors at the Fukushima Daiichi Nuclear Power Station had been brought into a condition equivalent to "cold shutdown" (IAEA 2011).

In contrast to Fukushima, according to the IAEA, there was no damage to the Onagawa Nuclear Power Plant, located closest to the epicenter (IAEA 2012, the final report will be available in 2013). The plant experienced very high levels of ground shaking and some flooding from the tsunami, but was able to shut down safely (IAEA 2012). According to the Tohoku field survey there were runup heights of almost 13 m near the power plant (Mori et al. 2011).

5.2.2 Damage Outside of Japan from the 2011 Tohoku Event

Loss of life outside of Japan was minimal due to warnings and evacuations; but there were two confirmed distant deaths, one in California (Wilson et al. 2012) and one in Indonesia (The Jakarta Globe 2011). Financial damage outside of the Japan source region was quite extensive. Greater than \$30 million damage occurred on the Hawaiian islands of Oahu, the big island of Hawaii, Maui, and Kauai (Abercrombie 2011). Moderate to strong currents were observed in all coastal harbors and marinas in California, leaving at least two dozen marine facilities with damage totaling over \$50 million (Wilson et al. 2012). A relatively small but noteworthy amount of damage was inflicted on French Polynesia (Reymond et al. 2012) and the Galapagos Islands (USGS 1971 to present). Houses were destroyed in Pisco, Peru, and several buildings were destroyed at Dichato, Chile (USGS 1971 to present).

5.3 NGDC Tsunami Data Archive for the 2011 Tohoku Event

As of 3 October 2012, NGDC/WDS has collected maximum tsunami amplitudes from 289 tide gauge observations, 34 tsunameter, primarily DART®, station observations, and more than 5,400 eyewitness reports and post-tsunami field survey measurements. These observations were added to the NGDC historical tsunami database and were overlaid onto the calculated tsunami travel time map shown in Fig. 5.1.

5.3.1 Post-Tsunami Field Survey Data

After the 2011 tsunami, researchers throughout Japan conducted tsunami surveys along a 2,000 km stretch of the Japanese coast (Mori et al. 2011). These data were added to the NGDC database and represent the largest tsunami survey dataset ever collected for one event. The dataset includes more than 5,200 locations (31.5–43.7° N) with runup heights (elevation at maximum inundation), maximum water level, maximum horizontal distance of inland flooding or inundation, modeled estimated arrival time of the largest wave, and reliability. These heights were measured from sea level excluding the astronomical tide. Inundation distance and run-up heights “were measured within a few centimeters accuracy from watermarks on building, trees, and walls by using a laser range finders, a real-time kinematic (RTK) GPS receiver with a cellular transmitter, and total stations. Run-up height was determined from the maximum landward extent of debris and seawater marks” (Mori et al. 2011). The maximum runup height was 40 m at Ofunato. Figure 5.2 shows plots of the total number of deaths, runup or maximum water height, and maximum inundation by

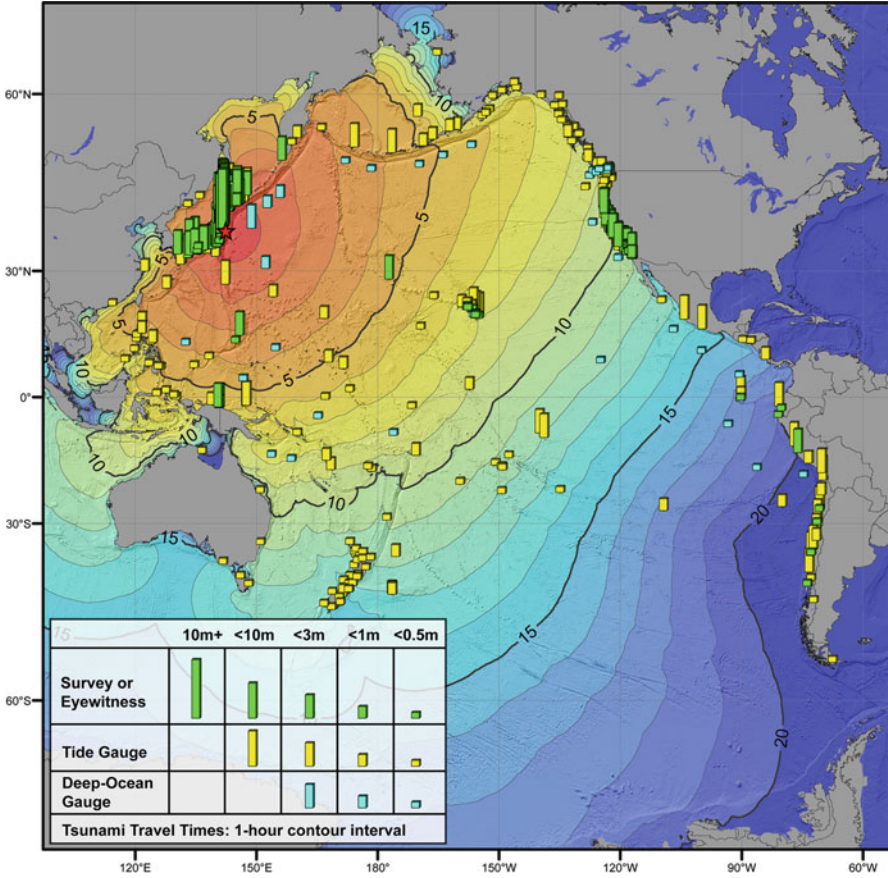


Fig. 5.1 Plot of the 11 March 2011 magnitude 9.0 Japan earthquake epicenter; water heights from tide gauges, DART® stations, field surveys, and eyewitness accounts that observed the tsunami wave; overlaid onto the calculated tsunami travel time map (contour intervals are in hours) (Source: NGDC/World Data Service for Geophysics)

latitude from 35.5° to 42° N. The highest values in all three plots are in the region from 38° to 40° N, near and just north of the epicenter at 38.3°N. These data will be very useful for understanding and modeling tsunami generation, propagation, and inundation of dry land, particularly in the near field relative to tsunami generation.

The NGDC database also includes field survey data for Indonesia (BMKG 2011), French Polynesia (Reymond et al. 2012), Mexico (Jonathan et al. 2011), and the west coast of the U.S. (Wilson et al. 2012). Additional field survey data will be added as it becomes available.

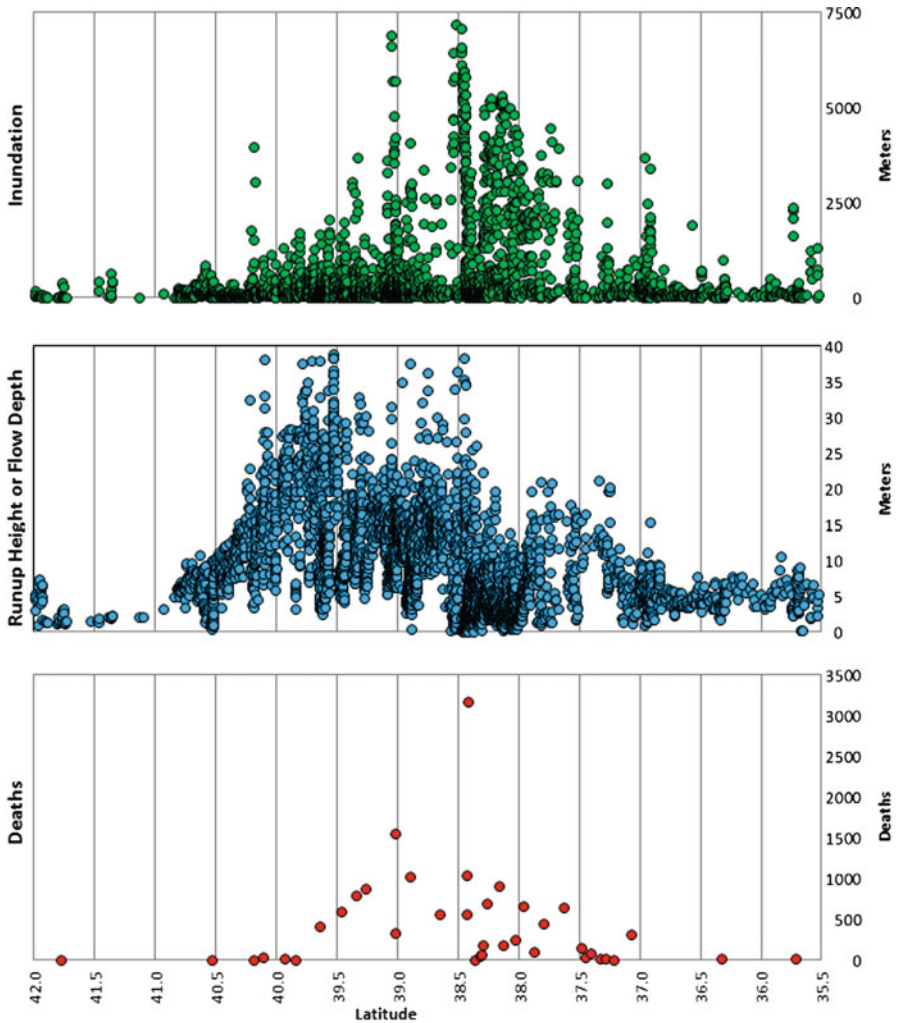


Fig. 5.2 Latitude-based graphs of total deaths for selected principalities and prefectures, run up or maximum water height, and maximum inundation distance from the 11 March 2011 Tohoku, Japan tsunami. The epicenter is at 38.3°N (Source: NGDC historical tsunami event database compiled from UNESCO/IOC 2011; Mori et al. 2011)

5.3.2 Bottom Pressure Recorder (BPR) Data

The tsunameter system is the primary component of the tsunami observational network, with each system sited in the deep-ocean near potential tsunami sources. As a tsunami wave propagates across the open ocean, DART® and internationally equivalent tsunameter systems register the passage of a tsunami and transmit

observations to NOAA's two Tsunami Warning Centers and warning centers around the world. These observations are used to identify the tsunami source, a refinement of the initial earthquake parameters including magnitude that are based purely on seismic information (Percival et al. 2011). The refinement is accomplished by inversion, or fit, of observations at tsunameter stations to modeled tsunami wave forms from a precomputed propagation database. The inversion algorithm is used to assess the parameters of the tsunami source based on tsunameter observations. Source parameters revised to represent the tsunami source are then used to improve the forecast of tsunami arrival time, wave amplitude, and inundation or flooding at specific far-field coastal locations (Titov 2009). Both near-field and far-field tsunameter data are used post-event to further research tsunami wave propagation and the energy dissipation along its path, and to improve near-field forecasting.

Each tsunameter consists of an anchored seafloor bottom pressure recorder (BPR) and a companion moored surface communication buoy. Pressure is converted to sea surface height and transmitted via Iridium satellite at 6-h intervals for standard monitoring. High-resolution 15-s integrations are internally recorded on a memory card by each BPR unit. These data are available either remotely or upon recovery of a BPR unit during station service operations. Presently, there are two tsunameter technologies in widespread use: The United States and internationally deployed DART® II and the Easy-to-Deploy (ETD) system deployed by international partners. Both technologies incorporate the same electronics and sampling schemes, but the compact ETD system is deployed as a disposable unit with an operational life in excess of 4 years. Internally recorded 15-s ETD data are currently only accessible remotely via satellite in 1-h time segments. Engineering efforts are underway to support data uploads spanning 1–2-weeks. ETD systems require significantly less expenses for deployment and operations. A more detailed description of the DART®, and therefore the tsunameter system along with a history of tsunami observations can be found in Mofjield (2009). Additional information is provided on the web site of the NOAA/PMEL National Center for Tsunami (<http://nctr.pmel.noaa.gov>).

As of this writing, the current Pacific Ocean DART® system consists of 43 stations: 33 are owned and operated by US/NOAA, 6 by Australia, 2 by Russia, 1 by Chile, and 1 by Ecuador (set up September 2012). The 2011 Tohoku event was observed and recorded on all of these stations, except 6 NOAA, 2 Australian, and the 1 station that was not yet deployed, for a total of 34 records. Of these, 18 are 15-s high-resolution records from retrieved BPR units and 16 are real-time records from ETD systems or from BPRs that have not been serviced.

Tsunami waves as high as 10 cm were observed at deep-ocean stations located almost 16,000 km away from the earthquake source. At DART® station 21413, located 1,278 km southeast of Tokyo and approximately 1,280 km east-southeast of the epicenter, the tsunami height was 1 m. The largest wave height ever recorded in the deep ocean was observed to be 1.8 m (peak-to-trough) at DART® station 21418 located 833 km northeast of Tokyo and approximately 527 km east of the epicenter. The actual tsunami height at this station is expected to be larger since the returned observation is a 1-min average over four base frequency samples, but will likely

remain unknown since this BPR was lost during recovery operations. A specific feature of this event is that the tsunami propagates in the deep ocean as one, two, or three large waves and then exhibits a strong and rapid decay with a long tail of waves having significantly lower amplitudes. Using satellite altimeter data Song et al. (2012) show that the amplification of the first tsunami waves is caused by the merging of the tsunami front when it travels along ocean ridges and seamount chains in the Pacific Ocean resulting in the doubling of the wave height and destructive potential in certain directions.

The 2011 Tohoku tsunami was recorded by a number of Japanese cable BPRs on observational networks operated by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Earthquake Research Institute (ERI), and Japan Meteorological Agency (JMA), and at Canadian BPRs from the NEPTUNE-Canada and VENUS geophysical networks. These data are available from the corresponding agencies.

Bottom pressure recorder data from all reporting tsunameters and ETDs for the 2011 Tohoku event were added to the NGDC water-level database following data processing and quality control. The addition of these real-time and retrospective Tohoku data, brings the NGDC event database holdings, as of September 2012, to 147 BPR records from the Pacific Ocean, Caribbean Seas, Gulf of Mexico, and Atlantic Ocean. This includes 127 high-resolution 15-s time series recovered and processed retrospectively and 20 real-time records. Tsunami events that occurred after 2006 are well represented in the database due to increased hazard awareness and observational technology following the 2004 Sumatra tsunami. Longer periods of observations exist for a finite number of stations occupied for research beginning in the 1980s prior to establishment of the real-time sensing network. Three stations south of the Alaska-Aleutian Archipelago and two stations off of the U.S. coast of Oregon State have provided observations starting in 2002. In addition, DART@46406 (51406), located in the Central Pacific 5,370 km southeast of Hawaii has been occupied since 2003. All available real-time and high-resolution 15-s tsunameter data for the 2011 Tohoku event are available on the NGDC website (<http://ngdc.noaa.gov/hazard>). Additional data are available upon request to haz.info@ngdc.noaa.gov.

5.3.3 *Tide Gauge Data*

Maximum tsunami wave heights for the 2011 Tohoku event were measured in Japan by a “huge tsunami gauge” network consisting of water pressure sensors that are installed at wharves to measure extremely large tsunamis with amplitudes beyond the measuring range of the regular tide gauges. In general, this tsunami was observed at more than 60 Japanese tide stations situated on all Japanese islands according to Koizumi (2011).

The 2011 Tohoku tsunami was observed at tide gauges located in 30 Pacific Rim countries, in Antarctica, and on the West coast of the Atlantic Ocean at Arraial do Cabo, Brazil.

NGDC has processed 1-min time-series US tide gauge data that contain the 2011 Tohoku tsunami signal: 11 records from the US Pacific Islands, 7 records from the Alaska region, and 13 records from the US West coast. Including these Tohoku data, as of September 2012, NGDC has collected 1-min data from a total of 188 tide-gauge stations: US Pacific islands (11 records), Alaska region (31 records) and US West coast (35 records), US East coast (59 records), Caribbean Seas (16 records) and from the US Gulf Coast (38 records). The period with 1-min observations on most of these stations is from 01 January 2008 to the present. These data could be used to investigate tsunamis and other extreme events requiring high-resolution records. These data are available upon request to haz.info@ngdc.noaa.gov.

5.4 Model Output and Products

The NOAA tsunami forecasting system combines observations and models to produce timely and accurate predictions for guidance. Typical model output includes tsunami arrival time, wave amplitude, and flooding forecasts at model grid points corresponding to specific locations selected because of population, infrastructure, or financial interest. Additionally, current predictions are output but validation of these predictions is hampered due to the lack of observations.

The NOAA tsunami forecast system utilizes the Method of Splitting Tsunamis (MOST) model (Titov and Synolakis 1997, 1998), for both real-time forecasting and for time-insensitive hazard assessment and research, to simulate the three processes of tsunami evolution: generation, propagation, and flooding of typically dry land. Digital Elevation Models (DEMs) constructed by NGDC using the best available topography and bathymetry data, a propagation database consisting of a continuous and discrete set of fault segments along subduction zones around the world, and community specific models, are all central to the MOST methodology. Figure 5.3 shows the propagation forecast of maximum amplitudes calculated with the NOAA tsunami forecast model for the 2011 Tohoku, Japan tsunami.

The central components of the NOAA tsunami forecast system were developed with warning operations in mind, but each are resources that can be further leveraged to conduct a suite of activities ranging from basic research to hazard assessment and emergency planning at all government levels. Digital Elevation Models (DEMs), a database of precomputed tsunami propagation, and 75 community-specific forecast models for the U.S. coastal States and territories are all elements of the system. Overlapping DEMs constructed by NGDC along the coasts of Washington, Oregon, and California, DEMs encompassing the Hawaiian Islands, and those along finite

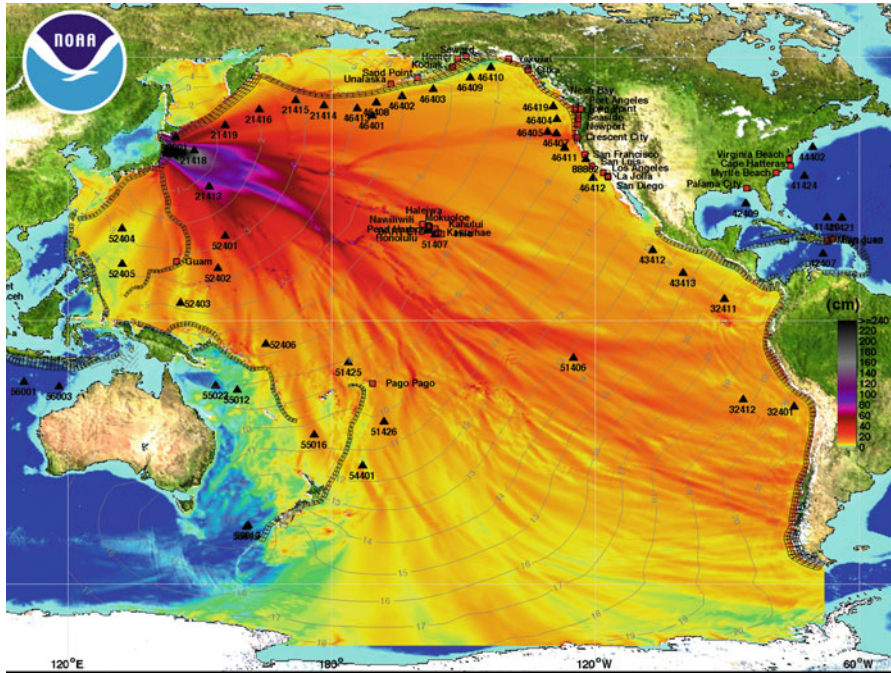


Fig. 5.3 The propagation forecast of maximum amplitude calculated by the NOAA forecast model for the 11 March 2011 Tohoku, Japan tsunami. The colors correspond with maximum amplitudes in the range 0–240 [cm] indicated by the color bar. – Filled colors show maximum computed tsunami amplitude in cm during 24 h of wave propagation. Black contours show computed tsunami arrival time

regions of Alaska and Pacific Island coastlines are all publicly available on the NGDC website. The MOST propagation database contains pre-computed tsunami propagation results from each discrete segment and a set of tsunami waveforms across the Pacific Basin over all grid points for tsunamis generated by earthquakes with a fault rupture over each segment. The propagation database is utilized by researchers and state emergency managers to conduct hazard assessments within their areas of responsibility to improve evacuation maps and update building zone maps. The total of 75 community-specific forecast models developed for operational flooding forecasting also provide the opportunity to investigate and plan for currents in ports and harbors as well as conduct hazard assessments on a fine resolution scale. Tsunami event-specific wave height and arrival times as compared with observations within the context of research are available at: <http://nctr.pmel.noaa.gov>. Operationally-determined model results are available on the two NWS TWC websites.

5.5 Water Level Data Processing

The NGDC water level database focuses on tsunamis and other extreme events, not on the features of the hydrological regime. This means that “event” records should be cleaned of all other components to the extent possible. Investigation of the extreme events requires special attention to all registered high-frequency variations and any integration over smaller time intervals will mask important “extreme features.” At the same time we try to avoid excessive pre- and post- processing as this could smooth or entirely remove all extreme characteristics from the record. A detailed description of tsunameter data processing and subsequent data quality control is provided by Mungov et al. (2012). The same processing techniques are applied to coastal 1-min tide-gauge data, where additional attention is paid to specific instrumental issues such as spikes and inverted observations. A modified despiking procedure is based on the application of two-level median filtering while the threshold limits are calibrated against observational data (Goring and Nikora 2002). All segments that are known to include a tsunami signal are visually, statistically, and spectrally inspected for quality assurance. This practice provides confidence that even the small details of the tsunami signal are not altered. For this reason we do not apply any automatic data processing.

To remove the tides we use a customized version of the tidal package of the Institute of Ocean Sciences (IOS, Sidney, BC, Canada) developed by Foreman et al. (2009). Details of the application are described in Mungov et al. (2012).

5.5.1 *Post-Processing to Extract “Clean” Tsunami Signals and Their Spectral Characteristics*

The “clean” tsunami signal is extracted by applying bandpass filtering of the residuals after the tidal analysis following Rabinovich et al. (2011) and Eblé et al. (2011). Each time band-passed filter parameters are calibrated against the data and the signal-to-noise ratio is investigated to ensure that we did not alter the tsunami record. In some cases, we prefer to leave some background noise or small spikes rather than distort or smooth the tsunami signal and corrupt the tsunami arrival times. Plots of tsunami signals obtained from DART® stations for the 2011 Tohoku, Japan tsunami are shown in Fig. 5.4.

5.6 Data Access

NGDC (<http://www.ngdc.noaa.gov/hazard>) and PMEL (<http://nctr.pmel.noaa.gov/>) are committed to delivering data and information in a manner that enables integration and supports multiple uses of data. Most of the data in the NGDC archive are in

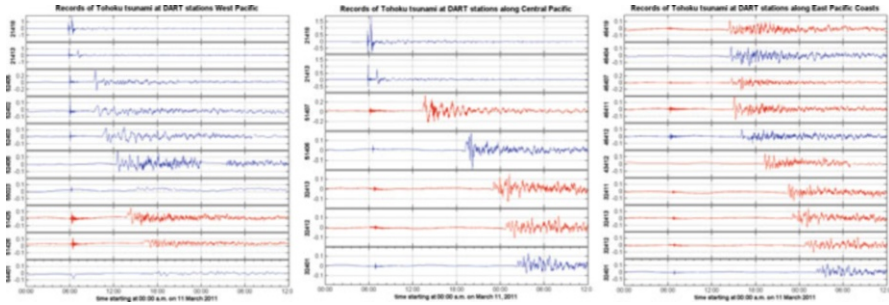


Fig. 5.4 Tsunami signals obtained from DART® stations for the 11 March 2011 Tohoku, Japan tsunami

the public domain and may be used without restriction, although users should cite data sources. These data can be searched from web maps or form interfaces by attribute (date, location, magnitude, etc.) and displayed as tables, reports, interactive maps, and imagery. For example, the maximum amplitudes from all of the tide gauge and DART® stations that observed the 2011 Tohoku tsunami can be found by searching the NGDC tsunami runup database forms interface. Additional details of the NGDC Tsunami Data Archive system are described by Dunbar et al. (2008).

The 2011 Tohoku tide gauge and DART® time-series data are not yet integrated with the runup database, but NGDC does disseminate summarized information for all recent and significant tsunami events. These web pages provide access to all available processed and archived 15-s high-resolution records and real-time data from all DART® stations where these specific events were recorded. The information provided has been verified prior to posting on the “DART® data” pages. These pages include a description of the earthquake event with links to the NGDC tsunami event and runups pages, the NDBC DART® system page, and to the Tsunami Travel Time Software used for development of tsunami travel time maps. On the tsunami travel time maps, all DART® systems reporting real-time and archived data are indicated.

5.7 Conclusion

In conclusion, NOAA covers a full suite of tsunami observations, data transmission, forecasting, post-event data processing, and data dissemination to a wide group of users. This large effort is made possible by each bureau of NOAA specializing in different areas of expertise, while simultaneously integrating their resources to create meaningful products for stakeholders. By continually examining each aspect in this process, NOAA will lead the ongoing effort to increase our understanding and ability to forecast the impact of future tsunami events, thereby allowing for science-based sound management and planning of U.S. coastal communities.

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