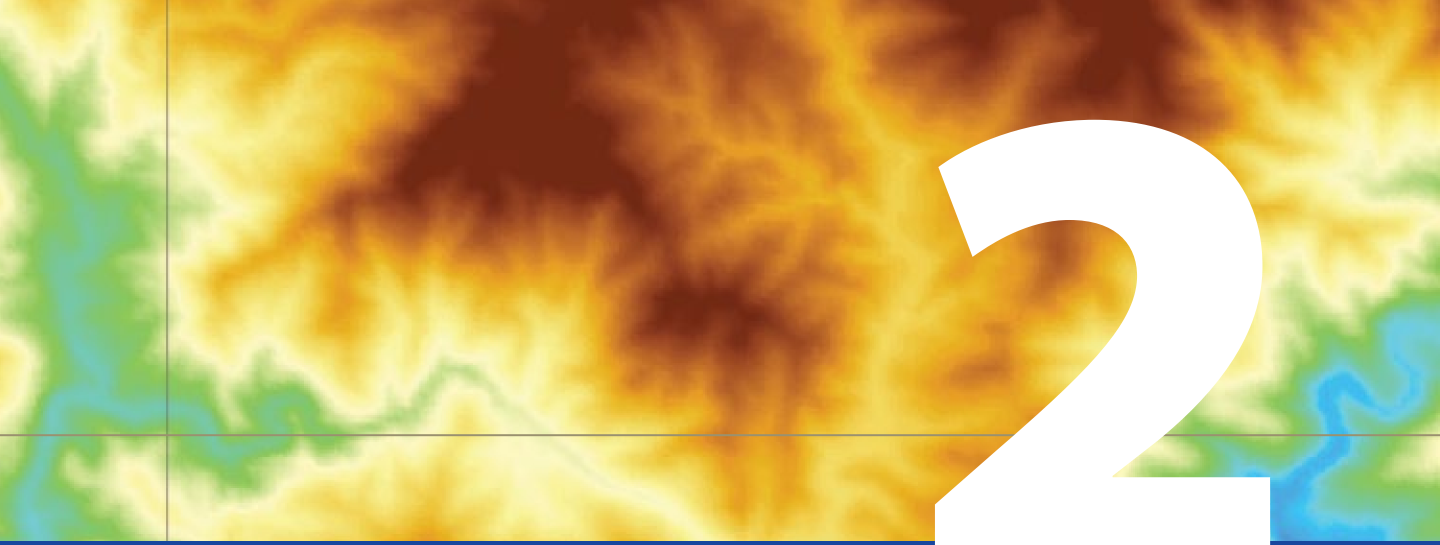

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Seamlessly integrating bathymetric and topographic data to support tsunami modeling and forecasting efforts

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Introduction

Tsunamis are ocean-spanning, natural, though infrequent, events that can lead to major disasters if coastal communities are not prepared. The December 26, 2004, tsunami in Indonesia is a prime example of this. But how do you prepare coastal communities for unavoidable flooding? Part of the answer lies in providing timely warnings after a tsunami has been generated somewhere in the ocean, usually by an undersea earthquake that displaces a large volume of water, though tsunamis may also be generated by submarine landslides and volcanic eruptions. Seismic waves travel through Earth much faster than tsunami waves travel through water, so except for communities immediately adjacent to the earthquake epicenter, there is usually some lead time that allows for warnings to be released and people to flee the coastal area. One of the major failures

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during the 2004 tsunami was the inability to warn coastal communities later struck by the waves. A mechanism to send warnings in the Indian Ocean simply did not exist, though major efforts are now under way to establish such a system.

The other part of preparing coastal communities for tsunamis is researching how tsunami waves behave in the ocean and how they flood the coast, typically by modeling tsunamis on a computer. Using specific scenarios, a tsunami modeler can determine the likely arrival time and wave height at a particular community. This modeled wave can then "flood" the computer version of the community, and the results can be used to identify which parts of the community are likely safe and which will likely be flooded or "inundated." Community planners and emergency responders can use this information to select evacuation routes and community evacuation centers and identify areas that need to be evacuated in a real event. They can also use this information in community planning, such as identifying safe places to build hospitals and schools, and where to develop new residential neighborhoods.

Underlying the accurate modeling of how a tsunami wave will strike and flood a coastal community are detailed representations of Earth's surface, both above and below water. Tsunami waves have extraordinarily long wavelengths (on the order of 25 kilometers/15 miles) and are strongly affected by the ocean bottom—their speed and direction are determined by the depth to the ocean floor, even in the deepest parts. In shallow water areas immediately adjacent to the coast, tsunami waves are even more affected by depth, gaining height as the depths shoal. Topographic information about the community itself is critical, as inaccuracies here will lead to inaccurate flooding in the tsunami models, ineffective planning based on flawed model results, and an inappropriate response during a real event.

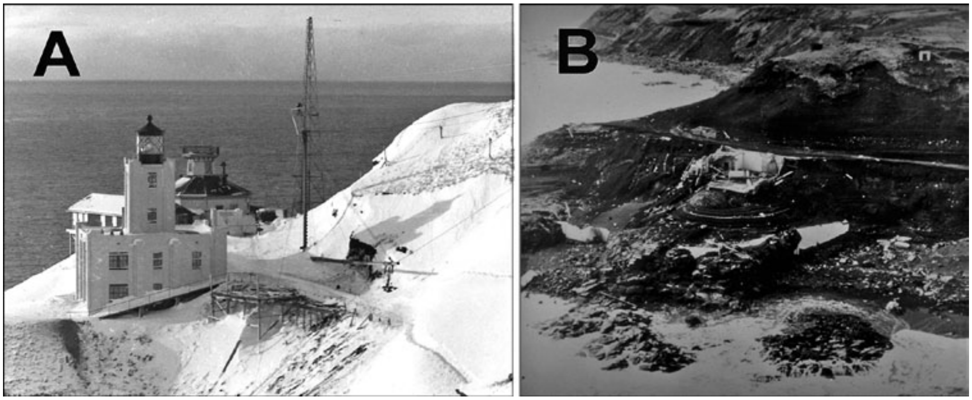

Figure 1. Photographs of the Scotch Cap Lighthouse on Unimak Island, Alaska, before (A) and after (B) the April 1, 1946, tsunami. The lighthouse was 10 meters (30 feet) above sea level and was destroyed; debris was deposited 35 meters (115 feet) above sea level. All five occupants were killed. Photos from the National Oceanic and Atmospheric Administration (NOAA)'s National Geophysical Data Center (NGDC) "Historical Tsunami Database." Courtesy of NOAA NGDC.

This chapter describes how we build high-resolution, integrated bathymetric–topographic digital elevation models (DEMs)—computer representations of Earth's solid surface—that are suitable for tsunami modeling, forecasting, and warning. We also present some of the challenges we've faced and lessons we've learned in developing these DEMs.

Power of tsunamis

Early on April 1, 1946, a large, magnitude 8.0 earthquake occurred along the Aleutian Trench south of Unimak Island, Alaska. The resulting tsunami devastated local communities, including the destruction of the Scotch Cap lighthouse (figure 1). The tsunami also propagated across the Pacific to cause damage and fatalities in California and Hawaii (Lander and Lockridge 1989). This event spurred the creation of the Pacific Tsunami Warning Center (`http://www.prh.noaa.gov/ptwc/`) and the development of tsunami travel-time charts for the Pacific Ocean.

The undersea Boxing Day earthquake (December 26, 2004) off of the island of Sumatra generated the most deadly tsunami in recorded history, killing more than 200,000 people around the Indian Ocean (National Geophysical Data Center 2009) before eventually traveling around the world (Titov et al. 2005). Video and photographs taken during the tsunami and shown on television news channels around the world (e.g., Guardian News 2009) seared this event into the public's consciousness (figure 2). The disaster resulting from the magnitude 9.0 earthquake renewed international interest in preparing coastal communities for tsunamis and led to the establishment of an Indian Ocean Tsunami Warning System (`http://ioc-tsunami.org/index.php`).

As with earthquakes, volcanic eruptions, hurricanes, and other natural hazards, tsunamis will occur in the future and will flood coastal areas. The question then becomes, "What can we do to ensure that tsunami events don't become disasters?" NOAA is responsible for preparing the U.S. coast for future tsunamis. NOAA monitors the world's oceans for tsunamis and tsunami-generating events—principally large earthquakes—and coordinates with coastal states and U.S. territories in community preparedness and emergency response to help achieve its goal of timely tsunami

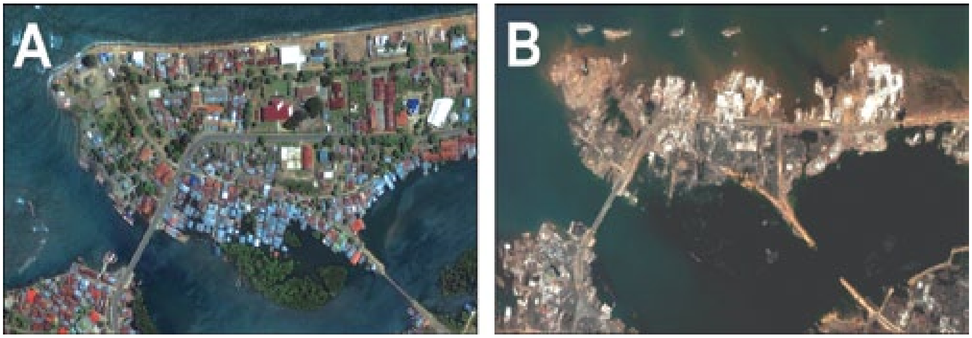

Figure 2. Banda Aceh, Indonesia, is shown before (A) and after (B) the 2004 tsunami. The tsunami is estimated to have reached 50 meters (165 feet) in height in Aceh province. Courtesy of DigitalGlobe.

warnings. New technologies are now being used for tsunami hazard assessment and community resiliency, including: 1) real-time tsunami forecasting, which provides both wave arrival time and estimated wave height (Titov 2009); 2) real-time tracking of tsunami waves in the deep ocean prior to landfall (Gonzalez et al. 2005); 3) building of detailed coastal digital elevation models (DEMs) that integrate seafloor bathymetry and land topography (e.g., Taylor et al. 2008a); 4) refined, more accurate tsunami modeling; and 5) creation of improved coastal inundation maps for use in preparing coastal communities and planning for emergency response. NOAA's National Geophysical Data Center (NGDC) hosts a long-term data archive of historical tsunami events and run-ups, photographs, tsunami deposits, and tide-gauge records that support tsunami research and mitigation

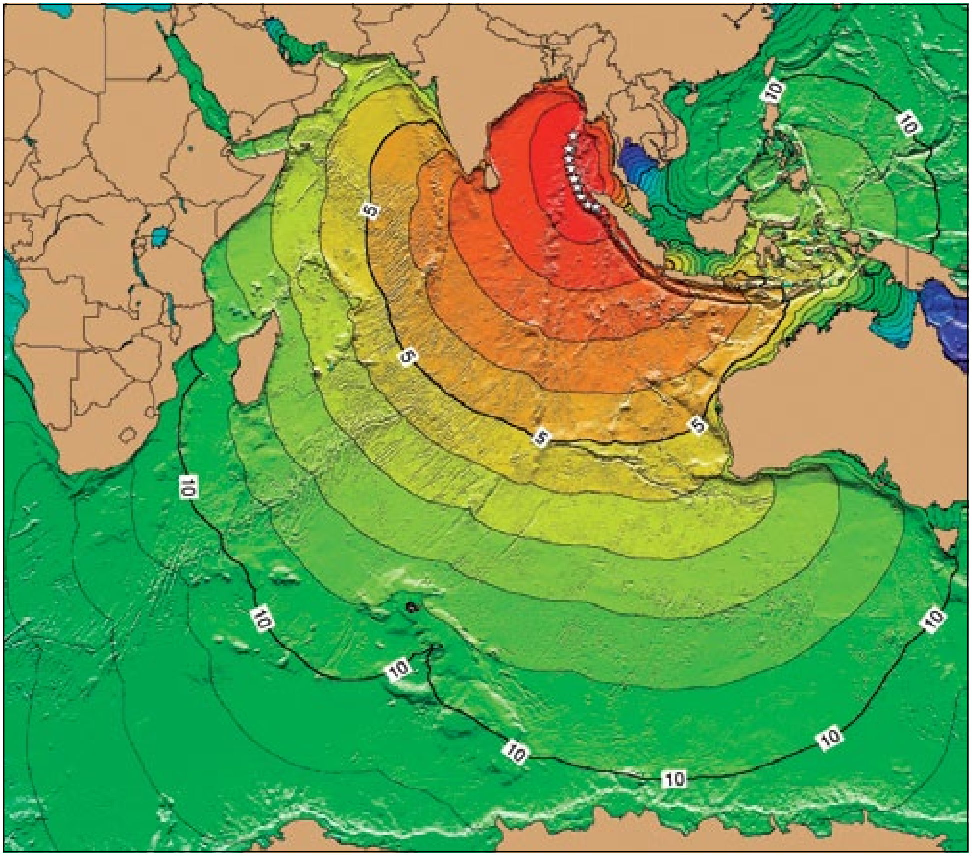

Figure 3. This is a travel-time map of the tsunami generated by the 2004 earthquake off the west coast of Sumatra, Indonesia. The bathymetry is from NGDC's ETOPO2 global relief model. Note how the 1-hour travel-time contours are more closely spaced on the shallow continental margins north of Australia and Indonesia, where tsunami waves traveled slower. Courtesy of NOAA NGDC.

(Dunbar et al. 2008). NOAA is also working with coastal states, through the National Tsunami Hazard Mitigation Program, to improve the resiliency of coastal communities and mitigate the damage caused by future tsunami events (Bernard 2005 and articles therein). NOAA's National Weather Service also works with coastal communities to reduce the potential for tsunami disaster through its TsunamiReady Program (`http://www.tsunamiready.noaa.gov/`), which helps community leaders and emergency managers strengthen their local operations.

Tsunami travel times across ocean basins are directly related to seafloor depth, thus knowledge of coarse ocean bathymetry (km-scale) is a first-order requirement for effective tsunami modeling and forecasting (figure 3). Tsunami waves travel faster in the deep ocean, leading to increased distance between 1-hour travel-time contours. In shallow coastal zones, the waves travel slower, and wave height increases to compensate. Even small features (tens of meters across) in the near-shore bathymetry and coastal land topography can influence which parts of the coast will flood during a tsunami. Elevation data in these areas therefore need to be of much higher resolution than data for the deep ocean to build detailed coastal DEMs, fully model tsunamis, and make accurate coastal inundation maps.

The role of DEMs in preparing coastal communities for tsunamis

What happens when a tsunami strikes the coast? The wave, or a series of waves, slows down, turns toward the coastline, and the wave height increases dramatically. The tsunami then washes across the coastline to flood normally dry inland areas. So what can be done to prepare coastal communities for such an event? Providing forecasts and warnings during real tsunami events is the immediate step to take, and our DEMs are an integral part of this effort. Building coastal DEMs is also part of the longer-term process of enhancing coastal preparedness (figure 4).

We integrate seafloor and land survey data into representations of Earth's solid surface that cross the coastline. Tsunami modelers use our DEMs in suites of numerical simulation codes that are capable of simulating the three processes of tsunami evolution: 1) generation by an undersea earthquake, volcanic eruption, or submarine landslide; 2) transoceanic wave propagation; and 3) inundation of dry coastal areas. This is true for both real-time tsunami forecasting and coastal preparedness.

For tsunami forecasting, modelers rely on scenarios, such as a large earthquake in Alaska's Aleutian Islands or hypothetical events that pose a great risk to the community. From these scenarios, modelers generate a simulated wave, which propagates across the ocean basin and inundates coastal

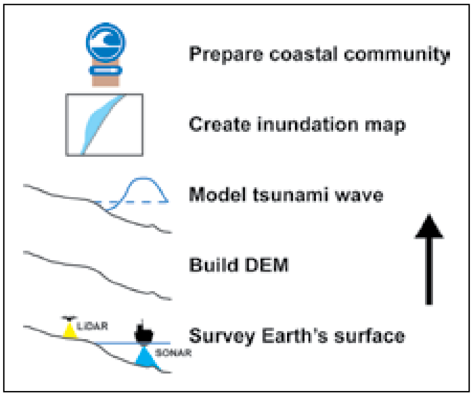

Figure 4. Digital elevation models are one step in the coastal preparedness process. Courtesy of NOAA NGDC.

DEMs (e.g., Bernard et al. 1994). During real events, measurements of the tsunami are compared with model results to identify the scenario that best matches the actual tsunami. The inundation results of that scenario are the basis for issuing forecasts and warnings.

For hazard assessment and community preparedness, the output from the various tsunami model scenarios is a series of inundation maps for the community, one for each tsunami scenario (e.g., Suleimani et al. 2002). These inundation maps are integrated into one community map showing the likelihood of flooding in various parts of the community. Local community planners and emergency responders can use inundation maps to prepare for the most likely, or largest, tsunami hazard facing their communities, including identifying evacuation routes and safe evacuation centers and posting evacuation signs communitywide.

Developing high-resolution coastal digital elevation models

NGDC began building high-resolution DEMs of select U.S. coastal regions in 2006 (e.g., Taylor et al. 2008d). Our team, in Boulder, Colorado, builds these integrated bathymetric–topographic DEMs to support tsunami modeling, forecasting, and warning efforts at the NOAA Center for Tsunami Research (`http://nctr.pmel.noaa.gov/tsunami-forecast.html`). The DEMs are part of the tsunami forecast system SIFT (Short-term Inundation Forecasting for Tsunamis) currently being

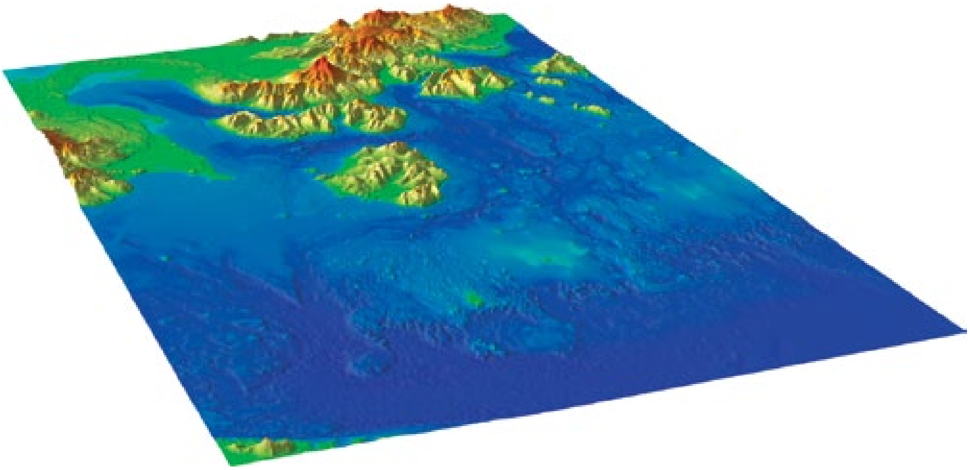

Figure 5. This is a perspective rendering of the King Cove, Alaska, DEM. Elevations range from 190 meters below sea level (dark blue) to 1,480 meters above sea level (red). Vertical exaggeration is times 2. Offshore bathymetry influences where and how the tsunami will strike the coast. High-resolution coastal inundation DEMs are digital representations of Earth's surface designed to capture near-shore and coastal morphologic features that may influence tsunami inundation. Because tsunami waves cross the coastline, the coastal DEMs must also span the coastline. Courtesy of NOAA NGDC.

developed by the NOAA Pacific Marine Environmental Laboratory (PMEL) for the NOAA Tsunami Warning Centers. The DEMs are used in the MOST (Method of Splitting Tsunami) model (Titov and Gonzalez 1997) developed by PMEL to simulate tsunami generation, propagation, and inundation (`http://nctr.pmel.noaa.gov/model.html`).

NOAA's real-time tsunami forecast system integrates coastal DEMs with deep-ocean wave observations from DART (Deep-ocean Assessment and Reporting of Tsunamis; `http://www.ndbc.noaa.gov/dart/dart.shtml`) buoys to provide detailed arrival time and inundation forecasts for specific coastal communities. This system provides accurate coastal forecasts well in advance of the wave arrival time (Wei et al. 2008). High-resolution DEMs are used to provide a baseline for testing the model before creating a lower-resolution version, which can simulate several hours of wave dynamics in less than ten minutes. These models are tested by comparison against tide gauge records of historical events, when this event data are available (Tang et al. 2008a, 2008b).

Figure 5 shows a perspective view of the integrated bathymetric-topographic DEM our team built for the King Cove, Alaska, area (Taylor et al. 2008a). To date, NGDC has built more than 30 tsunami inundation DEMs to support NOAA's tsunami forecast and warning efforts, which are accessible to the public at `http://www.ngdc.noaa.gov/mgg/inundation/`. The Web site also identifies U.S. communities where NGDC will build high-resolution coastal DEMs in the future.

Our high-resolution coastal DEMs are built to meet the requirements of the MOST model, relying upon high-resolution multibeam swath sonar bathymetric and aerial topographic lidar data where available. These requirements (table 1) include: 1) a global, geographic coordinate system rather than a local system (e.g., UTM zone), as tsunamis can propagate across ocean basins; 2) a mean high water (MHW) vertical datum for modeling of maximum flooding; 3) the ESRI ArcGIS ASCII grid file format; and 4) "bare earth" (i.e., buildings and trees are excluded from the DEM). Every cell in the DEM must be square in the geographic frame and contain an elevation value. The DEM also must be "seamless" at the coast. In other words, the DEM should not introduce a false ledge or step at the coastline. As described in more detail below, such artificial ledges can be introduced inadvertently unless appropriate precautions are taken when integrating the various elevation datasets.

Grid area	Lahaina, Hawaii
Coverage area	156.55° to 156.9° W; 20.7° to 21.1° N
Coordinate system	Geographic decimal degrees
Horizontal datum	World Geodetic System 1984 (WGS 84)
Vertical datum	Mean high water (MHW)
Vertical units	Meters
Cell size	1/3 arc-second
Grid format	ESRI ASCII raster grid

Table 1. These are the PMEL specifications for the Lahaina, Hawaii DEM. Courtesy of NOAA NGDC.

Steps in the DEM development process

We follow these basic steps in building our coastal DEMs:

1. Gather elevation data from multiple sources
2. Convert data to common file format and common horizontal and vertical datums (reference frames)
3. Evaluate and edit the data
4. Generate the DEM
5. Evaluate the DEM
6. Post the DEM online for public access and delivery to PMEL

Steps 3 through 5 are repeated iteratively numerous times as anomalies or artifacts are found in preliminary DEMs, their cause determined, data corrected, and a new version of the DEM created. Some problems cannot be overcome, typically due to data limitations, and are so noted in the reports that we write describing how each DEM is built. We must also address the problem that land and marine elevation data in the coastal zone are typically referenced to different vertical datums, and is collected by different instruments on different platforms and in different terrestrial environments.

1) Gather elevation data from multiple sources

We develop our coastal DEMs using the best available digital elevation data, obtaining coastline, bathymetric, topographic, and shoreline-crossing data from numerous federal, state and local government agencies, universities, and private companies (table 2). Data are assessed for quality and accuracy both within each dataset and between datasets to ensure consistency and gradual topographic transitioning along the edges of datasets.

Topographic data we typically use include topographic grids of the U.S. Geological Survey (USGS) National Elevation Dataset (NED; `http://ned.usgs.gov/`), the NASA Space Shuttle Topography Mission (SRTM; `http://srtm.usgs.gov/`), and high-resolution (1- to 10-meter point spacing) lidar surveys flown from aircraft. These data commonly include values over water bodies (typically zero for NED and SRTM grids) or water surface returns (lidar), which we remove using a detailed coastline. We assemble the coastline from various datasets and manually adjust it to match our best coastal elevation dataset, typically a high-resolution coastal lidar survey flown at low tide.

Lidar is the principal method used in the United States for mapping land topography. An aerial lidar pulse bounces off land features and is returned to the aircraft (figure 6A). The return includes the tops of vegetation (trees, bushes, etc.), buildings, and other human-made structures. The effects of such features on tsunami waves are not clearly understood and cannot be modeled accurately, so tsunami modelers usually require them to be removed from the DEMs. Such a surface free of trees and buildings is referred to as "bare earth." A large part of the data processing necessary to build a bare-earth tsunami inundation DEM is removing trees and buildings from the lidar survey data.

The USGS NED topography represents this bare-earth ground surface, while the SRTM topography includes vegetation and buildings.

Recently, the U.S. Army Corps of Engineers' Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX; `http://shoals.sam.usace.army.mil/`) began employing a lidar system capable of measuring the seafloor in the shallow coastal zone (through the water down to roughly 20 to 30 meters). JALBTCX is now using this system as part of the CHARTS (Compact Hydrographic Airborne Rapid Total Survey; Heslin et al. 2003) Program to map U.S. and international shallow coastal zones in high detail. This has been historically difficult to do, as survey ships typically cannot safely navigate in very shallow water, resulting in a data gap between offshore bathymetric soundings and the coastline. As bathymetric features in this shallow zone can affect tsunami waves, this new data type significantly improves the accuracy of the DEMs and subsequent tsunami modeling results.

Multibeam swath sonar is the primary tool used today to map the deeper seafloor. This is generally accomplished from a GPS-navigated ship, with hull-mounted sonar sending out a "ping" at right angles to the ship track (figure 6B). The sonar records multiple returns ("beams") from the seafloor, which can be used to calculate the seafloor depth across the ship track. Pings occur several seconds apart. As the ship moves between pings, a swath of the seafloor along the ship track is surveyed—hence the term "multibeam swath." Multiple tracks some distance apart are usually sufficient to completely map a region.

DATA TYPE	SOURCE	HORIZONTAL DATUM	VERTICAL DATUM	YEAR
Lidar topography	Horry County, South Carolina	South Carolina State Plane (feet)	NAVD88	2005
National Elevation Dataset topography	U.S. Geological Survey	NAD 83 geographic	NAVD88	1970s–80s
Mean High Water coastline	National Geospatial-Intelligence Agency	NAD 83 geographic	Mean high water	1998–2002
Shoreline-crossing beach profiles	Coastal Carolina University	South Carolina state plane (feet)	NAVD88	2006
	Coastal Science & Engineering Inc.	South Carolina state plane (feet)	NGVD29	2005
Hydrographic surveys	National Ocean Service, NOAA	NAD 83 geographic	Mean low water	1925–72
	U.S. Army Corps of Engineers	South Carolina state plane (feet)	Mean low water	2005–06
Interferometric sonar surveys	U.S. Geological Survey	UTM Zone 17 (meters)	Mean lower low water	1999–2003
Digitized soundings and features	National Geophysical Data Center, NOAA	WGS 84 geographic	Mean high water	2006

Table 2. The Myrtle Beach, South Carolina, DEM was built using these datasets. Courtesy of NOAA NGDC.

Of critical importance is proper measuring of the speed at which sound travels through the water, as sonar systems actually record travel time. Sound speed in the water is dependent upon seawater temperature, pressure, and salinity. Pressure varies as a function of depth, and salinity is mostly constant, while temperature varies with depth, currents, time of day, etc. During seafloor mapping surveys it is generally ideal to measure water temperature at least once a day or with changing weather conditions.

Also consider that sonar sends out a cone/triangle of sound that expands with depth. Thus, in shallow water the triangle is narrow and the beams/depths are closely spaced. In deep water the triangle is significantly wider and the beams/depths are farther apart. As a result, multibeam swath sonar provides more detail in shallow waters while revealing more of the seafloor in deeper water. However, a small feature that may affect a tsunami wave in shallow water will have much less impact in deep water, so the effect of an "expanding triangle with depth" (figure 6) is not that significant for tsunami modeling.

Our team relies on several bathymetric databases to build coastal DEMs, most of which are located at NGDC. NOAA's National Ocean Service (NOS) is responsible for ensuring safe navigation in U.S. coastal waters. The agency does this by conducting bathymetric surveys to identify navigational hazards and by publishing nautical charts. The database of NOS hydrographic surveys (`http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html`) is managed by NGDC. Global multibeam swath sonar survey data, primarily collected by academic institutions, are also archived, managed and disseminated to the public by NGDC (`http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html`). Other sources of bathymetry include the USGS and the U.S. Army Corps of Engineers.

Beach profiles—long transects that start on land and run offshore—are particularly valuable for capturing the relief of Earth's surface in the coastal zone. These profiles typically have very high

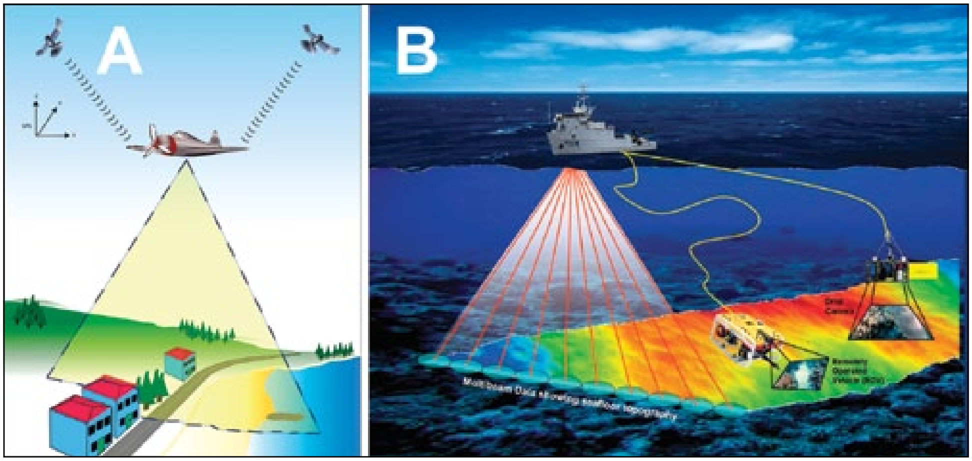

Figure 6. This figure illustrates (A) an airborne topographic lidar survey and (B) a ship-borne bathymetric multibeam swath sonar survey. Courtesy of NOAA NGDC.

resolution along the profile (elevations every meter or so) but can be widely spaced (hundreds of meters apart). This is generally not a problem, as coasts tend to have fairly consistent "beach faces" over long intervals. These beach profiles can also capture migratory or short-lived small sand features that do not represent the long-term beach morphology. What these profiles do add, however, is the ability to tie land and bathymetry survey data together to a common vertical datum and help ensure that the coastal zone in the DEM is truly seamless. In other words, if either the land or seafloor data are not consistent with the beach profiles after vertical datum conversion to MHW, then there is a problem somewhere. Without shoreline-crossing beach profiles, it can be difficult to determine the vertical accuracy of near-shore data and uncover problems with the vertical datum conversion. Most beach-profile data are collected by research scientists and may be available through their academic institutions.

2) Convert data to common file format and common horizontal and vertical datums (reference frames)

A common question when taking an elevation measurement is "Where on Earth am I?" Fundamentally, the answer is "I'm somewhere relative to somewhere else." Positions on Earth's surface have to be defined relative to something, which is called a "datum" (a reference frame or coordinate system). Horizontal datums include: 1) geographic coordinates, such as the World Geodetic System of 1984 (WGS 84) and North American Datum of 1983 (NAD 83), measured in latitude and longitude degrees; and 2) local datums, such as UTM zones (Universal Transverse Mercator), usually measured in meters from specified positions on Earth's surface. Vertical datums include tidal, geodetic, geoid, and ellipsoid.

Because elevation data are collected by numerous methods, in different environments, at various scales and resolutions, and for multiple purposes, it is referenced to a wide variety of horizontal and vertical datums. Building of accurate, reliable, and seamless coastal DEMs requires that the data be converted to common horizontal and vertical datums and to common units and file formats (for gridding and visualization).

The relationships and transformational equations between horizontal datums are well established, and most GIS software can readily perform the needed mathematical transformations. Converting between land (geodetic) and bathymetric (tidal) vertical datums requires leveling of a tide station to the local geodetic datum. Figure 7 illustrates how tidal datums are tied to geodetic datums. For the continental United States, Canada, and Mexico, the geodetic datum is North American Vertical Datum of 1988 (NAVD88). Puerto Rico, the U.S. Virgin Islands, Hawaii, and Alaska (for the most part) are not leveled to NAVD88, and land elevations are typically assumed to be roughly equivalent to mean sea level (MSL), though NOAA's National Geodetic Survey is currently establishing geodetic reference frames for Puerto Rico and the U.S. Virgin Islands. Bathymetric soundings, on the other hand, are typically referenced to mean lower low water (MLLW), so that ship captains know the least depth they may encounter to avoid running aground. For the DEM to be seamless at the coastline, land and seafloor elevation data must be converted to a common vertical datum. If a common vertical datum is not established, a false ledge or step may be introduced at the coast; the size of the vertical offset between the two datums may be one meter/three feet or more. Using a DEM that contains such a datum step can cause the modeled tsunami wave to behave differently than a real one would, resulting in an inaccurate prediction of coastal inundation.

The tsunami inundation modeling software MOST requires a horizontal datum of WGS 84 for consistency with ocean-spanning DEMs and a vertical datum of mean high water (MHW) for modeling of maximum flooding. We use Safe Software's (`http://www.safe.com/`) Feature Manipulation Engine (FME) to convert datasets to NAD 83/WGS 84; the difference between these two geographic datums is insignificant at DEM scales. FME is also used to convert point elevation data to ESRI (`http://www.esri.com/`) ArcGIS shapefile format and elevation grids or DEMs to ESRI raster format for GIS visualization and assessment.

Where available, we use VDatum (`http://vdatum.noaa.gov/`) to convert between various tidal and geodetic vertical datums. VDatum is a tool developed for vertical datum conversion in U.S. coastal areas, though it does not yet provide complete coverage of the U.S. coastal zone. In areas without VDatum, we use either constant offsets of the tidal relationships recorded at scattered NOAA tide stations (`http://tidesandcurrents.noaa.gov/`) or sloping grids that interpolate between the tide stations.

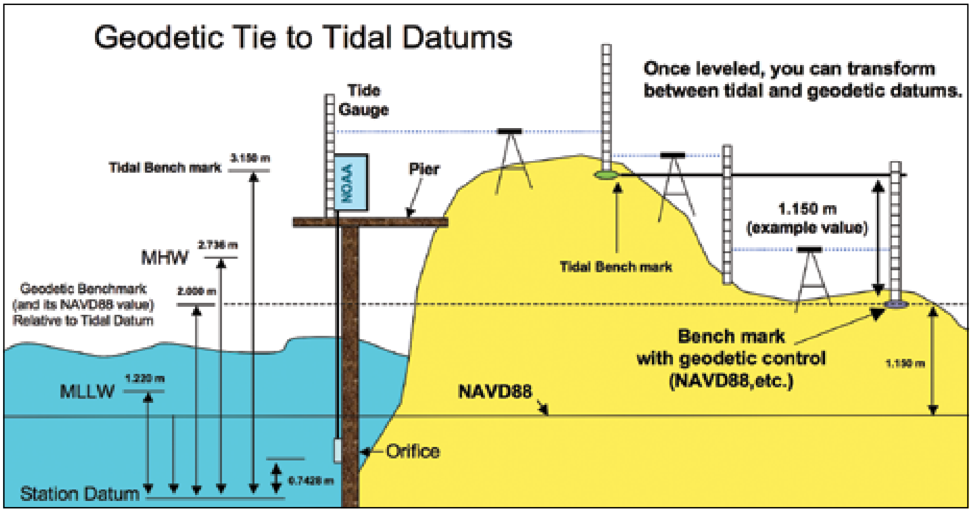

Figure 7. This example of the relationship between tidal and geodetic vertical datums shows a local tide station measuring normal wave-height variability and calculating mean lower low water, and mean high water. Leveling of a tide station's benchmarks to an established geodetic network (e.g., a survey station with a measured geodetic height) permits conversion between the vertical datums. In this case, MHW is 1.886 meters (0.736 + 1.150) above NAVD88, so an NAVD88 height of 4.886 meters is equivalent to a MHW height of just 3 meters (4.886 − 1.886). Courtesy of NOAA NGDC.

3) Evaluate and edit the data

The most time-consuming and difficult part of building high-resolution coastal DEMs is evaluating and editing the various elevation datasets. We rely on ArcGIS and Applied Imagery's (`http://www.appliedimagery.com/`) Quick Terrain Modeler for GIS visualization, comparison, and editing of the datasets.

We have encountered many dataset problems in the course of building some thirty coastal DEMs to date. These problems fall into several broad categories: 1) gross errors in the elevation of single points; 2) values representing the water surface, rather than the seafloor; 3) values representing buildings or vegetation, not the ground surface; 4) morphologic and anthropogenic change that has occurred since the survey data were collected; and 5) incorrect or incomplete metadata, such as misidentified or undefined datums.

Older NOS hydrographic surveys, dating to the late nineteenth century, were conducted before the advent of digital technology (ca. 1965). Many of these surveys were subsequently hand-digitized by contractors from the original paper survey charts; for those surveys without digital representation, we occasionally hand-digitize soundings from the original hydrographic survey charts for inclusion in the DEM. Although previously digitized soundings are compared to the paper charts for accuracy, some errors nevertheless remain. Figure 8 illustrates the results of one such error that we discovered during the building of a coastal DEM for King Cove, Alaska.

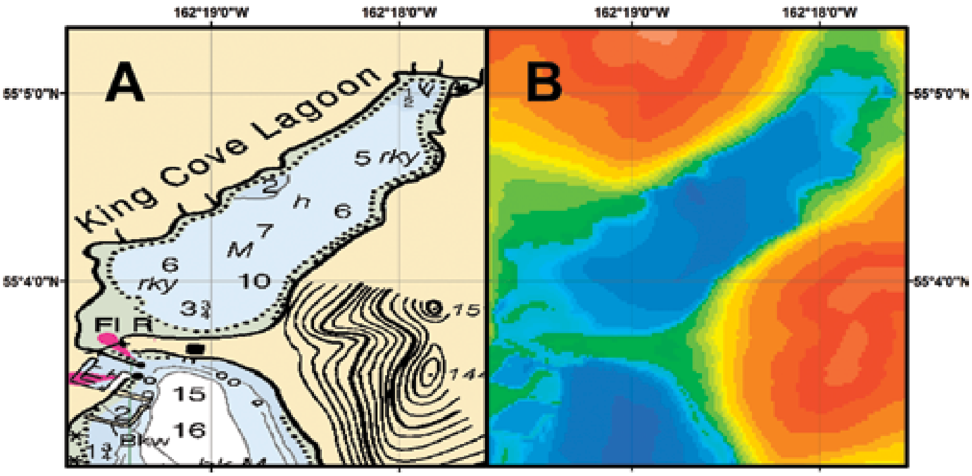

Figure 8. The sounding "2" on the chart along the northwestern margin of King Cove Lagoon (A) had been improperly digitized as "20" in this survey, resulting in an anomalous deep (dark blue) in the DEM (B). This sounding was corrected before building a new DEM for this area. Courtesy of NOAA NGDC.

Figure 9 illustrates the inclusion of values for the water surface in datasets. In this case, elevation grids from the SRTM, flown by NASA in February 2000 (`http://www2.jpl.nasa.gov/srtm/`), have "zero" values over the open ocean (blue) near Dutch Harbor, Alaska (Taylor et al. 2008c). Many topographic datasets include such ocean-surface values, especially lidar data. We remove these values by clipping such datasets to a detailed coastline of the region, which we typically have to develop ourselves.

Another problem, inherent particularly in older datasets, is morphologic change after data collection. Figure 10 illustrates one such case near Myrtle Beach, South Carolina, where a short channel connecting two rivers shifted between 1934, when the original NOS hydrographic survey was conducted, and 2005, when a topographic lidar survey measured the area (Taylor et al. 2008e). Morphologic change may occur as a result of: 1) channel dredging to maintain safe shipping; 2) the building of jetties that block the along-shore migration of beach sand; 3) major river flooding

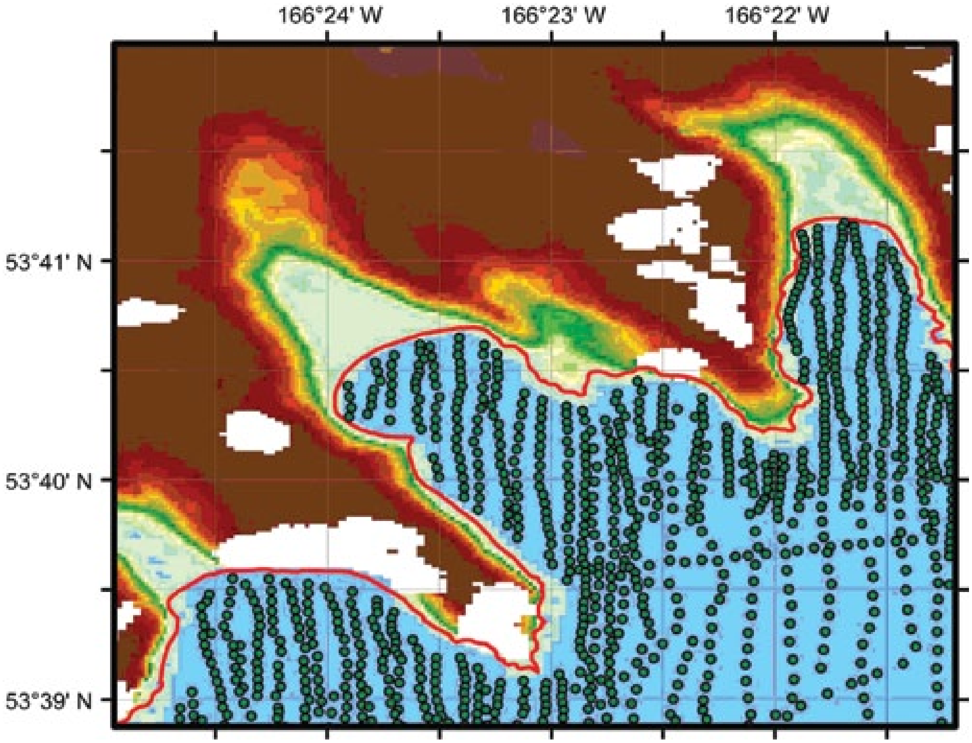

Figure 9. For this example of elevation values in SRTM grids along the Aleutian coast near Dutch Harbor, Alaska, ocean-surface values are blue. NOS hydrographic soundings are represented by green dots. Note the gaps (white) in the SRTM data, which are another problem inherent to this dataset. The coastline is in red. We clip the SRTM data to the coastline to eliminate these ocean-surface values. Courtesy of NOAA NGDC.

that erodes banks and causes river channel migration; and 4) strong hurricanes and accompanying storm surges that transport, deposit, or erode coastal sands, completely reworking coastal sandbars and opening or closing entrances to harbors. Some modern, ultrahigh-resolution lidar surveys can even capture the small, natural, onshore-offshore seasonal transport of sand throughout the year.

4) Generate the DEM

After carefully evaluating the elevation point datasets, we build the DEMs by creating a digital surface (blanket) over the scattered data. This gridding process includes the averaging of multiple points into a single value if they fall within one grid cell (the fundamental DEM unit), or interpolating between cells if the point data are far apart—this occurs frequently in deep water, where soundings can be sparse. The elevation value of each cell is considered to span the entire cell,

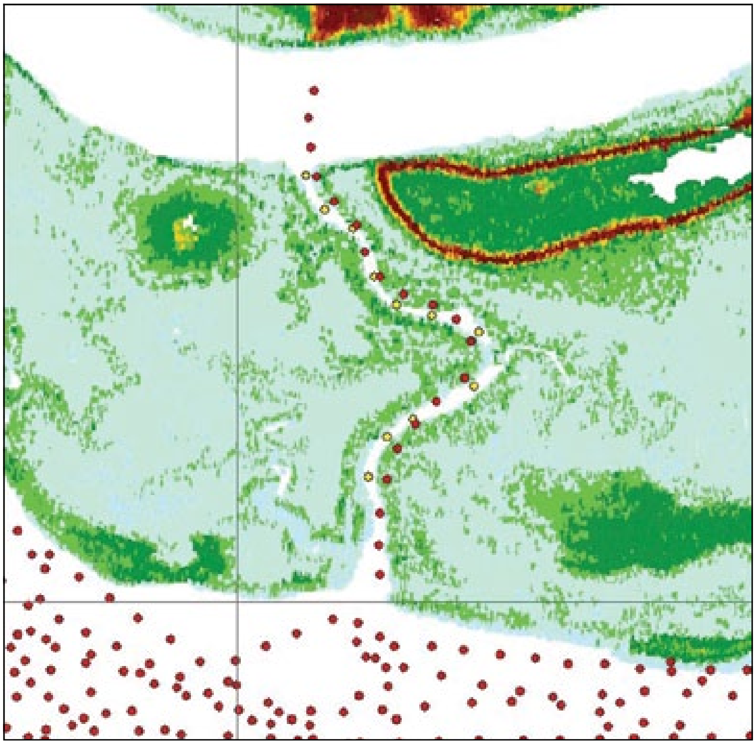

Figure 10. In this example of morphologic change, an NOS hydrographic survey in Horse Ford Channel, South Carolina, 1934 (red dots), is inconsistent with a 2005 topographic lidar survey, indicating that the channel has migrated over time. Because there has not been a more recent bathymetric survey of this channel, we manually shifted the hydrographic soundings to the center of the channel (yellow dots) for its representation in the Myrtle Beach DEM. Courtesy of NOAA NGDC.

creating a quilt of adjoining cells that are the DEM. Multiple software applications and techniques are available for creating this grid surface. NGDC uses GMT (Generic Mapping Tools; `http://gmt.soest.hawaii.edu/`) and MB-System (`http://www.ldeo.columbia.edu/res/pi/MB-System/`)—software applications funded by the National Science Foundation—to build the DEMs using a tight spline tension. MB-System is specifically designed to manipulate multibeam swath sonar data, though it can use a wide variety of data types, including ASCII xyz data.

Many datasets have data point spacings much larger than required for the coastal DEMs. This is especially true of bathymetric datasets, whose soundings are commonly quite sparse in deep water; NOS hydrographic soundings in deep water may be hundreds of meters apart. Shoreline-crossing beach profiles typically have point spacings on the order of a meter or less; however, profiles themselves may be spaced up to a kilometer apart. These datasets are separately surfaced with GMT to

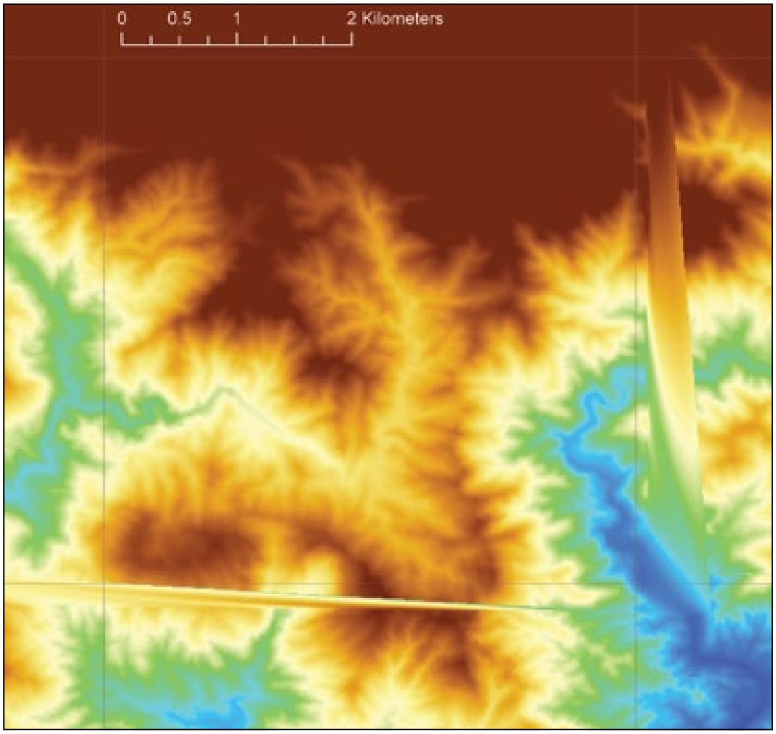

Figure 11. Here, artifacts are introduced by gridding without a data buffer. In this case, smaller DEMs were created by "tinning" (creating triangles between elevation points) without any buffer. This process connected disparate points where data gaps occurred along the edges of the smaller DEMs. These DEMs were then mosaicked together to build a larger DEM that contains gross artifacts along the edges of the smaller DEMs. Courtesy of NOAA NGDC.

infill regions between the data with estimated elevation values. The resulting pre-grids are closely cropped to the spatial extent of the data coverage area to prevent extrapolation into areas covered by other datasets.

The importance of having a data buffer surrounding the DEM cannot be overstated as the gridding algorithms need it to ensure interpolation across, rather than along, DEM boundaries (figure 11). We routinely seek and gather elevation data that lie within a box that is at least 5 percent larger than our final DEM boundary to avoid such edge effects.

5) Evaluate the DEM

We evaluate the DEMs with ArcGIS and FME, through visual inspection, comparison with source datasets (figure 12), and comparison with independent datasets, such as geodetic monuments and tidal bench marks. Where problems are discovered, we inspect the underlying datasets to determine the cause of the problem. As noted above, a DEM might contain errors for many reasons. We typically build twenty or more preliminary DEMs, each time discovering, tracking down, and fixing underlying data errors, before we consider a DEM acceptable.

6) Post the DEM online for public access and delivery to the PMEL

We post our completed coastal DEMs for public access on the NGDC Tsunami Inundation Gridding Project Web site (`http://www.ngdc.noaa.gov/mgg/inundation/`). Visitors may download the DEMs, with their corresponding metadata and detailed documentation, and search the site to learn which DEMs are completed or planned. We have also created the DEM Discovery Portal (`http://www.ngdc.noaa.gov/mgg/dem/`), an ESRI ArcIMS geospatial viewer for locating Web-published DEMs built by NOAA and other agencies.

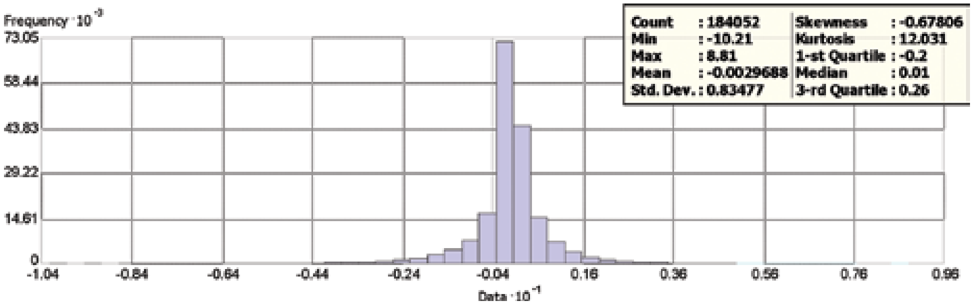

Figure 12. This histogram shows the differences between a coastal lidar survey file and the Montauk, New York, DEM. Differences cluster around zero, with only a handful of values—in regions where buildings are present and/or where several closely spaced elevation values are averaged—exceeding 2-meter discrepancy from the DEM. Courtesy of NOAA NGDC.

DEM uses

The integrated bathymetric–topographic DEMs that our team builds are intended for tsunami modeling, forecasting, and warning. However, because we have put much effort into ensuring DEM accuracy, quality, and seamlessness at the coast, these DEMs may be suitable for other purposes as well. These include hurricane storm-surge modeling, river flooding, and sea-level rise studies. Some common questions about our development of coastal DEMs include, "Why are you building tsunami inundation DEMs for the U.S. East Coast?", "Is there a high risk of tsunamis hitting the East Coast?", and "Should I sell my Long Island home?" Part of the answer is that NOAA is responsible to the nation for preparing all U.S. coasts for potential tsunamis, including the East Coast. Although the risk there is low, it is not zero (Dunbar and Weaver 2008). Submarine landslides have occurred along the eastern seaboard's continental slope in the recent geologic past, and present a locally generated tsunami threat (Driscoll et al. 2000). Tsunamis have occurred numerous times in the Caribbean since 1500, killing more people than all of the recorded tsunami fatalities in Alaska, Hawaii, and the West Coast (Lander 1997). Puerto Rico experienced one of the most deadly Caribbean tsunamis on October 11, 1918, (Reid and Taber 1919; National Geophysical Data Center 2009) after an earthquake at the western end of the island. Such events will likely occur again (Dunbar and Weaver 2008; Mercado-Irizarry and Liu 2007).

While a major earthquake, landslide, or volcanic eruption in the Caribbean is not likely to create a 30-to-50 meter-high tsunami striking Long Island, New York—like the devastating one that hit Indonesia in 2004—it could create a roughly meter-high tsunami there. Even small tsunamis have the potential to cause considerable damage. The Kuril Islands magnitude 8.3 earthquake of November 15, 2006, created a small tsunami near Japan that traveled across the Pacific, striking Hawaii and California with unusually strong currents and waves nearly two meters high in a few places. As a result, a swimmer in Hawaii was roughly drug into a seawall, and some docks in Crescent City were damaged or destroyed (USA Today 2006). The NOAA Tsunami Watch issued for Hawaii was cancelled prior to the tsunami landfall there, though small sea-level changes and strong or unusual currents were listed as possible for some coastal areas. Local emergency response personnel alerted swimmers to leave the waters and the beach, but no large-scale coastal evacuation was mandated or necessary: the forecast was accurate and emergency response appropriate. Similarly for the U.S. East Coast, the potential location of coastal flooding, even in a small event, needs to be identified and provided to local community planners and emergency personnel in advance so that they can plan for and provide the appropriate warnings and response in case of a real event.

The future of DEMs

What does the future hold for DEMs? Obviously, they will become more accurate as more detailed surveys of the coastal zone are conducted in the coming years, especially with the advent of new elevation measuring instruments and advanced processing techniques. Improvements will also occur in determining the relationships between different vertical datums. But more importantly, the next-generation of coastal DEMs will need to include estimates of uncertainty in the elevation value assigned to each cell. Are they accurate to within 1 meter, a tenth of a meter, 10 meters? Are they more accurate in some areas and less accurate in others? How will these uncertainties translate into uncertainties in the location of the coastal inundation line from different tsunami modeling scenarios? In other words, can community planners and emergency responders rely on the accuracy of the coastal inundation lines that tsunami modelers give to them? These are the kinds of questions that we and other coastal DEM builders are asking ourselves so that we can meet the challenges ahead.

References

Bernard, E.N., ed. 2005. *Developing tsunami-resilient communities*. Springer, The Netherlands, 184 pp.

Bernard, E., C. Mader, G. Curtis, and K. Satake. 1994. *Tsunami inundation model study of Eureka and Crescent City, California*, NOAA Technical Memorandum ERL PMEL–103, Seattle, 80 pp.

Driscoll, N. W., J. K. Weissel, and J. A. Goff. 2000. Potential for large-scale submarine slope failure and tsunami generation along the U.S. mid-Atlantic coast. *Geology 28*: 407–410.

Dunbar, P. K., and C. S. Weaver. 2008. *U.S. States and Territories National Tsunami Hazard Assessment: historical record and sources for waves*. NOAA Tsunami Program Special Report, U.S. Department of Commerce, NOAA, National Geophysical Data Center, Boulder, Colo.

Dunbar, P. K., K. J. Stroker, V. R. Brocko, J. D. Varner, S. J. McLean, L. A. Taylor, B. W. Eakins, K. S. Carignan, and R. R. Warnken. 2008. Long-term tsunami data archive supports tsunami forecast, warning, research and mitigation. *Pure and Applied Geophysics 165*, 2275–2291.

Gonzalez, F. I., E. N. Bernard, C. Meinig, M. C. Eble, H. O. Mofjeld, and S. Stalin. 2005. The NTHMP Tsunameter Network. In *Developing tsunami-resilient communities*, ed. E. N. Bernard. Springer, The Netherlands, 25–39.

Guardian News. 2009. Indian Ocean Tsunami 2004. Guardian News, United Kingdom. `http://www.guardian.co.uk/world/tsunami2004`.

Heslin, J. B., W. J. Lillycrop, and R. W. Pope. 2003. CHARTS: An evolution in airborne lidar hydrography. *Proceedings of the U.S. Hydro 2003*. The Hydrographic Society of America, March 24–27, Biloxi, Mississippi, paper 5.2, 4 pp.

Lander, J. 1997. *Caribbean tsunamis: an initial history*. Presented at the Caribbean Tsunami Workshop, June 11–13. Sponsored by Sea Grant College Program, University of Puerto Rico.

Lander, J. F., and P. A. Lockridge. 1989. *United States Tsunamis*. Publication 41–2. U.S. Department of Commerce.

Mercado-Irizarry, A., and P. Liu, eds. 2007. *Caribbean tsunami hazard*. Proceedings of the NSF Caribbean Tsunami Workshop, San Juan, Puerto Rico, March 30–31, 2004, 364 pp.

National Geophysical Data Center. 2009. *NOAA/WDC Historical Tsunami Database at NGDC*. NOAA National Geophysical Data Center, Boulder, Colorado. `http://www.ngdc.noaa.gov/hazard/tsu_db.shtml`.

Reid, H. F., and S. Taber. 1919. *The Porto Rico earthquake of 1918*. House of Representatives, 66th Congress, 1st Session. Document No. 269. November 19, 1919.

Suleimani, E. N., R. A. Hansen, R. A. Combellick, and G. A. Carver. 2002. *Tsunami hazard maps of the Kodiak area, Alaska*: Alaska Division of Geological & Geophysical Surveys Report of Investigation 2002–1, 16 p., 4 sheets, scale 1:12,500. `http://www.dggs.dnr.state.ak.us/pubs/pubs?reqtype=citation&ID=2860`.

Tang, L., C. Chamberlin, and V. V. Titov. 2008. *Developing tsunami forecast inundation models for Hawaii: Procedures and testing*. NOAA Tech. Memo. OAR PMEL–141, 46 pp. `http://www.pmel.noaa.gov/pubs/PDF/tang2985/tang2985.pdf`.

Tang, L., V. V. Titov, Y. Wei, H. O. Mofjeld, M. Spillane, D. Arcas, E. N. Bernard, C. Chamberlin, E. Gica, and J. Newman. 2008. Tsunami forecast analysis for the May 2006 Tonga tsunami. *Journal of Geophysical Research*, 113, C12015, doi: 10.1029/2008JC004922.

Taylor, L. A., B. W. Eakins, K. S. Carignan, R. R. Warnken, T. Sazonova, and D. C. Schoolcraft. 2007. *Digital elevation model of Montauk, New York: Procedures, data sources, and analysis*. NOAA National Geophysical Data Center, Boulder, 25 pp. `http://www.ngdc.noaa.gov/mgg/inundation/tsunami/data/montauk_ny/montauk_ny.pdf`.

Taylor, L. A., B. W. Eakins, K. S. Carignan, R. R. Warnken, T. Sazonova, and D. C. Schoolcraft. 2008a. *Digital elevation model of King Cove, Alaska: Procedures, data sources, and analysis*. NOAA National Geophysical Data Center, Boulder, 25 pp. `http://www.ngdc.noaa.gov/mgg/inundation/tsunami/data/king_cove_ak/king_cove_ak.pdf`.

Taylor, L. A., B. W. Eakins, K. S. Carignan, R. R. Warnken, T. Sazonova, and D. C. Schoolcraft. 2008b. *Digital elevation model of Lahaina, Hawaii: Procedures, data sources, and analysis*. NOAA Technical Memorandum NESDIS NGDC-10, Boulder, 19 pp. `http://www.ngdc.noaa.gov/mgg/inundation/tsunami/data/lahaina_hi/lahaina_hi.pdf`.

Taylor, L. A., B. W. Eakins, K. S. Carignan, R. R. Warnken, D. C. Schoolcraft, T. Sazonova, and G. F. Sharman. 2008c. *Digital elevation model of Dutch Harbor, Alaska: Procedures, data sources, and analysis*. NOAA Technical Memorandum NESDIS NGDC–4, Boulder, 25 pp. `http://www.ngdc.noaa.gov/mgg/inundation/tsunami/data/dutch_harbor_ak/dutch_harbor_ak.pdf`.

Taylor, L. A., B. W. Eakins, K. S. Carignan, R. R. Warnken, D. C. Schoolcraft, and G. F. Sharman. 2008d. *Digital elevation model of Port San Luis, California: Procedures, data sources, and analysis*. NOAA Technical Memorandum NESDIS NGDC–3, Boulder, 24 pp. `http://www.ngdc.noaa.gov/mgg/inundation/tsunami/data/port_san_luis_ca/port_san_luis_ca.pdf`.

Taylor, L. A., B. W. Eakins, K. S. Carignan, R. R. Warnken, G. F. Sharman, D.C . Schoolcraft, and P. W. Sloss. 2008e. *Digital elevation models of Myrtle Beach, South Carolina: Procedures, data sources, and analysis*. NOAA Technical Memorandum NESDIS NGDC–1, Boulder, 19 pp. `http://www.ngdc.noaa.gov/mgg/inundation/tsunami/data/myrtle_beach_sc/myrtle_beach_sc.pdf`.

Titov, V. V. 2009. Tsunami Forecasting, *The sea, volume 15: Tsunamis*. Harvard University Press, Cambridge, Mass., and London, England, 371–400.

Titov, V. V., and F. I. Gonzalez. 1997. *Implementation and testing of the method of splitting tsunami (MOST) model*, NOAA Technical Memorandum ERL PMEL–112, Seattle, 11 pp. `http://www.pmel.noaa.gov/pubs/PDF/tito1927/tito1927.pdf`.

Titov, V., A. B. Rabinovich, H. O. Mofjeld, R. E. Thomson, and F. I. Gonzalez. 2005. The global reach of the 26 December 2004 Sumatra tsunami. *Science 309*: 2045–2048.

USA Today. 2006. Small tsunami hits Hawaii; ocean surges off California coast after Japan quake. USA Today, McLean, Va. `http://www.usatoday.com/news/nation/2006-11-16-hawaii-tsunami_x.htm`.

Wei, Y., E. Bernard, L. Tang, R. Weiss, V. Titov, C. Moore, M. Spillane, M. Hopkins, and U. Kânoğlu. 2008. Real-time experimental forecast of the Peruvian tsunami of August 2007 for U.S. coastlines. *Geophysical Research Letters 35*, L04609, doi: 10.1029/2007GL032250.