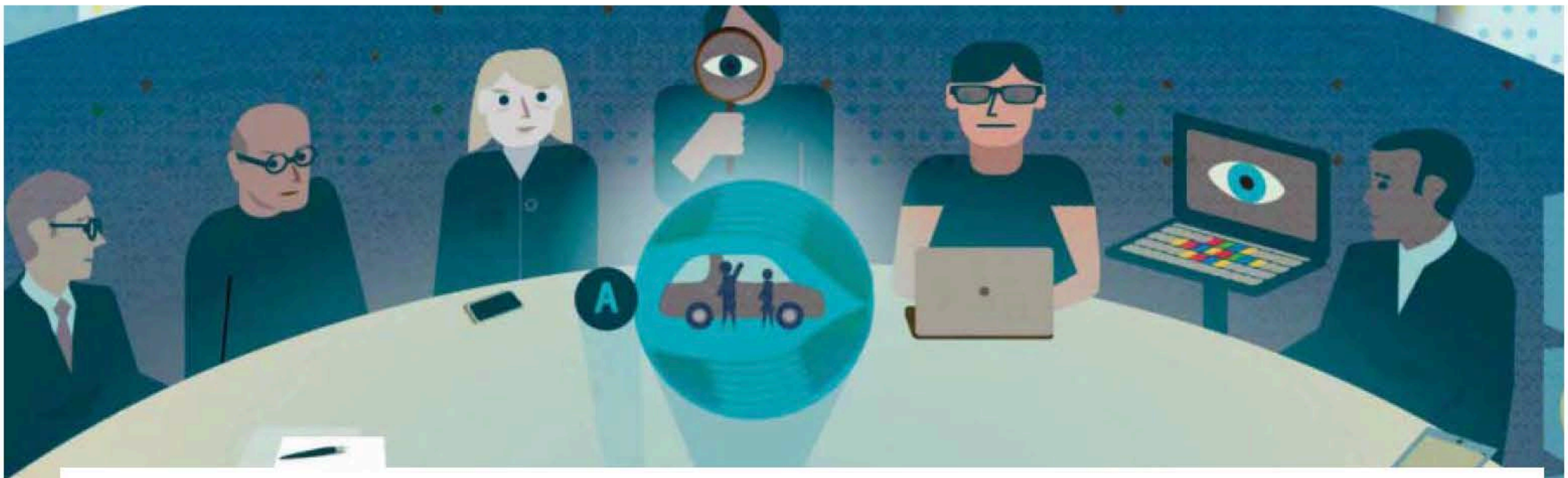

Protecting Our Shorelines: Modeling the Effects of Tsunamis and Storm Waves

Dylan Keon, Cherri M. Pancake, and Harry Yeh, Oregon State University

Predicting the complex behavior and aftermath of coastal tsunamis and storm surges is inherently difficult. Real-time disaster warning requires rapid computation with reliable accuracy and effective output presentation. The authors present two ways to leverage high-performance computing resources to address these challenges.

In the US, 123 million people live in counties with ocean shorelines, requiring massive infrastructure investments to support and protect those populations. Nevertheless, tsunamis, storm waves associated with hurricanes and nor'easters, and other extreme wave events can induce destructive flooding causing billions of dollars in damage. When Hurricane Sandy struck New York and New Jersey in 2012, the catastrophic storm surge resulted in damages exceeding US$71 billion.[1] Indirect damages—such as the flooding of the New York subway system and the two-day closure of the New York Stock Exchange—caused even greater economic impact.

The 2011 East Japan tsunami killed more than 18,000 people and caused economic setbacks in the range of US$195–305 billion.[2] Coastal infrastructures designed to protect against tsunamis, such as breakwaters, seawalls, and dykes, were breached, and reinforced concrete buildings engineered to be "invulnerable" to tsunamis were toppled. Most notably, the Fukushima Daiichi Nuclear Power Plant failure released radioactive contamination, forcing residents to abandon nearby cities, towns, and

THE DIFFICULTY OF TRANSLATING THEORY INTO PRACTICE

The tsunami inundation maps needed to plan evacuation routes and strategies are typically based on a single credible worst-case scenario. The inundation zone for storm surges is determined similarly, but uses the National Oceanic and Atmospheric Administration's (NOAA's) five standard hurricane category levels to establish evacuation zones well in advance.

However, the devastating building and infrastructure damage caused by the East Japan tsunami in 2011, Hurricane Katrina in 2005, and Hurricane Sandy in 2012 proved that identifying inundation zones alone does not adequately address the potential risk sources (see Figure A). The failure of critical coastal infrastructures (major bridges, ports, fuel storage facilities, power plants, and so forth) not only causes enormous economic setbacks but also triggers secondary life-threatening situations.

Analyzing buildings' and infrastructures' likely resistance requires not just maximum run-up heights and inundation zones but also time histories of water-flow depths and velocities to establish the likely strength of the water's force. Flow depth and velocity measurements are more difficult to compute than maximum inundation limits and are thus the focus of active research.

Additional challenges must be addressed before theoretical results can be translated into practice. Engineering design is governed by guidelines that indicate the stresses a structure must be able to withstand, as well as how frequently forces of that magnitude might occur—similar to the way insurers describe the "100-year" floodplain. The American Society of Civil Engineers and US Department of Transportation are developing guidelines based on 1,000- and 2,500-year events for tsunamis; hurricane storm surges are normally evaluated using 50-, 100-, and 500-year events. With a lack of a sufficient number of historical events, developing a reliable probabilistic analysis for hurricanes is challenging—and even more so for tsunamis. Current guidelines are based on inundation depths alone and are necessarily very conservative. We need more cost-effective guidelines based on time-series analysis of stresses at different moments during the wave event.

(a)

(b)

Figure A. Extreme wave forces destroy even well-built buildings and infrastructure. (a) 2011 East Japan tsunami water and water-borne debris obliterated most coastal structures across a wide area. (Source: photo by Harry Yeh.) (b) The 2005 Hurricane Katrina storm surge destroyed even reinforced concrete bridges and roadways. (Source: photo by Hermann Fritz.)

villages. Four years later, the radiation remains uncontrolled, and decommissioning the reactors would cost upward of US$15 billion.[3] This accident also triggered the shutdown of all nuclear power plants in Japan; as of this time, none has been reactivated.

HIGH-PERFORMANCE COMPUTING FOR HAZARD PREDICTION AND MITIGATION

Given their devastating economic and societal impact, tsunamis and extreme storm-induced waves cannot be ignored. Although impossible to prevent, storm-related damage can be reduced through technology paired with thoughtful preparation. In this article, we address the challenges of modeling the highly complex, multiscale behavior of extreme coastal hazards. In particular, we discuss how high-performance computational, data and networking resources—collectively referred to as *high-performance computing* (HPC)—can advance hazard prediction and mitigation. We include both tsunami and storm wave hazards because, although their characteristics are distinct, their effects are similar.

Aided by advances in computational modeling and more widely available HPC systems, researchers can predict the location of a tsunami or hurricane's landfall as well as the height of the associated water run-up. These predictions reflect the primary strategy for saving lives: physically evacuating people from threatened areas. Effective evacuation is determined by three factors. First, a clear evacuation plan and supporting infrastructure must be implemented, including the establishment of several routes away from the coastline, preparedness of public safety officials, and reliable public warning and communications systems (see the sidebar "The Difficulty of Translating Theory into Practice"). Second, varying amounts of lead time in evacuation tactics must be accounted for. Potential hurricanes or severe marine storms can be tracked days in advance. A tsunami, however, might be generated across the ocean or only a few hundred miles off shore; because the forces generally travel at hundreds of miles per hour, there might be several hours or only a few minutes of warning. Third, successful evacuation ultimately depends on how quickly and cooperatively individual citizens react (see the sidebar "Incorporating the Human Factor in Disaster Simulations").

CHALLENGES OF MODELING COMPLEX, MULTISCALE TSUNAMI AND STORM SURGE BEHAVIOR

A tsunami is generated by seafloor dislocation, typically due to a seismic event. Other causes include landslides, underwater or coastal volcanic eruptions, and meteorites. Underwater earthquakes can displace the seafloor over a large area, often 100–500 km long and 50–150 km wide. The generated waves are long compared with the water's depth and can propagate great distances without diminishing in energy. They travel swiftly across the deep ocean, slowing and rising as they near the shore. Such waves can impact remote sites thousands of kilometers away.

Estimating a tsunami's source conditions is difficult, requiring massive, precise seismic monitoring data to identify the characteristics accurately enough to determine the fault displacement (magnitude and location alone are not enough). The configuration of the seafloor affects a tsunami's propagation, even in the 4,000 m–deep abyssal plain. Detailed deep-water bathymetry data (depth below sea level) is needed, but sparse data exists for many regions. Because of their long wave characteristics, tsunamis can interact with and become transformed by complex underwater features such as continental shelves, islands, reefs, and shoals. Consequently, where, when, and how a tsunami reaches and inundates the coastline can vary substantially. The problem is clearly multiscale: models must deal with scales that range from hundreds of kilometers for a tsunami's wavelength in deep water to a few meters as the tsunami strikes coastal features and infrastructures.

A storm surge is an abnormal rise in water level caused by an extreme storm. It is fundamentally different from a tsunami, although it might have similar effects. Storm surges are generated by wind stresses on the sea surface, enhanced by atmospheric pressure (that is, low barometric pressure causing the sea level to rise). They only occur in regions with a shallow and wide continental shelf, which controls the surge's length. Therefore, storm surges are limited to the coastline where the storm hits—they do not propagate across the ocean.

Accurate storm-surge prediction requires not just bathymetry of the continental shelf and coastline but also spatiotemporal data representing the storm's wind fields and barometric pressure as they change over time. Tracking the storm and predicting the wind fields are essential elements of storm-surge predictions. Today, with the aid of satellites, we can track storms fairly well and issue warnings well ahead of time. However, predicting the waves' size and timing in specific locales remains difficult. Building and

INCORPORATING THE HUMAN FACTOR IN DISASTER SIMULATIONS

Wave behavior is difficult to model, but it is easier to quantify than human behavior. Although drowning causes most human casualties, an inundation can collapse structures, making the occupants vulnerable to traumatic injuries. Between the shoreline and the run-up zone's inland edge, building and occupant survival depend on site characteristics, design, and construction materials.

Historical tsunami data suggests that a tsunami's physical severity, although important, does not determine the fatality rate. Rather, the critical factors influencing human survival seem to be the effectiveness of tsunami warning systems and the extent to which prior education actually motivates people to evacuate in a timely manner. Suitable warnings must be transmitted to disperse populations, even when people might be asleep or otherwise disengaged from traditional transmission media. Evacuees must know what to do and which routes to take under what circumstances. Moreover, motivating the correct behavior is a challenge in itself. It can be difficult to convince people of the risk of an extreme event that has never occurred in their lifetime, and even more difficult to deter thrill seekers, who move toward rather than away from the event.

Researchers have modeled human behavior during wave hazard events by developing agent-based models that produce animations showing tsunami arrival and inundation, warning transmission patterns, and possible population response, taking into account such variables as the timing and success of warning messages.[1] Recently, investigators developed a framework for simulating and visualizing a tsunami's progression and for simulating human response; the interactive Web-based interface incorporates a mathematical casualty model that includes gender and age factors when estimating fatalities.[2,3] Such visualizations can capture a coastal community's attention and reinforce the need to respond quickly and appropriately to hazard warnings. However, they are still rudimentary and available for only a few coastal communities.

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infrastructure damage are typically due to wind-driven wave actions that ride on the slowly varying surge, but it is hard to accurately model wave-surge interactions and the resulting wave amplification. As with tsunamis, this is a multiscale problem: the horizontal length scale of hurricanes and nor'easters is about 1,000 km, but their effect on structures is on the scale of meters.

Research groups have long worked on computational models to more accurately predict tsunami and storm-surge behavior. Unfortunately, current models are limited to specific aspects, such as wave generation, propagation, progressive inundation and overland flows, sedimentation or undercutting of land features, and wave impact on structures. Arriving at a prediction requires the stepwise application of independent models, with each step introducing another layer of approximation and uncertainty. (The sidebar "Is It 'Safe' to Base Decisions on Wave-Behavior Simulations?" further discusses the consequences of this uncertainty.) We need comprehensive models for tsunamis and storm surges that more accurately approximate these interactions. Such models have not been developed yet because we cannot dynamically link such multiscale, multiphysics models at meaningful enough levels of accuracy to achieve comprehensive computations and integrate them with the vast seismological, geophysical, and engineering data.

HPC EXAMPLES FROM THE TSUNAMI COMMUNITY

Years ago, tsunami researchers questioned whether HPC could help address the difficulties inherent to modeling tsunami behavior. The tsunami community is somewhat unique in that predicting tsunami propagation and behavior is necessarily multidisciplinary, requiring expertise from disciplines such as seismology, oceanography, geology, hydrodynamics, and coastal engineering. Tsunami research was therefore collaborative from its

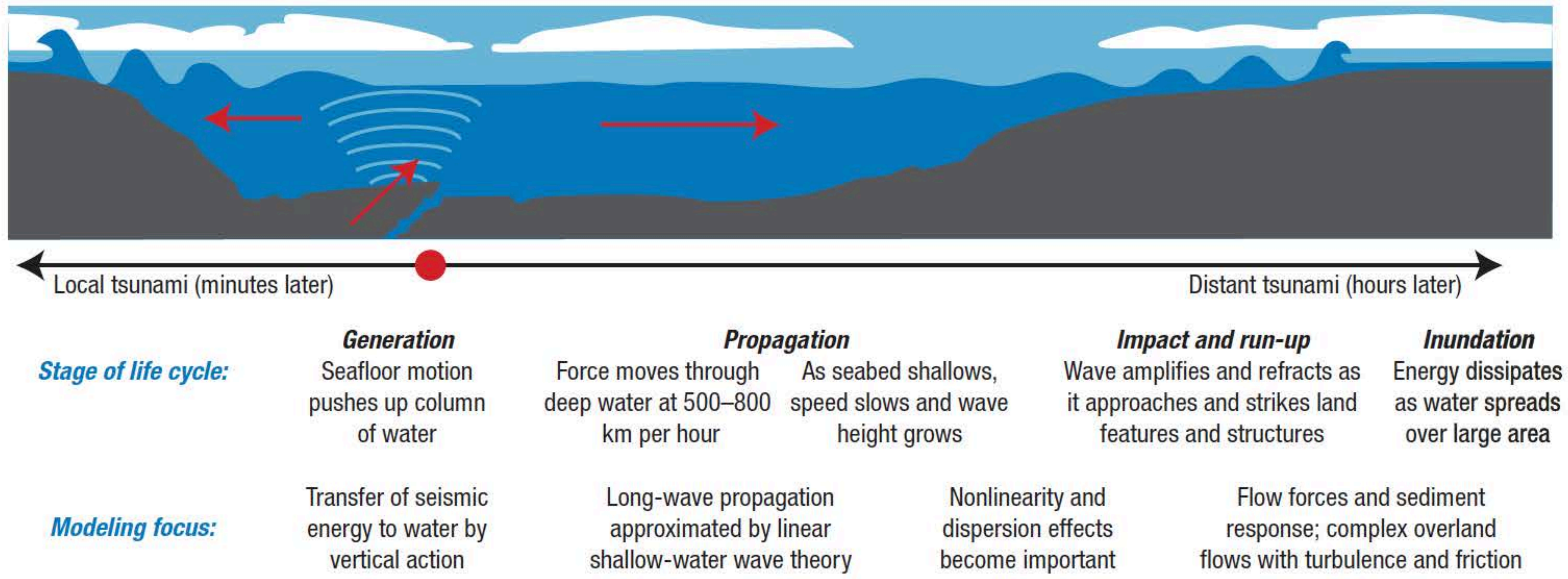

FIGURE 1. The tsunami life cycle and modeling needs for each stage. Although storm surges have different origins, their modeling needs parallel those of tsunamis' later stages (near-shore propagation, run-up and impact, and inundation).

inception, and some of those disciplines were among the earliest users of HPC resources.

Figure 1 illustrates a tsunami's life cycle and the forces to be modeled during each stage. Modeling a tsunami's generation and propagation requires accurate bathymetry and topography data to predict wave behavior. Deep-water areas are typically represented by coarse-resolution bathymetry (for example, 1-km point spacing) because the variation of seafloor relative to its mean depth is small. In contrast, finer-resolution grids (approximately 100 m; see Figure 2) of bathymetry and topography data are needed to model near-shore areas. The actual wave run-up on shore is modeled using very-fine-resolution grids (approximately 5 m). To satisfy a model's stability criteria, a small computational time step must be set so that the wave propagates only one spatial grid space at a time. Modeling tsunami propagation and inundation is therefore conducted using a multigrid or adaptive-grid scheme. This type of modeling requires significant computing power and is best performed using parallel processing on a computational cluster. High-resolution bathymetry and topography input data and time-series output data can be quite voluminous. Researchers also need analytical capabilities to visualize, interpret, and compare large

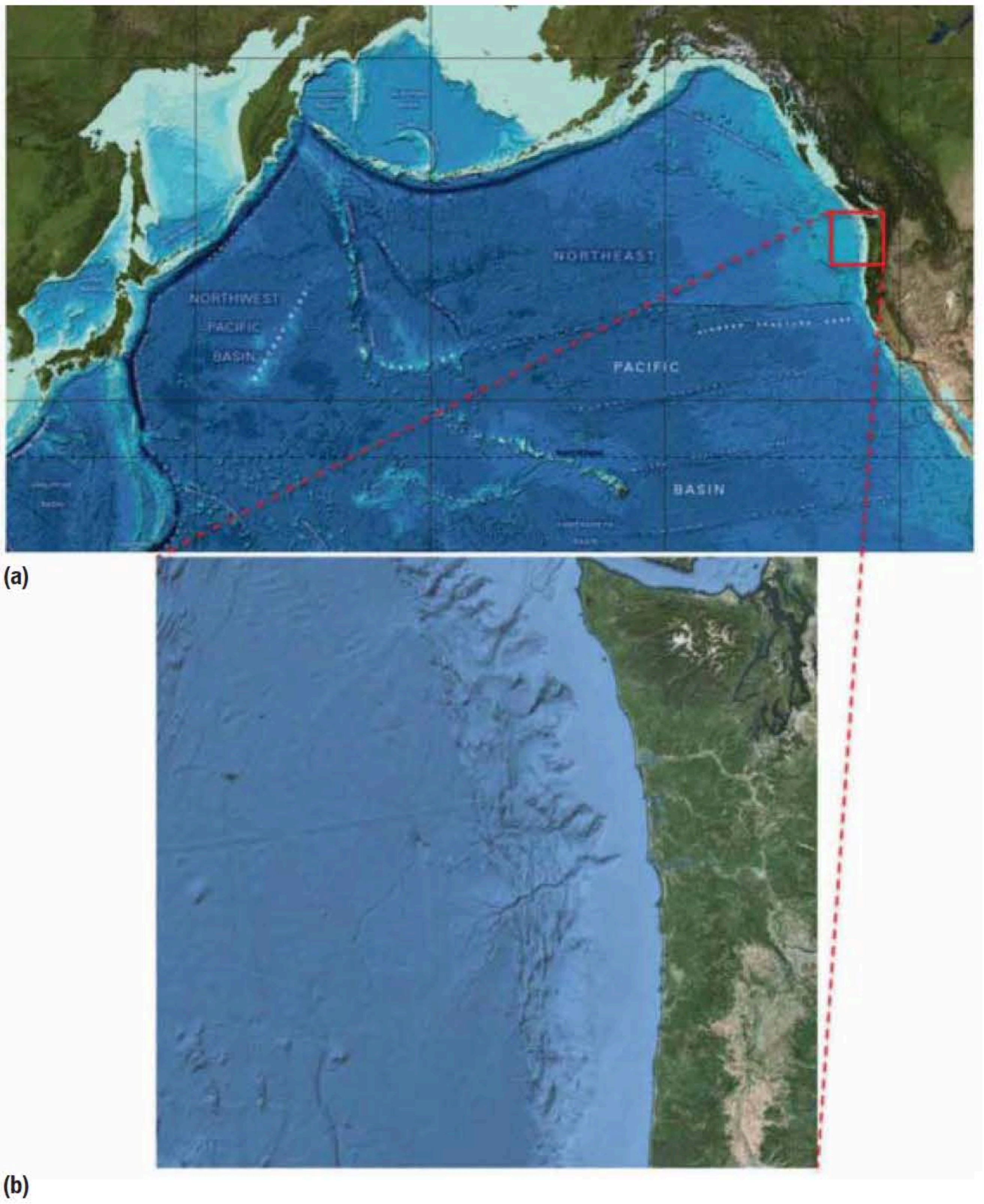

FIGURE 2. Bathymetry (underwater topography data critical for modeling tsunamis and storm surges) has variable resolution, depending on who created it and why. (a) General Bathymetric Chart of the Oceans data shows the North Pacific's deep-water bathymetry. (b) A Google Earth inset shows finer detail for the continental margin along the Oregon and Washington coasts.

IS IT “SAFE” TO BASE DECISIONS ON WAVE-BEHAVIOR SIMULATIONS?

Hazard models can help save lives and mitigate economic damages. Even when reasonably accurate predictions are possible, mitigating an event’s impact depends on how well the population prepares and how far in advance it evacuates. Consider the recent examples of Hurricane Sandy and the East Japan tsunami.

HURRICANE SANDY

Owing to advances in numerical simulations, real-time monitoring systems, and satellite imagery, we can now make accurate short-term predictions (2–3 days out) of hurricane intensities and tracks. In 2012, two days before Hurricane Sandy’s landfall, the National Weather Service issued a coastal flood warning predicting a 4- to 8-ft storm surge in New York Harbor; 15 hours later, it updated the prediction to a 6- to 11-ft surge. A post-event field survey found that measured surges in the area were uniformly 11 to 12 ft[1] (so the storm surge exceeded the prediction, but not by much).

Flooding caused by Hurricane Sandy crippled New York’s subway system, but the ultimate impact was minimal because of the Metropolitan Transit Authority’s (MTA’s) preparations. Only four days after the storm, 80 percent of the system was operating—an amazingly swift recovery from such a major event. MTA’s risk mitigation was made possible by previous experiences: a local flash flood in 2007 closed the subway system, and Hurricane Irene threated it the year before Sandy; in fact, Irene’s storm surge very nearly paralyzed the subway system. Because of those forewarnings from recent smaller events, MTA was better prepared for Hurricane Sandy.

EAST JAPAN TSUNAMI

Tsunamis originating at a distant location give sufficient advance warning (usually a number of hours), but the available evacuation time is much shorter than for hurricanes. Tsunami propagation can be monitored in real time via tide gauges and ocean-bottom pressure transducers deployed specifically for that purpose (NOAA’s Deep-Ocean Assessment and Reporting of Tsunamis system). When the triggering earthquake occurs near a shoreline, the evacuation lead time can easily be less than 30 minutes; in that case, the deep-water tsunami-monitoring system alerts are immaterial, and the only immediate warning is likely to be the ground shaking from the earthquake. The real difficulty is predicting the wave run-up’s height. Unlike a typical storm surge, both distant and local tsunamis have nonuniform run-up distributions. The East Japan tsunami exemplifies predictions gone awry.

Because it is located along an undersea fault zone, Japan has historically suffered from tsunamis. In response, the Japanese developed the world’s most advanced coastal protection structure system. As discussed in the sidebar “The Difficulty of Translating

model outputs. HPC resources facilitate access to big data, allowing quick processing of large time-series simulation datasets.

Although HPC computing and data resources are increasingly commonplace, their requirements exceed the resources of a typical tsunami research group. We provide two examples of how the tsunami research community leverages shared HPC resources to evaluate computational models and enable new approaches for assessing the effects of tsunamis. Tsunami researchers collaboratively designed and developed both systems.

Example 1: Sharing and cross-comparing community models to evaluate different scientific approaches

Computational modeling is a powerful tool, allowing scientists to study potential tsunami events’ characteristics, impacts, and prediction. More comprehensive models allow more accurate simulation of the modeled phenomena, but they also impose complex requirements for data, computational resources, and knowledgeable interpretation. Individual users find grappling with these problems difficult. Consider, for instance, bathymetry grids for both deep-water and near-shore areas. Those datasets are maintained by different agencies and/or sources and at different scales. They can be difficult to acquire, and special expertise is required to accurately match fine-scale data points with coarser-scale data from the same or neighboring areas. The challenges are further complicated when the task is to compare the relative effectiveness of different approaches under specific scenarios. Because independent groups, sometimes from different disciplines, developed the models, each model

Theory into Practice," they developed engineering guidelines based on water levels from historical disaster records. For example, the Fukushima Daiichi Nuclear Power Plant's design basis was a 5.7 m–high tsunami,[2] which was the height of the 1960 Chilean tsunami. That earlier tsunami, however, was generated about 17,000 km away. The 2011 East Japan tsunami was generated only 120 km from shore, resulting in a 15 m–high tsunami—almost three times the design height. This circumstance triggered the nuclear disaster. In many locations, the measured run-up heights were more than 50 percent higher than predicted.[3–5] Thus, the ability to predict the size of wave events in specific locations remains far from satisfactory.

Is overpredicting an event's severity the answer? For the 2011 East Japan tsunami, the high casualties were due, at least in part, to two contrasting factors. First, almost exactly one year before, a tsunami originating in Chile approached Japan.[6] The Japanese Meteorological Agency (JMA) issued warnings of a "significant" 3 m–high tsunami, but the actual height was less than 1.2 m. This overestimation in 2010 led some people to delay evacuation in 2011, when the tsunami proved to be much larger. Second, during the 2011 event, JMA issued an immediate warning three minutes after the earthquake, forecasting a 3 m–high tsunami. Twenty-eight minutes after the earthquake, the warning was updated to 6 m. By that time, people in Ofunato had only four minutes to evacuate from what turned out to be a 15 m–high tsunami. The initial (3-m) announcement made people in some areas decide not to evacuate. These examples show how inaccurate predictions create false perceptions that end up costing lives.

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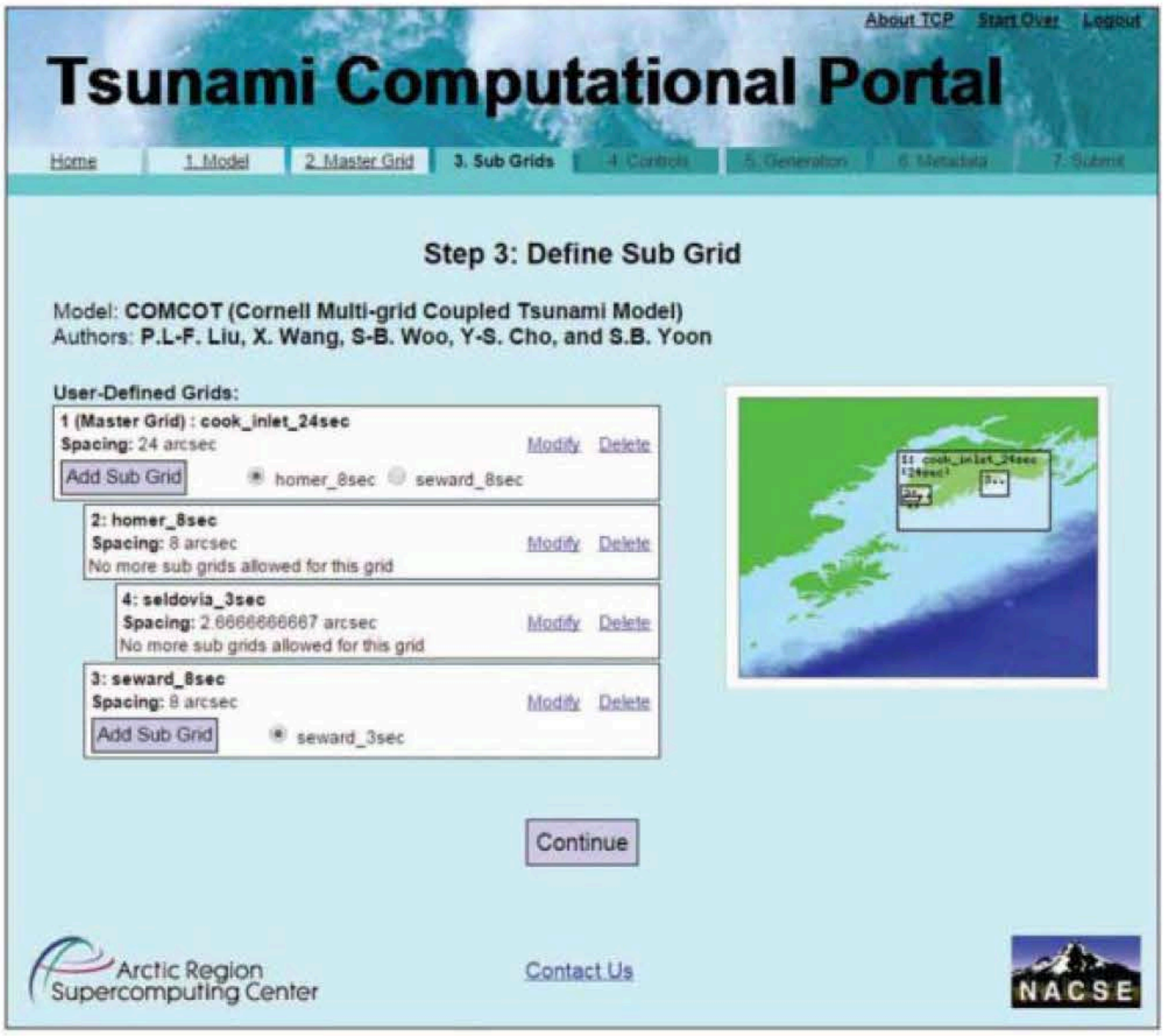
has unique controls, input requirements, and output formats.

HPC and tsunami experts collaboratively developed the Tsunami Computational Portal (TCP) to address these problems. It provides access to multiple tsunami model codes without the difficulties usually involved in managing data, configuring model runs, accessing computational resources, and managing results from multiple simulations. An integrative, Web-based interface provides the illusion of a single environment in which research models can be executed and compared (see Figure 3).

TCP was designed with a strong focus on usability. Although many TCP aspects are user friendly, users still must have domain knowledge. They do not, however, have to understand the individual models' intricacies or acquire and align the geospatial data because TCP handles all integration issues. Users select the region affected by a historical event or define a new region for either the tsunami's source or the inundation area from various bathymetry grids, including one with global coverage. All parameter settings have "intelligent defaults"—values that a group working with each model's original developers tuned to the specific region and event. Each user's prior selection history is retained and easily reloaded or loaded across different models to facilitate running multiple models on the same conditions. Users select the number and duration of time steps for generating output, which is retained within the users' accounts.

Behind the scenes, TCP components run at the Northwest Alliance for Computational Science and Engineering (NACSE) at Oregon State University, the Arctic Region Supercomputing Center (ARSC) at the



Step 3: Define Sub Grid

Model: **COMCOT (Cornell Multi-grid Coupled Tsunami Model)**
Authors: **P.L-F. Liu, X. Wang, S-B. Woo, Y-S. Cho, and S.B. Yoon**

User-Defined Grids:

1 (Master Grid) : cook_inlet_24sec
Spacing: 24 arcsec
● homer_8sec ○ seward_8sec

2: homer_8sec
Spacing: 8 arcsec
No more sub grids allowed for this grid

4: seldovia_3sec
Spacing: 2.6666666667 arcsec
No more sub grids allowed for this grid

3: seward_8sec
Spacing: 8 arcsec
● seward_3sec

FIGURE 3. The Tsunami Computational Portal (TCP) supports the comparison and analysis of results from different tsunami generation, propagation, and run-up models. In this example, the user selects the region of interest by defining the subgrids to be modeled with successively finer resolution; the best available bathymetry and topography data are then extracted from TCP's geodatabase at the Northwest Alliance for Computational Science and Engineering in Oregon and packaged with the model parameters for remote execution on a high-performance computing system at the Arctic Region Supercomputing Center in Alaska.

University of Alaska Fairbanks, and on the user's browser client. However, users are unaware of the TCP's distributed nature. They define spatial regions and configure model controls using the NACSE Web portal and then submit jobs for execution. Configuration parameters and spatial data are automatically packaged and delivered peer-to-peer to an HPC system at ARSC for processing. The results are automatically returned to the TCP database at NACSE for postprocessing and delivery to the user. Since TCP's introduction, users have conducted more than 800 model runs and used the results in many comparative analyses.

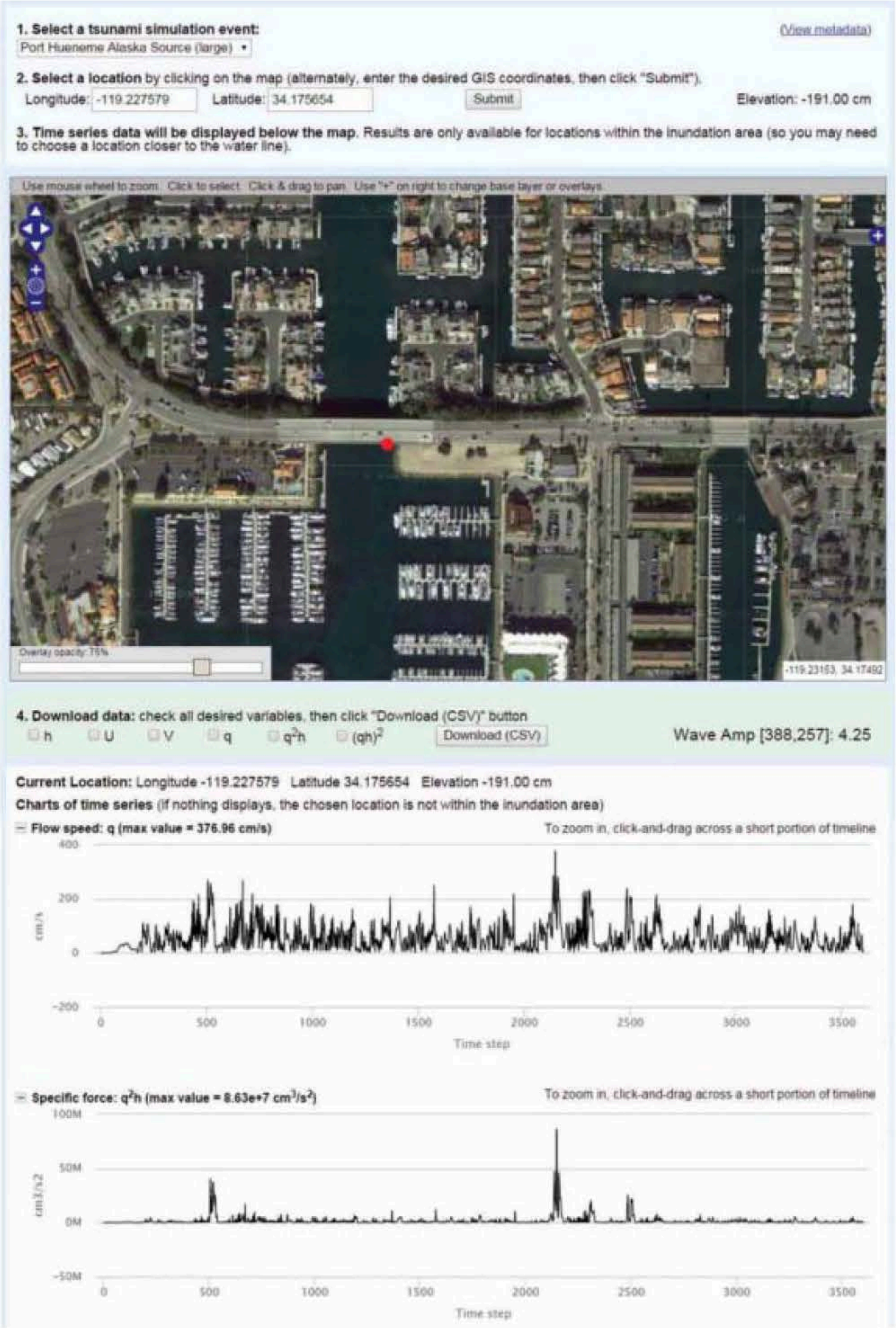
Example 2: Facilitating assessment of tsunami effects on structures

Unprecedented damages caused by major tsunamis such as the 2011 East Japan tsunami highlight the need to do more to protect buildings, bridges, oil and gas storage facilities, power plants, and other coastal structures. This requires assessing the risks in enough detail to appropriately build or reinforce these structures (see the sidebar "The Difficulty of Translating Theory into Practice"). Performance-based tsunami engineering (PBTE) was designed for this purpose. It is similar to the performance-based earthquake engineering that is used to improve earthquake readiness.

Engineers must examine tsunami effects in specific locales and analyze the forces that key structures encounter during tsunami run-up, impact, and inundation. However, a tsunami simulation's output data can be quite large and difficult to query for a specific location. Recent HPC hardware and software advances have allowed the development of the PBTE Data Explorer, a Web-based portal in which engineers interactively query and analyze large datasets of wave behavior from tsunami simulations (see Figure 4).

Users start by choosing a coastline area and a specific event (simulated tsunami). The bathymetry and topography datasets are loaded, along with road and bridge locations and as much structural information as possible based on the available geospatial data. Users can interactively explore inundation effects by selecting specific structure locations, such as a critical bridge's downstream abutments. The tool next extracts—at subsecond speed—a time series of the tsunami inundation data (flow velocities and depth) at that location by indexing into large output grids across hundreds of time steps. The retrieved data is then used on the fly to calculate parameters for structural analysis (maximum specific force, maximum overturning moment, and so on). For engineering sensitivity analysis, users can zoom in on charts and move the cursor to interactively identify how and where conditions change; they can also download the calculations.

Taking a "temporal history" view of wave-flow conditions enables us to estimate not only the water's force, but also other effects such as buoyancy forces, scour effects when the wave liquefies the ground supporting the structure, and impact forces of floating debris. By making information available quickly and in the derived form needed for engineering analysis, the tool allows in-depth analysis of different hazard scenarios.



1. Select a tsunami simulation event:
Port Hueneme Alaska Source (large)

2. Select a location by clicking on the map (alternately, enter the desired GIS coordinates, then click "Submit").
Longitude: -119.227579 Latitude: 34.175654 Elevation: -191.00 cm

3. Time series data will be displayed below the map. Results are only available for locations within the inundation area (so you may need to choose a location closer to the water line).

Use mouse wheel to zoom. Click to select. Click & drag to pan. Use "+" on right to change base layer or overlays.

Overlay opacity: 75%

4. Download data: check all desired variables, then click "Download (CSV)" button
☐ h ☐ U ☐ V ☐ q ☐ q²h ☐ (qh)²

Wave Amp [388,257]: 4.25

Current Location: Longitude -119.227579 Latitude 34.175654 Elevation -191.00 cm

Charts of time series (If nothing displays, the chosen location is not within the inundation area)

Flow speed: q (max value = 376.96 cm/s)

To zoom in, click-and-drag across a short portion of timeline

Specific force: q^2h (max value = 8.63e+7 cm^3/s^2)

To zoom in, click-and-drag across a short portion of timeline

FIGURE 4. The Performance-Based Tsunami Engineering Data Explorer allows engineers to analyze the forces exerted on coastal structures and infrastructure, from the wave's arrival to the turbulence's final dissipation. With the Explorer's fast and effective spatio-temporal data accessibility, engineers can conduct sensitivity analyses.

The need for real-time disaster simulation and characterization is compelling for scientific as well as practical and humanitarian reasons. Accurate models of tsunami and storm-surge behavior and their effects on buildings and coastal infrastructures are still emerging. In the face of climate change and potential sea-level rise, models that can effectively predict when and where to evacuate coastal populations and that can assess coastal structures and proactively make them more resilient are of increasing importance. HPC breakthroughs enable capabilities that were beyond comprehension a decade ago. For researchers, access to large-scale computational and data resources could remove the roadblocks that previously forced them to isolate aspects of extreme wave events, such as wave generation versus wave impact on structures.

HPC enables us to comprehensively study and model these phenomena, promising major breakthroughs such as realistic loss-prediction models and a science-based rationale for coastal zoning regulations for populated coastal areas with key structures. Guidelines for more resilient infrastructure could be formulated, such as for retrofitting structures to increase their resistance to extreme waves or for cost-effectively remediating coastal lands at risk for soil-related failures.

To ensure widespread adoption by engineers, government agencies, and other decision makers, the methods must be practical and economically feasible. Public safety organizations that issue warnings, oversee evacuation procedures, and secure key facilities must be able to compute accurate predictions within serious time constraints. It's worth noting that a Japanese research group recently took a small step toward simulation-based, rapid tsunami warning using RIKEN's K supercomputer, and we anticipate more such examples.[4]

If HPC capabilities continue to advance rapidly, we will be able to automatically predict and characterize wave threats in real time, so that evacuation warnings are more accurate, timely, and likely to be heeded.

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