Development of a Model for Real-Time Tsunami Forecasting: from VTCS to MOST

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ABSTRACT

We describe the development, testing and implementation of a tsunami real-time forecast model, the Method Of Splitting Tsunami (MOST). MOST is now used as an operational forecast model for the National Oceanic and Atmospheric Administration's Tsunami Warning System, and as a tsunami hazard assessment tool in the U.S., and in many countries around the world. Every step in the development of MOST marked new scientific challenges, improvements of technological and computational capabilities, and new demands of the engineering and hazard mitigation communities for applied and benchmark modeling tools for tsunami hazard assessment.

Keywords: tsunami, long wave, tsunami numerical model, MOST, ComMIT, forecasting, early warning.

INTRODUCTION

On 11 March 2011, scientists from the National Oceanic and Atmospheric Administration (NOAA)'s Center for Tsunami Research (NCTR) were concluding a training session on tsunami modeling at the Tanzania Meteorological Agency at Dar es Salaam, using the

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Method Of Splitting Tsunami (MOST) model, with a web-enabled interface, the Community Interface for Tsunamis (ComMIT) (Titov et al. 2011). During the last day of the training program, when everything was ready for the final evaluation, notification of a fairly strong earthquake off the coast of Japan arrived. Half an hour later, watched in disbelief, the amplitude as the tsunami at the tsunameter (The Economist 2003) –the instrument also known as tsunamograph or Deep-ocean Assessment and Reporting of Tsunamis (DART)– closest-to-Japan-coast climbing to a never-before-imagined amplitude of nearly 2 m, at a depth of 5 km. Inadvertently, the final examination included the real-time forecast of tsunami flooding that was about to occur.

This M_w 9.1 earthquake generated a tsunami which devastated Japan's east coast on 11 March 2011, resulting in the costliest known disaster, and the worst damage in Japan's history since World War II. While Japan suffered the vast majority of the damage and victims from the tsunami, many coastlines around the Pacific, including Chile's, experienced flooding. The Pacific Tsunami Warning Center (PTWC) assessments, much improved since the 2004 Boxing Day event, were issued timely and appropriately for most of the population at risk in the Pacific, sadly, beyond the near-field impact areas in Japan. Part of the improved U.S. Tsunami Warning System (TWS) was by then the newly-developed tsunami flooding forecast capability based on MOST.

This capability was exercised to produce the first-ever forecast of tsunami inundation in Hawai'i, as part of the operational warning capability test. In addition, MOST was also used in different parts of the world to evaluate the Tohoku tsunami impact, beyond the operational responsibilities of the U.S. TWS, as a proof of concept test for the distributed tsunami forecast capability envisioned for the future (Kânoğlu et al. 2015). Scientists in the U.S., New Zealand, Turkey, and Tanzania worked collaboratively using the same source data to produce coordinated and standardized tsunami hazard assessments for this event.

MOST has since undergone additional tests to become an operational model for the U.S. Tsunami Warning Centers (TWCs) for tsunami flooding forecasting. We summarize here the experience and process of the development of the operational capabilities in MOST.

EARLY DEVELOPMENT

The original tsunami propagation code that later became the basis of MOST was developed at the Novosibirsk Computing Center of the Siberian Division of the Russian Academy of Sciences (SDRAS) of what was then the Union of Soviet Socialist Republics (USSR) during the years 1984–1989. A novel numerical scheme was applied to solve the nonlinear shallow water-wave (NSW) equations, without artificial viscosity or application of a friction factor (Appendix I). The technique was based on the splitting method, also known as the method of fractional steps, at that time actively being developed by S. K. Godunov's group in Novosibirsk (Godunov 1973). Dimensional splitting produces two hyperbolic systems, one in each propagation direction, longitudinally and latitudinally, i.e., it creates two two-dimensional (one spatial plus one temporal directions, 1+1D) problem; each problem was then solved with the method of characteristics, with all real and distinct eigenvalues. The characteristic form of the governing equations made the explicit numerical realization of a well-posed boundary-value problem possible, with an efficient numerical scheme, again refer to Appendix I for details.

The above numerical model was first presented to the international community during the 14th International Tsunami Symposium in Novosibirsk (31 July–10 August 1989), by the SDRAS (Titov 1989, Titov 1988). This was the start of series of scientific meetings kicking off the "Decade for the Natural Disaster Reduction" (Bernard 1991). At the time, only tsunami propagation results with fully reflective boundaries were presented, and they were benchmarked with an analytical solution. The code was then applied to the 1983 Sea of Japan tsunami, simulating propagation from its inferred source onto the coast, so as to qualitatively compare the distribution of computed offshore amplitudes with measurements along the eastern coastline of Honshu. Another landmark workshop took place at the Marine Science Center of the University of Southern California (USC), at Catalina Island on 15–18 August 1990, where V. V. Titov presented the Novosibirsk Computing Center's finite-difference three-dimensional (two spatial plus one temporal directions, 2+1D) algorithm (Liu et al. 1991).

Further development of the tsunami numerical model occurred at USC during 1992–1997. The focus was adding inundation onto dry land computations, a vexing problem with a moving boundary, for which no adequate mathematical conditions then existed; earlier computations of the climb of a bore on a beach by Hibberd and Peregrine (1979) (HD) used ad-hoc algorithms; pioneering computations by Pedersen and Gjevik (1983) solved a form of the Boussinesq equations using an elegant Lagrangian formulation which allowed a simple boundary condition at the shoreline; (Kim et al. 1983) had opted for a boundary integral (BIEM) solution of Laplace's equation for water waves. None of these methods were transferable easily then to 2+1D formulations, particularly for non-idealized geometries.

To study the 2+1D terminal effects and runup of tsunamis, we started with the development of the 1+1D model, known then as VTCS–2 (Titov and Synolakis 1995), which solved the NSW equations without using artificial viscosity or friction factors. After testing the dispersion, absorption and mass conservation characteristics of the numerical scheme, VTCS–2 was applied to the canonical problem (a constant depth region connected to a sloping beach) for the solitary wave runup problem investigated by Synolakis (1987), both experimentally and analytically. Titov and Synolakis (1995) applied the model to both nonbreaking and breaking waves, producing excellent agreement with the Synolakis' laboratory results, both in the time histories of the surface elevations during the evolution of the wave, and for the maximum runup.

A distinct feature of the model was that it did not use any artificial viscosity or friction terms. Hibberd and Peregrine (1979) developed the first published algorithm to numerically study the runup of an infinite bore, a very important first step. Synolakis (1986) noted its inadvertent shortcomings, and attempted to improve it, also on an ad-hoc basis. The propagation on dry land involves both runup and rundown, and grid points need to be introduced and removed, as appropriate, or more precisely, as practical in any specific scheme.

As discussed by Synolakis (1989), the HD algorithm used a different numerical procedure for the rundown, to avoid the prediction of negative depths, and the entire procedure was not robust, when applied to evolution over composite beaches. The tip of evolving fronts up or down dry lands is fast moving, while the flow depths are very small, a fact whose significance in educating populations at risk not to assume that the waves will move onland with the same speed it does in the surfzone was not appreciated for about a decade later (Synolakis and Bernard 2006, Kânoğlu et al. 2015). In a code without friction, it was and still remains a challenge to develop a robust algorithm, without spurious numerical instabilities rapidly becoming numerical overflows, and contaminating the entire computation.

The resulting shoreline algorithm of Titov and Synolakis (1995) was simpler than existing ones at the time for rough slopes (Kobayashi et al. 1987) for the NSW, and, expectedly simpler than the finite-element solution of the Lagrangian form of the 2+1D Boussinesq equations developed by Zelt (1991). A remarkable feature of the algorithm was its ability to model the runup of breaking waves, which are simulated in MOST as bore-like fronts, without additional boundary treatments when breaking occurred, only using the finite-difference scheme dissipation of higher frequencies. The explanation is that the NSW equations preserve momentum and mass, and are not influenced by details of breaking, a manifestation of G. B. Witham's bore rule. Titov and Synolakis (1995) commented that "why these simple equations [referring to the depth-averaged shallow water-wave equations] can even model some details of breaking is still quite puzzling." These observations were recently re-discovered by Couston et al. (2015).

VTCS–2 was then extended into 2+1D, hence is name at the time VTCS–3. The splitting method was used again and the 1+1D runup technique described above was applied virtually unchanged to the two propagation dimensions; Titov (1997) provides a comprehensive description of the two models. VTCS–3 was then applied to the first large scale 2+1D laboratory experiment, the solitary wave propagation around a conical island, which, while planned before it were completed right after by the 1992 Flores tsunami (Yeh et al.

1994). This tsunami hit Babi Island, off Flores creating counterintuitive high runup on the backside of the island. In the laboratory incarnation, once solitary waves hit the front side of the island, they split into two waves, moving with their crests nearly perpendicular to the shoreline, propagated around the island and finally collided behind it, creating spectacular interference and counterintuitive high runup, similar to that observed in the field (Liu et al. 1995, Briggs et al. 1995, Kânoğlu 1998). Comparisons of VTCS–3 results with the laboratory data not only showed good agreement in front of the island, but also behind it, where the two wave fronts collided, for both time histories of surface elevations and for the maximum runup.

The conical island laboratory experiment did not produce measurements on the enhanced runup along the portion of the shoreline shadowed by the island, as observed during the 2010 Mentawais tsunami (Hill et al. 2012). The reason was that the experiments with the conical island did not have a sloping beach installed at the end of the wave basin opposite to the wave generator. Additionally, runup was not measured along the absorbing back wall of the basin. This phenomenon of the islands not sheltering the coastlines along mainlands behind them was explored by Stefanakis et al. (2014) using active learning, which involves an emulator based on Gaussian processes to guide the selection of the query points in the parameter space.

In the early nineties, both because 2+1D runup could not be evaluated efficiently with existing methods by most non-coastal engineering groups and because bathymetric/topographic data of adequate resolution were not readily available, threshold models (models with a 10 m high reflective vertical wall a certain "threshold" depth) were favored in geophysical studies (Satake 1994, Piatanesi et al. 1996). Titov and Synolakis (1998) applied VTCS–3 with a 5 m depth threshold for the 1994 Kuril Islands tsunami, and a hybrid 2+1D offshore, 1+1D near-shore computation for the 1996 Peruvian tsunami, as threshold computations, because no high-resolution bathymetric and topographic data existed to make meaningful calculations. They then applied VTCS–3 to the 1993 Nansei–oki tsunami and calculated the runup around the Okushiri Island, with 50-, 150-, and 450-m grid resolutions, and also used two threshold models with a vertical wall at 10 m and 50 m depths.

All these computations were compared with field measurements revealing that the resolution of available bathymetric and topographic data sets was more critical than the grid resolution, in the reliability of the overall computation. Interpolating from a coarse grid to produce a finer grid improves numerical accuracy and convergence in the specific numerical computation, but may not necessarily improve physical realism. Claiming that a hazard study is accurate up to 10 m, when interpolated geographical data from 100 m grids were used, this is misleading because there may well be sub-grid features in the area under study. Titov and Synolakis (1998) found that a 150-m grid resolution was necessary to qualitatively reproduce the overall runup distribution, but that a 50-m grid was needed to reproduce the extreme runup, as observed. One important conclusion from Titov and Synolakis (1998) was that small bathymetric features affected runup to the first order, a conclusion subsequently shown analytically by Kânoğlu and Synolakis (1998).

The canonical problem of solitary wave propagation, the conical island experiment, the Okushiri data and several other datasets eventually became reference benchmarks for testing tsunami models (Synolakis et al. 2008), and were the basis of two benchmarking workshops, see Yeh et al. (1996) and Liu et al. (2008). The VTCS models (and later MOST) was a tsunami code tested with all available problems of laboratory and analytical cases in both workshops.

DEVELOPMENTS TOWARD NOAA'S REAL-TIME FORECAST TOOL

Before the 2004 Indian Ocean Tsunami

In 1997, MOST was first introduced as the progression of the VTCS numerical techniques as a tsunami forecast tool (Titov and González 1997). The transition was funded by the Defense Advanced Research Projects Agency (DARPA), which had planned to use MOST to develop tsunami hazard mitigation tools for the Pacific Disaster Center (PDC), and then forecast tsunami impact in Hawai'i from potential tsunami sources in the Alaska–Aleutian subduction zone; at the time Hawai'i was widely considered as the most vulnerable locale in the Pacific.

The DARPA methodology was the first to use a new type of data, from a newly developed tsunamograph instrument, later called DART. It measured tsunami amplitudes with a bottom pressure recorder (BPR) intereting changes in the static pressure at the ocean floor, triggered by the passing tsunami waves as they propagated over the instrument. DART was developed by NOAA's Pacific Marine Environmental Laboratory (PMEL), and sensitive to about 1-cm high long-waves at 6000-m depth. (González et al. 1998).

At first, measurements were not transmitted to NOAA in real time, but were recovered from the BPR after a year-long deployment. MOST used the BPR records of the 1996 Andreanov tsunami to test the long-distance tsunami propagation simulation capability (Fig. 1). The testing checked MOST's accuracy when using spherical earth coordinates, the influence of the Coriolis forces on tsunami propagation, and the sensitivity of the characteristics of tsunamis to earthquake source parameters.

The specific finite-difference scheme of MOST exhibits mild numerical dispersion in the computed solution for propagating long waves, in a certain range of parameters. This feature of MOST was used to simulate dispersion during long-distance propagation, without the complexity and computational cost of the dispersive models with explicit dispersion terms (Burwell et al. 2007). The latter identified the optimal grid resolution and parameter set to simulate the linear dispersion model. The effects of dispersion in long-wave propagation are discussed by Zhou et al. (2012), Glimsdal et al. (2013), An and Liu (2014), Løvhold et al. (2015), and Okal and Synolakis (2016), who show that its main effect may be the change in the sequencing between the first and second leading waves.

The DARPA study was the foundation of the real-time model forecast capability using tsunamograph recordings, further developed into the pilot version of Short-term Inundation Forecast for Tsunamis (SIFT) as discussed in Titov et al. (2005b). SIFT introduced standardized three levels of telescoping computational grids in MOST, zooming into the forecast coastal location to resolve the coastal area with adequate mesh resolution for accurate inundation modeling. In SIFT, the inundation grid resolution was < 150 m, and $< 50m$, whenever the data and required warning times allowed. Tsunami observation data from the 1993 Okushiri Island, 1994 Kuril Islands and 1996 Andreanov Island tsunamis (Titov and Synolakis 1997, Titov et al. 2005b) confirmed these choices and solidified the standard for the inundation model resolution, first suggested by Titov and Synolakis (1997) for useful inundation predictions. We note that careful tests of convergence are required for any hazard impact projections, and are usually performed by sequentially reducing the step size (consistent with the computational fluid dynamics condition), until there are minimal changes in the final results. For example, when studying harbors, a resolution of 5 m or less may be required, depending on the size of coastal structure (Maravelakis et al. 2014).

Simulation of tsunami runup in realistic geophysical conditions by an enlarged group of users, especially in locales with large flat coastal areas, prompted the introduction of an artificial friction term to constrain the energy dissipation during flooding, see for example Bernatskiy and Nosov (2012), thus the Manning formulation was introduced in MOST. The proper friction coefficient for specific areas is determined by multiple testing and comparisons with existing inundation measurements (Tang et al. 2009), given that it is this stage where friction can mostly affect predictions.

SIFT uses MOST as its core tsunami simulation tool, as described in detail in Titov (2009). A forecast scenario in SIFT consists of a propagation model whose results are then input in separate coastal inundation models, focused on specific portions of coastlines. A propagation scenario consists of a combination of precomputed propagation simulations (referred to as unit sources), derived from minimizing the differences of actual tsunamograph measurements from an initial scenario based on seismic measurements alone. Each unit "source" or "run" is the result of an evolution simulation from a particular tsunami source of $M = 7.5$, which is part of a continuous line of sources, along major known tsunamigenic areas around the world.

Over 1700 such propagation runs are stored in NOAA-PMEL's database which describe tsunami propagation offshore, but the actual flooding forecast is produced using a nonlinear inundation model at high resolution. Near-shore tsunami dynamics and flooding are thus estimated through the telescoping grids from the propagation runs of unit sources of $\sim$ 7 km resolution to the inundation model resolution of $\sim$ 50 m.

Post the 2004 Boxing Day Tsunami

The 2004 Indian Ocean tsunami (Geist et al. 2006) killed nearly one quarter million of unwarned coastal residents (most of whom were uninformed of tsunami hazards), and underscored the need for accurate and timely tsunami forecasts. The first simulation of the 2004 tsunami using MOST was produced approximately eight hours after the earthquake; it was far from real-time, at the time of the simulation, the tsunami was claiming one of its last victims in South Africa, and it was based on only one measurement from Cocos Island. The forecast only included offshore estimates of tsunami amplitudes (Titov et al. 2005a). Nevertheless, the often pressing nonstop demands for model data for months after the event vividly demonstrated the need for real-time forecasts, not just for the tsunami warning systems, but also for search and rescue operations, emergency relief planning, resources distribution planning and many other unexpected uses. The fact that the eight–hour late simulation (however crude) might have been the only information from ground zero for a catastrophic tsunami had been hugely underestimated.

NOAA then decided to start implementing the SIFT inundation forecast capabilities into operational tsunami warning systems, through the realization that forecast information was also important for hazard assessment immediately after an event. MOST became the core component of NOAA's operational forecast system and the next ten years of MOST advancement were focused on increasing robustness, accuracy, and development of site-specific models for the most vulnerable U.S. coastal communities.

Developing models that will be run on demand under the pressure of tsunami warning operations is quite different from traditional model development and application in tsunami research. An operational model must provide accurate, robust and rapid results with minimal, or better yet, no interaction at all from programmers. These challenging and conflicting requirements are discussed by Tang et al. (2009) for operational tsunami flooding forecasts, and by Kânoğlu and Synolakis (2015) in terms of methodology.

Continuous testing of the model capability with all available tsunami data, especially in real-time mode, was a basic aspect of the development process. Tsunami triggering earthquakes are large scale experiments providing source information and tsunami measurements for testing. Since the first real-time experimental DART detection of the 17 November 2003 Rat Island, Alaska tsunami, over 50 tsunamis have been detected by DARTs; most of them occurred during SIFT development. Table 1 lists representative test results of the SIFT effort. This continuous benchmarking possibly makes MOST the most benchmarked tsunami model in existence at the time of writing.

The full U.S. array of 39 DARTs was completed in 2008 (Fig. 2); since 2003, there is at least one tsunamograph record for all tsunamis which impacted coastlines. The earthquake location and the DART data provide the necessary information to adequately define the initial sea state and provide input for the high-resolution inundation models to produce the tsunami coastal impact forecast (Titov 2009, Percival et al. 2011). Hence, every tsunami detected by DARTs post 2003 was analyzed using MOST, to determine the possible accuracy of the newly-developed then flooding forecast modules. Most of these tests were performed in real time, before the tide gage records of the arriving-at-the-coast tsunami were available, so as to develop standard operational procedures. A simple metric was used to assess the error of maximum predicted versus measured amplitudes at tide gages, for each observation with a better than 4 to 1 signal-to-noise ratio as follows:

$$E_{forecast} = \mid H_{forecast} - H_{observation} \mid / H_{observation} \times 100\%. \tag{1}$$

Table 1 lists representative events examined and hundreds of real-time forecasts of tsunami time series at coastal sea-level gages. The table summarizes only “true” forecasts that have been completed in real time, before the measurement data had become available. Later assessments of each event usually produces better accuracies and includes more comparisons.

Obviously, estimates of $E_{forecast}$ depend on the choice of the metric used for the accuracy assessment. $E_{forecast}$ is intentionally oversimplified for comparison purposes, and substantial improvements are possible. For example, our maximum metric ignores the complexity of the forecast of tsunami waves later in the train. NOAA unpublished testing has shown that the leading wave and one or two crests immediately behind it are generally modeled with much higher accuracy than later waves. In some cases, when the largest amplitudes appear several hours after first arrival or more, the underestimate of later amplitudes results in larger overall error, and often the sequencing –which wave carries the largest amplitude in a far-field tsunami– changes, as recently explained by Okal and Synolakis (2016). Nevertheless, the $E_{forecast}$ values illustrate that SIFT provides robust assessments of potential tsunami hazards, and for the larger amplitudes better accuracy, exactly when most needed, i.e. when there is a higher damage potential. Quantitative assessment of the flooding forecast accuracy have been more elusive, because there were no flooding events in the areas where high-resolution forecast models were available. All this changed on 11 March 2011.

The 2011 Tohoku Tsunami

The 11 March 2011 Tohoku tsunami created havoc in Japan and panic throughout the Pacific, testing tsunami preparedness at coastlines around the “Ring of Fire” to their limits. Japan suffered the worst. While very few were killed beyond Japan, all coastlines of the Pacific experienced the tsunami, including waves up to 3-m high and flooding in Chile. The tsunami caused tens of millions of US$ in monetary losses outside of Japan. The event also created an unprecedented quantity of data to test existing tools and opportunities to develop new ones. The sheer number of observations, the number of witness accounts and especially the amount of instrumental data for this single event rivals the combined amount of tsunami information collected for all prior historical events, dating back to 2000 BC. The wealth of measurements for this event is still being updated, classified and researched.

During the Tohoku tsunami, the first real–time operational tsunami flooding forecast was produced. The SIFT forecast system, based on DART data assimilation by MOST was being tested at NOAA's TWCs on 11 March 2011; however, it was not yet a part of the TWCs' standard operating procedures. The DART observation system was fully deployed, and 32 site-specific flooding forecast models –most of the planned ones for the Pacific– were already installed at the TWCs for operational testing. The forecast was produced jointly by a test team spread across the world and several time zones, including Seattle, Alaska, Hawai'i and Tanzania, where part of the development team was conducting the United Nations Educational, Scientific and Cultural Organization (UNESCO)–sponsored MOST model training referred to earlier. This exercise was a glimpse of the future distributed tsunami warning and forecast capability envisioned by Bernard et al. (2006). The team produced this pan-Pacific propagation computation, about 90 minutes after the earthquake, right after two DARTs (one U.S.-owned and one Russian-owned) recorded a half-period of the propagating tsunami (Fig. 3), and it became the "authoritative" propagation forecast (the one that fits the tsunamograph measurements best), used widely in further assessments. It was also immediately available to ComMIT users, so they could assess the tsunami threat at different locations around the Pacific (Borrero et al. 2013).

The propagation forecast was used as the initial conditions for high-resolution MOST runs for 32 coastal communities in the U.S., producing fast flooding forecast predictions for TWCs' assessments. The first areas of concern for the U.S. TWCs were the Hawaiian Islands and the West Pacific Territories. Midway Island is one of the closest U.S. territories to the source with estimated tsunami wave arrival 4 h 40 min after the earthquake. At the time, the population of the Midway Atoll National Wildlife Refuge comprised 81 people and hundreds of thousands of protected bird species. The entire population lived on Sand Island with highest elevation of 11 m above sea level. Because of the vulnerability of the location, Midway was one the first sites chosen for the tsunami flooding forecast model. The results showed extensive flooding on both islands of Midway Atoll, but less severe on Sand Island. The residents evacuated to the highest point of the island, which was the third floor of the Charlie Barracks. The information that flooding was expected, but that the wave would not flow over the entire island, was conveyed to the Refuge staff by the TWCs, who thus helped to avoid panic and possible causalities. The flooding forecast was confirmed accurate by both the instrumental measurements from tide gages that were received in real time and by post-event assessments of the flooded area (Fig. 4). The forecast helped the people on the island; however, the animal inhabitants were less fortunate. More than 110,000 of Laysan and black-footed albatross chicks, approximately 22 percent of that year's albatross production, and at least 2,000 adult birds were lost to tsunami flooding on Midway Atoll.

The next priority of the U.S. TWCs was the Hawaiian Islands, about three hours of propagation time past the Midway Atoll. The comparisons of the results of the forecast with the measurements from the Midway tide gage increased the confidence in the forecast for Hawai'i. Six of the planned twelve high-resolution inundation models were already developed for Hawai'i and were utilized. The highest amplitudes were predicted for the Kahului harbor with extensive flooding forecasted in the port. No tsunami inundation was predicted for the Honolulu harbor. Evacuation orders were issued for Hawai'i approximately one hour before the arrival of the tsunami, because the practice at the time was to either evacuate all the islands or none. Later, comparisons of the tide gage measurements with predictions at the forecast points vindicated the decision to evacuate. Civil defense surveys taken the following morning confirmed extensive flooding in Kahului, Maui, and elsewhere. Unfortunately, no detailed quantitative measurements of the flooded areas were taken at the time, and most, if not all, potential eyewitnesses were evacuated. Further, critical data to quantify the accuracy of the flooding forecast were lost in the rapid cleanup that followed. There are a few videos documenting the flooding in Kahului, Maui, and in Kona, Hawai'i (aka the Big Island), but they provide only qualitative data and they have yet to be analyzed as in Fritz et al (2012).

The MOST forecast predicted tsunami amplitudes over 2 m at several locations along the

US West Coast, which were comparable with the Hawai'i tide gage measurements. However, the West Coast was spared from flooding by a significant low tide, which coincided with the time of maximum tsunami wave arrival. While in Hawai'i the tides have a range of approximately 60 cm, many locations along the West Coast experience large tidal variations during the day. The forecast for Crescent City predicted a 2.5 m tsunami, confirmed by the tide gage record (Fig. 5). However, the largest tsunami in the wave train arrived when the tide was 2 m below high water, and mercifully no flooding occurred there or anywhere else along the West Coast. Nevertheless, one person was killed, swept by strong currents and sudden water movements below the high tide mark. Had the tsunami occurred at a different time, Crescent City and other coastal towns might have experienced significant flooding and more lives may have been lost.

Even the limited impact of the 2011 Tohoku tsunami along the West Coast demonstrated that including tidal components affected the flooding forecast. NOAA's examination of the forecasting of tide-gage records for several tsunami events indicates that interaction of tsunamis with tides is fairly linear. Coastal sea-level predictions can accurately be obtained by adding tidal components to tide-less tsunami forecasts up to the coastline. The inundation, however, may not be accurately obtained through linear superposition, and has to be computed at changing tide levels. The capability of linearly combining the tidal model to the flooding forecast model input is now being implemented for the next version of operational SIFT. Tsunami currents are suspected to be strongly affected by tides, particularly in ports (Kalligeris et al. , in review), and this requires more careful implementation of tidal prediction into models.

In addition to SIFT at NOAA's TWCs, a basin-wide propagation forecast is available for input in MOST inundation models via the Internet-enabled ComMIT interface. ComMIT runs MOST locally, but downloads the initial data from the same database of propagation runs as the operational SIFT system. Thus, forecast scenarios can be used by ComMIT users without interfering with the TWCs operations. During the Tohoku 2011 event, while the tsunami was propagating, ComMIT users produced local forecasts for the same scenario. For example, Borrero et al. (2013, 2015a), and Borrero and Goring (2015) produced a MOST forecast and hazard assessment studies for the Tohoku and other tsunamis via ComMIT, providing a real-time prediction of the potential impact at several New Zealand locations, including ports. Their forecasts were later confirmed by comparisons with tide gage measurements.

The average accuracy of all 32 forecasts ($E_{forecast}$), when compared with the maximum amplitudes at the tide gages, was approximately 70% (Table 1). The gages measuring amplitudes greater than 1 m exhibited 74% accuracy, and those measuring amplitudes greater than 1.5 m were predicted with 87% accuracy, confirming that locations of potential flooding can be robustly forecasted.

Advancing the distributed forecast concept further, NOAA developed a prototype web tool, Tweb, which allows sharing forecast results created with ComMIT, for different coastlines, via a graphical web client (Bernard and Titov 2015). The tool is now being tested by NOAA an operational forecast dissemination tool.

Implementation as a NOAA Operational Capability

Making these flooding forecast tools operational at the NOAA's TWCs required more than the one real-time test in 2011. Operational testing and evaluation (OT&E) was conducted to ensure robustness and to develop standard operating procedures for using SIFT and its tsunami flooding forecast models in TWCs operations. The Tohoku tsunami data was one of four sets of event data used by TWCs staff to test the tool, which also included data from the 2007 Kuril Islands, 2009 Samoa, and 2010 Chile tsunamis (Fig. 6). During the course of nearly two years of testing, four more tsunamis occurred that were also *naturally* included in the operational tests. In 2013, after almost two years of unprecedented OT&E at TWCs, the first-ever real-time forecast capability based on MOST became operational in August 2013.

This testing during the 2011 tsunami was one big step toward the goal referred to as the

the holy grail by the tsunami science community, i.e., accurately predicting tsunami flooding, before the tsunami arrives at any coastline. Efforts of the entire tsunami community for several decades contributed to the creation of a forecast-capable computer code. Scientific standards and benchmarks, laboratory data, computer science developments, engineering and operational implementation of the DART system and many other scientific and engineering milestones had to be achieved before MOST was able to produce its operational flooding forecast during the Tohoku event.

WORLDWIDE APPLICATION OF MOST

MOST has been applied in tsunami hazard studies around the world (Rossetto et al. 2011). Its first "public" demonstration was during the 24th International Tsunami Symposium (14–16 July 2009) (Satake et al. 2011a, 2011b), for the real-time assessment of the 15 July 2009 Fiorland, New Zealand tsunami by Uslu et al. (2011). Over 100 tsunami scientists (including personnel from several TWCs) at the Akademgorodok Science Center of SDRAS in Novosibirsk watched the fortuitous show of NOAA personnel producing a inundation forecast right there and projected on the conference room screen. By serendibity, this was the same room where the discussions for the development of inundation models took place twenty years earlier (See the "EarlyDevelopment" section).

A similar concept as the SIFT database and real-time forecast of NOAA, but using a different approach, is employed by the Joint Australian Tsunami Warning Centre (JATWC) at the Bureau of Meteorology, Australia. Rather than employing unit sources, JATWC uses earthquakes with magnitudes of 7.5, 8, 8.4, and 9 at specified locations. It then employs a propagation database, prepared with MOST. Comparisons of predictions from the two scenario databases for the 3 May 2006 Tonga and 12 September 2007 Sumatra events are provided in Greenslade and Titov (2008). The same kind of database is in the process of development for the Mediterranean (Kânoğlu et al. 2012).

VTCS models and its later version, MOST, have been used in several PhD theses (Borrero 2002, Barberopoulou 2006, Uslu 2008, Kalligeris 2016). MOST was also used in support of fundamental research studies such as to identify landslide dislocation sources from earthquake generated sources considering shoreline runup distribution (Okal and Synolakis 2004), to recover seismic moments from tsunameter records (Okal and Titov 2007), investigating satellite altimetry usage for improved early detection and warning (Hamlington et al. 2012), focusing phenomena observed from N-wave type initial wave displacement (Kânoğlu et al. 2013) and sequencing of tsunami –later waves in the train becoming higher than the leading one– (Okal and Synolakis 2016).

Several historical events have been investigated with MOST to confirm chronicled and eyewitness accounts gathered in field surveys through interviews with survivors. Examples include the modeling that followed the post-event surveys of the 1 April 1946 Aleutian tsunami in the far-field (Okal et al. 2002) and in the near-field (Okal et al. 2003), the 9 July 1956 Amorgos, Greece, tsunami (Okal et al. 2009), the tsunami earthquake of 22 June 1932 in Manzanillo, Mexico (Okal and Borrero 2011), the 9 February 1948 tsunami off Karpathos, Greece (Ebeling et al. 2012), and the Dwarskersbos, South Africa, 27 August 1969 meteotsunami (Okal et al. 2014).

MOST has been extensively used in hazard studies on the U.S. West Coast, especially for the development of inundation maps for California (Borrero et al. 2001, 2004, Barberopoulou et al. 2009, 2011), for Crescent City, California (Uslu et al. 2007, Dengler et al. 2008), for probabilistic tsunami hazard analyses (Uslu 2008), for the probabilistic tsunami hazard assessment for Seaside, Oregon (González et al. 2009), for hazards assessment resulting from harbor modifications (Dengler and Uslu 2011); and the real time (Tang et al. 2012) and hindcast (Wei et al. 2013) studies for the 11 March 2011 Japan tsunami.

In terms of worldwide application, other than the studies discussed earlier in the context of validation for the 12 July 1993 Okushiri, 4 October 1994 Kuril Islands, and 21 February 1996 Peru events, the 12 July 1998 Papua New Guinea (Synolakis et al. 2002, Lynett et al. 2003), the 2004 Boxing Day (Titov et al. 2005a), the 17 July 2006 Java (Fritz et al. 2007), the 15 August 2007 Peru (Wei et al. 2008), and the studies of the 29 September 2009 Samoa (Okal et al. 2010, Fritz et al. 2011, Zhou et al. 2012) tsunamis were also performed using MOST. Hazard studies with MOST include tsunamis from possible future earthquakes off Sumatra (Borrero et al. 2006), regional earthquakes off Peru (Okal et al. 2006), other megathrusts in the Indian Ocean (Okal and Synolakis 2008), sources in the South China Sea (Okal et al. 2011), in the Mediterranean (Mitsoudis et al. 2012, Valle et al. 2014, England et al. 2015), and unpublished studies in North Africa, the Caribbean and the Gulf of Mexico.

CONCLUSIONS

MOST has been a useful tool for real-time tsunami forecasts and warnings and for applied hazard mitigation. We can draw a few conclusions, helpful in understanding the impact of numerical modeling in coastal engineering.

1. During the development of MOST, there was extensive testing using laboratory, analytical and field data. Titov and Synolakis (1998) tested VTCS–3 with the conical island experiments and confirmed that the code could model the enhanced runup on the lee side of the island. They then used measurements from the 1993 Hokkaido-Nansei-Oki, 1994 Kuril Islands, and 1996 Peru tsunamis, cases which presented substantial computational challenges, such as extreme > 30 m runup, overland flows over a peninsula, and flows over sandbars into lagoons and beyond. In every computational methodology, particularly when moving fluid fronts are involved, there are always unimagined issues and details, necessitating further refinements and convergence checks. Continuous testing of numerical methods in geophysical fluid mechanics with measurements from past events is the only proven way for developing reliable practices.
2. MOST was developed through extensive research efforts, migrating from a 1+1D propagation to a 2+1D propagation, from Cartesian to geophysical coordinates, from a variable grid to telescoping grids, from a frictionless code to one that includes a friction factor. Every transition was tested and results compared with archived

versions of earlier codes and benchmarks, to ensure that there were no inadvertent programming errors introduced as source files were edited for improvement. Further, the gradual transitioning allowed for evaluating the impact of the coding additions on the final results, especially since the changes were introduced one at a time. Convergence was checked at every stage. While similar evolution may appear impractical, it still remains unwise to develop numerical procedures from scratch, without first understanding the solution of simpler idealized problems.

3. The source code was disseminated only through special training sessions, often organized by UNESCO, sometimes through individual collaborative work, via specific agreements. Nevertheless, MOST became one of the most used tsunami code in research (Rueben et al. 2011, Løvhold et al. 2013). The open source distribution model was not employed for MOST for several reasons. One was to ensure quality control. MOST is an operational code, and tsunami warnings are held to a higher standards with very specific requirements, different from goals of research-focused hazard studies which produce consultancy reports and journal papers. To ensure such quality control with an open-source distribution model requires substantial resources have yet to become available. Besides, there are several excellent "free" BT and NSW codes available for (See Brocchini (2013) for a review of BT models.). Their outputs may differ slightly, for the same initial conditions; however, these differences dwarf the uncertainties in source characterization, or the differences in results when convergence is not checked, or results obtained by inexperienced users.

The minimum "training" requirement for MOST were established to avoid situations when high-end tsunami inundation codes are used improperly to forecast future flooding disasters and to make important policy implications that may cost people's lives. It is not untypical to wonder while reading such studies how convergence of the computations was checked, or even how the grid sizing was determined, since the hydrodynamic models are often treated as an off-the-shelf black box, without references to original publications and with limited or no tests by community–wide accepted benchmarks.

4. The developers of MOST had substantial personal experience in tsunami field surveys. Field surveys often reveal previously unidentified flow patterns. The longshore variation of runup observed in the 1992 Nicaraguan event, the enhanced runup on the lee side of Babi island in 1992, and along the west coast of the Mentawai Islands in 2010 in regions sheltered by smaller offshore islands, and the first tsunami hydrograph measured by field teams in Kessenuma in 2011 (Fritz et al. 2012) are good examples. Further, tsunami survey teams interview eyewitnesses. Their testimonies can lead to paradigm changes, such as the existence of leading depression N-waves first documented in Nicaragua in 1992 (Tadepalli and Synolakis 1994). Surveys not only provide outreach possibilities to educate populations at risk, at a critical time immediately after a disaster, when locals are most interested in extreme natural phenomena, but also provide geophysical context to the visiting scientists.

In this regard, applied hazard studies must be considered in a fairly broad context, and include the author's personal field experiences, particularly in the interpretation of the results. Someone who has not walked on flooded lands, mused over differences in inundation between adjacent beaches, debated why a single structure was left standing while all others were flattened, debated whether a debris-mark on a surviving tree was from the tsunami or carried by the wind, listened to sometimes widely different eyewitness accounts for the same location, or wondered if an overland sediment blanket is consistent with the tsunami that just happened, likely cannot fully interpret a historic report, understand what differences changes in grid resolution can make, or ultimately put flooding predictions in the proper context. As Synolakis and Kânoğlu (2015) argued, what doomed the Fukushima nuclear power plant was the sub-standard pre-disaster coastal engineering study, which not only did not use appropriate design earthquakes, and there was apparently no tsunami-specific field experience among the Tokyo Electric Power Company (TEPCO) engineers to put their flooding predictions in the proper historic and societal context.

Predicting the future evolution of coastal engineering is futile and any such attempt will border science fiction. Two decades ago, reliable real-time flooding forecasts were imagined, but no one believed them possible in the near future, but it happened. The immediate next step is the development of timely nearfield warnings, available in 10 min or less after the earthquake ends, as robust as the farfield warnings, which are now very much "under control" (Okal 2015). Preliminary tests of the near-field flooding forecast capability using the 2011 Tohoku data (Fig. 3) and 2015 Chile tsunami forecast (Tang et al. 2016) already show promising results. MOST will further evolve in response of these new goals, and developments under way improve numerical efficiency with parallelization, implement more robust boundary conditions, include more modular structure to allow for faster and more accurate forecasts. There are no immediate plans for MOST to become a full 3-D hydro code, or even add implicit dispersion terms –there are many excellent codes that already have these capabilities. We have little doubt that MOST will continue to be part of the world's defense against tsunamis, as undoubtedly will other excellent computational codes.

We envision that within a decade, real-time flooding forecasts will be possible, within ten minutes or less after an event. We look forward to better documentation to determine if dispersion, compressibility, and stratification are important in flooding forecasts, and to better understanding breaking wave interactions and large scale coherent structures in ports (Borrero et al. 2015b). The plan is to develop design tsunami hydrographs for every tsunami shelter in the world (Fritz et al. 2012, Kânoğlu et al. 2015). We also look forward to standardized training of scientists and engineers, performing tsunami hazard studies and the regulators or consultants who review them.

In all tsunami engineering endeavors and developments, we caution scientists and engineers to carefully ponder Albert Einstein's dictum, "everything should be made as simple as possible, but not simpler."

APPENDIX I. MATHEMATICAL FORMULATION

The 2+1D NSW equations are

$$\begin{aligned} h_t + (uh)_x + (vh)_y &= 0, \\ u_t + uu_x + vu_y + gh_x &= gd_x, \\ v_t + uv_x + vv_y + gh_y &= gd_y, \end{aligned} \tag{2}$$

where $h = \eta(x, y, t) + d(x, y, t)$, $\eta(x, y, t)$ is the amplitude, $d(x, y, t)$ is the undisturbed water depth, $u(x, y, t)$ and $v(x, y, t)$ are the depth-averaged velocities in the x- and y-directions, respectively, and g is the acceleration of gravity. The model does not include a bottom friction term. A variety of boundary and initial conditions can be specified to solve the NSW equations. In general, tsunami generation caused by instantaneous bottom displacements, i.e., $d_0(x, y, t = 0)$, which could be evaluated through Okada's (1992) formulation, is applied at the sea surface.

The splitting method reduces the numerical solution of the 2+1D problem into consecutive solutions of two 1+1D problems:

$$\begin{aligned} h_t + (uh)_x &= 0, \\ u_t + uu_x + gh_x &= gd_x, \\ v_t + uv_x &= 0, \end{aligned} \qquad \text{and} \qquad \begin{aligned} h_t + (vh)_y &= 0, \\ v_t + vv_y + gh_y &= gd_y, \\ u_t + vu_y &= 0. \end{aligned} \tag{3}$$

Each of the hyperbolic quasi-linear systems has all real and distinct eigenvalues and can be written in characteristic form as follows:

$$p_1 + \lambda_1 p_x = gd_x, \;\; q_1 + \lambda_2 q_x = gd_x, \;\; v' + \lambda_3 v' = 0, \tag{4}$$

where the Riemann invariants of this system are as follows:

$$p = u + 2\sqrt{gh}, \;\; q = u - 2\sqrt{gh}, \;\; v' = v, \tag{5}$$

and the three distinct eigenvalues are

$$\lambda_1 = u + \sqrt{gh}, \ \ \lambda_2 = u - 2\sqrt{gh}, \ \ \lambda_3 = u. \tag{6}$$

These characteristics are given in the x-direction and could be applied in the y-direction in a similar manner. Refer to Titov (1997) and Titov and Synolakis (1998) for the details of the application of the boundary conditions and the finite difference scheme to solve the system.

Note also that the 2+1D NSW equations in spherical coordinates are as follows:

$$\begin{aligned}
h_t + \frac{(uh)_\psi}{R\cos\varphi} + \frac{(vh\cos\varphi)_\varphi}{R\cos\varphi} &= 0,\\
u_t + \frac{uu_\psi}{R\cos\varphi} + \frac{vu_\varphi}{R} + \frac{gh_\psi}{R\cos\varphi} &= \frac{gd_\psi}{R\cos\varphi} + \frac{uv\tan\varphi}{R} + f\,v,\\
v_t + \frac{uv_\psi}{R\cos\varphi} + \frac{vv_\varphi}{R} + \frac{gh_\varphi}{R} &= \frac{gd_\varphi}{R} - \frac{u^2\tan\varphi}{R} - f\,u,
\end{aligned} \tag{7}$$

where ψ is longitude, φ is latitude, $h = h(\psi,\varphi,t) + d(\psi,\varphi,t)$, $h(\psi,\varphi,t)$ is the amplitude, $d(\psi,\varphi,t)$ is the undisturbed water depth, $u(\psi,\varphi,t)$ and $v(\psi,\varphi,t)$ are the depth-averaged velocities in the longitude and latitude directions respectively, g is the gravity acceleration, f is the Coriolis parameter ($f = 2\omega\sin\varphi$), R is the Earth's radius and ω is the angular velocity of the Earth. For computations, the equations are split into the following two 1+1D systems, as before. The two terms of the momentum equations, $uv\tan\varphi/R$ and $u^2\tan\varphi/R$, are usually omitted for computations due to smallness, to increase simulation speed.

$$\begin{aligned}
h_t + \tfrac{(uh)_\psi}{R\cos\varphi} &= 0,\\
u_t + \tfrac{uu_\psi}{R\cos\varphi} + \tfrac{gh_\psi}{R\cos\varphi} &= \tfrac{gd_\psi}{R\cos\varphi},\\
v_t + \tfrac{uv_\psi}{R\cos\varphi} &= 0,
\end{aligned}
\quad \text{and} \quad
\begin{aligned}
h_t + \tfrac{(vh\cos\varphi)_\varphi}{R\cos\varphi} &= 0,\\
v_t + \tfrac{vv_\varphi}{R} + \tfrac{gh_\varphi}{R} &= \tfrac{gd_\varphi}{R},\\
u_t + \tfrac{vu_\varphi}{R} &= 0.
\end{aligned} \tag{8}$$

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NOTATION

The following symbols are used in this paper:

d = undisturbed water depth;

d_0 = initial sea surface (seafloor) displacement;

f = Coriolis parameter;

g = acceleration of gravity;

h = total height of the water column measured from bottom (flow depth);

p, q, v' = Riemann invariants;

R = Earth's radius;

t = time;

u = horizontal component of depth-averaged velocity in x-direction (longitudinal);

v = horizontal component of depth-averaged velocity in y-direction (latitudinal);

η = amplitude;

λ = eignvalue;

φ = latitude;

ψ = longitude.

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List of Tables

TABLE 1. Representative forecast accuracies since 2004.

Event number	Event Date	Event location	Earthquake magnitude, M_w	Number of forecasts	Model accuracy
1	26 December 2004	Sumatra	9.1	-*	Amplitudes bellow noise
2	3 May 2006	Tonga	7.9	8	70%
3	15 November 2006	Central Kuril Islands	8.3	12	85%
4	13 January 2007	Kuril Islands	8.1	15	78%
5	1 April 2007	Solomon Islands	8.1	7	Amplitudes bellow noise
6	15 August 2007	Peru	8.0	14	95%
7	12 September 2007	Sumatra	8.4	16	95%
8	14 November 2007	Antofagasts	7.7	4	Amplitudes bellow noise
9	15 January 2009	Kuril Islands	7.7	7	Amplitudes bellow noise
10	18 February 2009	Kermadec Islands	7.3	-*	Amplitudes bellow noise
11	19 March 2009	Kermadec Islands	7.8	6	Amplitudes bellow noise
12	10 August 2009	Andaman	7.7	-*	Amplitudes bellow noise
13	29 September 2009	Samoa	8.0	15	75%
14	3 January 2010	Solomon	7.2	-*	Amplitudes bellow noise
15	27 February 2010	Chile	8.8	25	76%
16	6 April 2010	Northern Sumatra	7.8	-*	Amplitudes bellow noise
17	25 October 2010	Mentawai, Indonesia	7.7	-*	Amplitudes bellow noise
18	21 December 2010	Bonin Islands	7.4	6	Amplitudes bellow noise
19	25 December 2010	Vanuatu	7.3	1	Amplitudes bellow noise
20	11 March 2011	Tohoku	9.1	32	69%
21	6 July 2011	Kermadec Islands	7.6	2	Amplitudes bellow noise
22	11 April 2012	Sumatra	8.6	-*	Amplitudes bellow noise
23	27 August 2012	El Saldova	7.4	-*	Amplitudes bellow noise
24	5 September 2012	Costa Rica	7.6	-*	Amplitudes bellow noise
25	28 October 2012	Haida Gwaii	7.8	38	68%
26	7 November 2012	Guatemala	7.4	-*	Amplitudes bellow noise
27	7 December 2012	Honshu, Japan	7.2	54	Amplitudes bellow noise
28	6 February 2013	Santa Cruz Islands	7.9	30	78%
29	1 April 2014	Iquique, Chile	8.1	31	85%
30	12 April 2014	Solomon Islands	7.6	3	Amplitudes bellow noise
31	13 April 2014	Solomon Islands	7.4	-*	Amplitudes bellow noise
32	18 April 2014	Guerrero, Mexico	7.3	-*	Amplitudes bellow noise
33	19 April 2014	Solomon Islands	7.5	-*	Amplitudes bellow noise
34	14 October 2014	Nicaragua	7.3	-*	Amplitudes bellow noise
35	18 July 2015	Santa Cruz Islands	6.9	-*	Amplitudes bellow noise
36	16 September 2015	Chile	8.3	38	71%
Summary			Range of M_w	Total forecasts	Average accuracy
			7.2 - 9.1	364	79%

*Note: No high-resolution coastal forecast models were run. Only deep-water tsunami propagation forecast was performed based on DART data comparison.

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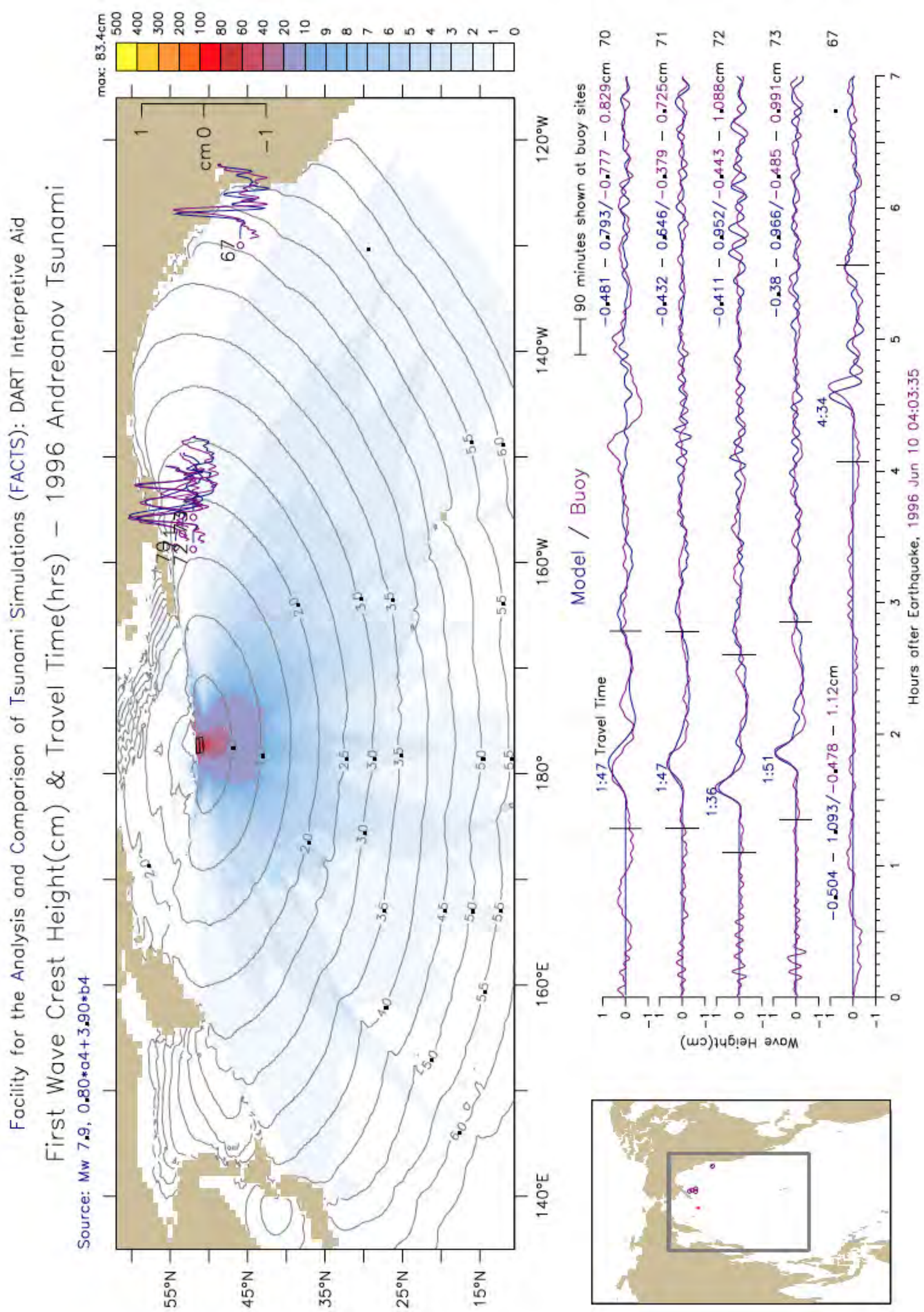

FIG. 1. MOST propagation model simulation of the 1996 Andreanov tsunami and comparison with bottom pressure recordings, one of the first open ocean records of a tsunami with a tsunameter. Red and blue lines represent buoy measurements and model estimates respectively.

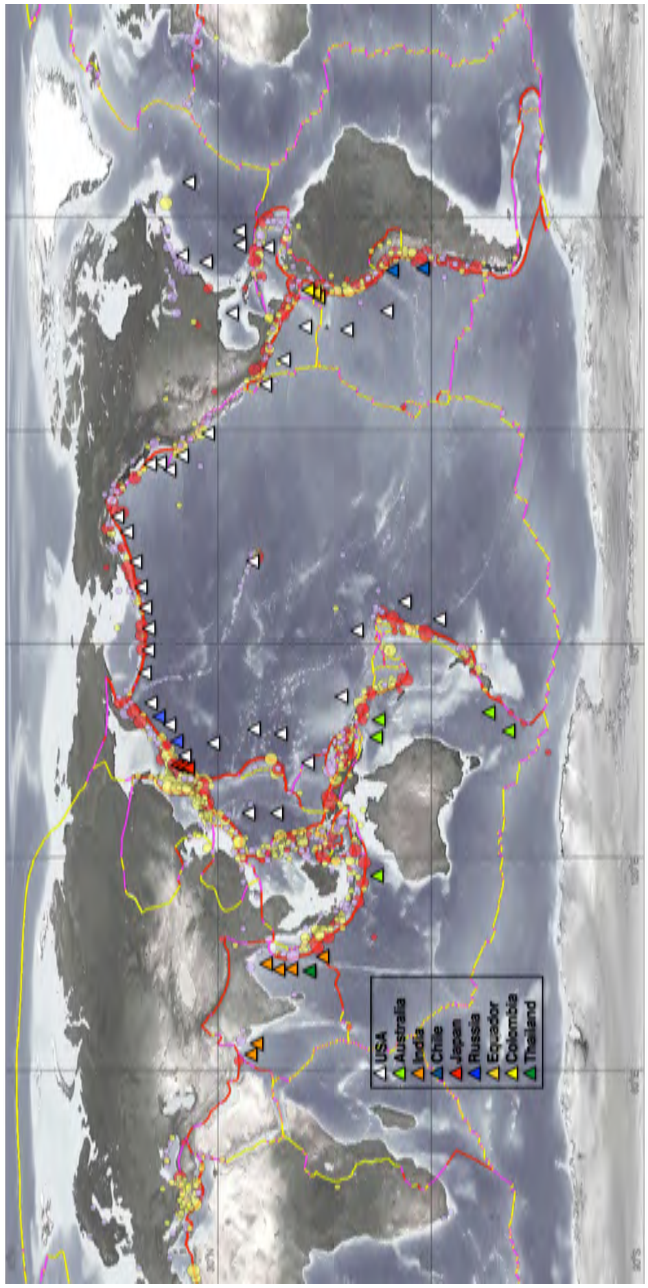

FIG. 2. Current DART array of the International Tsunami Warning System.

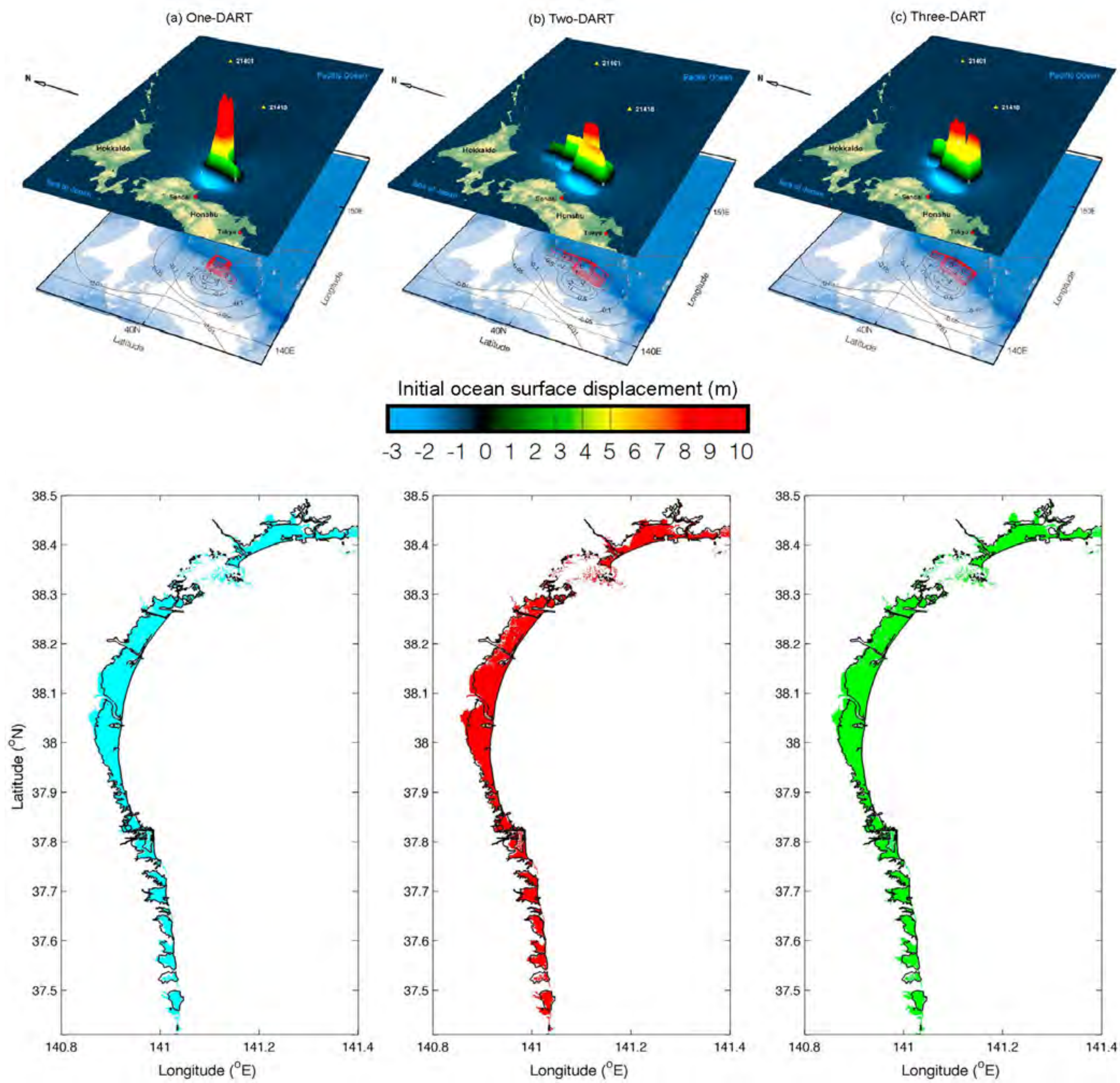

FIG. 3. Near-shore MOST estimates of the 2011 Tohoku tsunami flooding. Tsunami flooding area at Sendai plain area shown for three forecast sources obtained with (a) one-, (b) two- and (c) three-DART recordings (Kânoğlu et al. 2015).

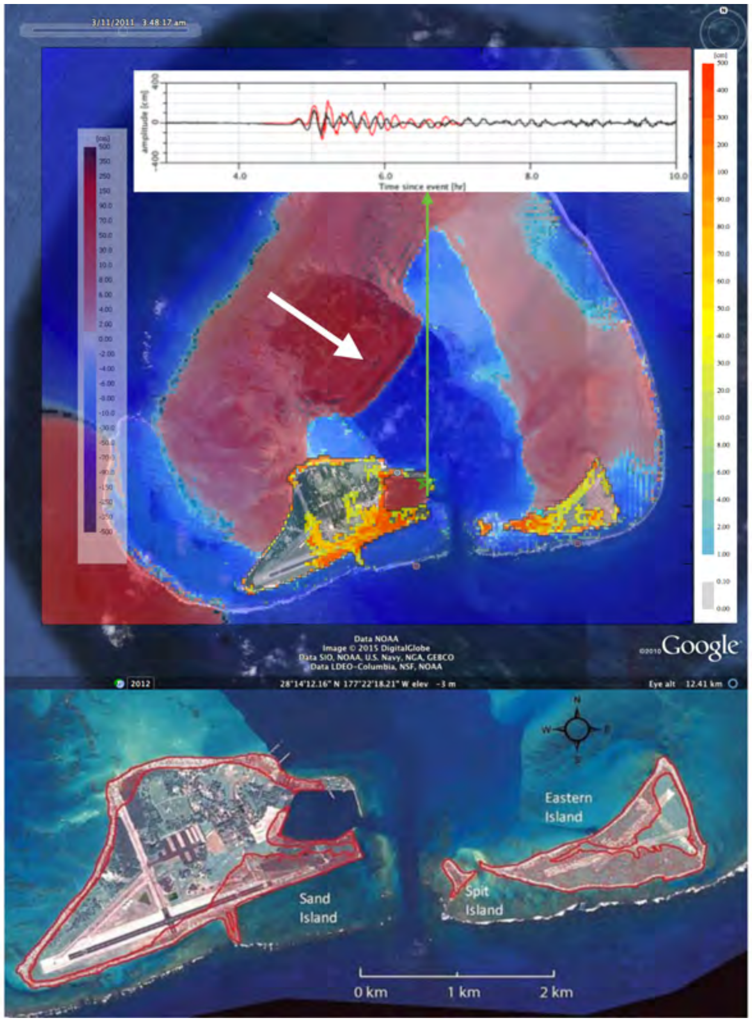

FIG. 4. Model forecast of flooding in Midway Atoll from the 2011 Tohoku tsunami. Upper panel shows MOST results with blue-and-red colors showing the second tsunami wave inundating the atoll lagoon (white arrow shows the direction of tsunami propagation) including comparison of forecast wave height estimate with tide gage measurement (inset). Green-yellow-red colors over the islands show maximum forecasted inundation. Bottom panel shows flooding area measured after the event.

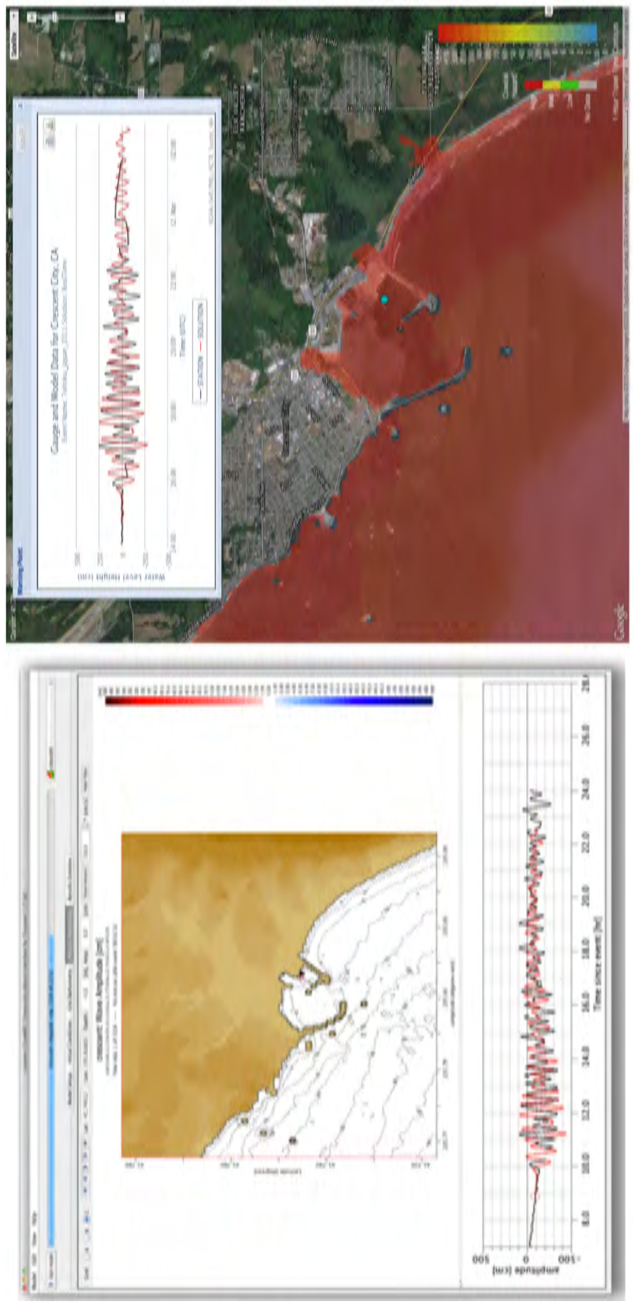

FIG. 5. MOST results for the 2011 Tohoku tsunami impact at Crescent City, California. Left panel shows tide gage model (red line) and measurement including tidal level change (black line) during the event. The location of the tide gage is shown as black triangle on the map. Right panel shows results of the same event simulation done at high tide level and associated flooding on Tweb map.

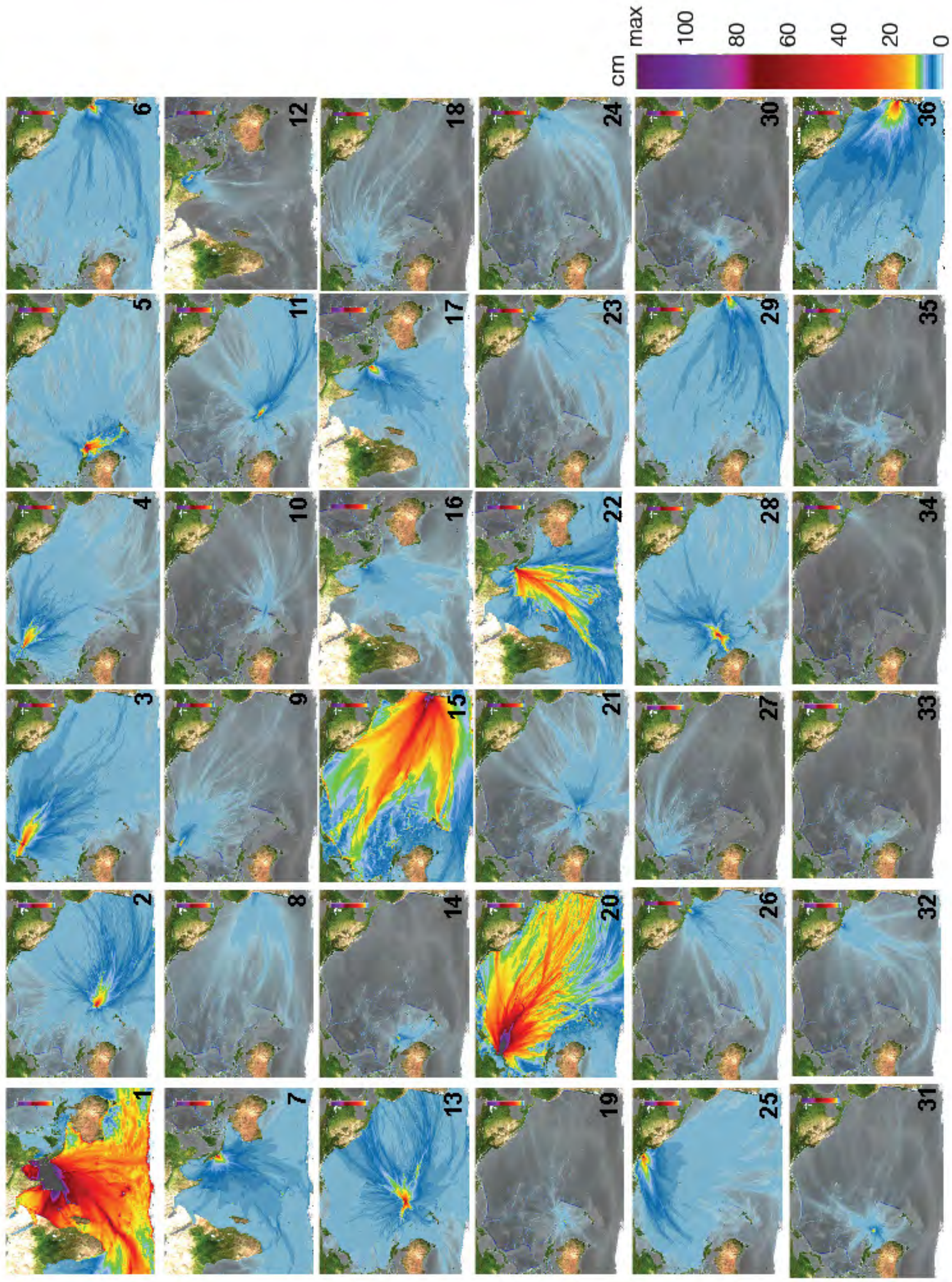

FIG. 6. Tsunami events since 2004 used in real-time benchmarking of MOST flooding forecast. The mosaic of maximum offshore amplitudes computed with MOST model are shown as representation of tsunami energy distribution during ocean-wide propagation. The tsunamis are listed in Table 1 and are given in chronological order left to right, top to down, starting from the 2004 Indian Ocean on top left, ending at 2015 Chilean tsunami on lower right. Thirty-six events shown in the figure are the tsunamis recorded at DARTs (except the Indian Ocean tsunami), the data that constrained the real-time assessment with the MOST model.