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Tsunamis: bridging science, engineering and society

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Tsunamis are high-impact, long-duration disasters that in most cases allow for only minutes of warning before impact. Since the 2004 Boxing Day tsunami, there have been significant advancements in warning methodology, pre-disaster preparedness and basic understanding of related phenomena. Yet, the trail of destruction of the 2011 Japan tsunami, broadcast live to a stunned world audience, underscored the difficulties of implementing advances in applied hazard mitigation. We describe state of the art methodologies, standards for warnings and summarize recent advances in basic understanding, and identify cross-disciplinary challenges. The stage is set to bridge science, engineering and society to help build up coastal resilience and reduce losses.

1. Introduction

Geological hazards are threats beyond the countries in which they originate, but they can also cause wide scale devastation and deaths across national boundaries. To wit, the 2004 Boxing Day tsunami impacted at least 16 countries directly [1], and tourists from many other overseas nations—about 1 in 20 000 of Sweden's population perished in this event. On a smaller scale, the 2010 eruptions of Eyjafjallajökull, Iceland interrupted air traffic over Europe for several days [2].

After the 2004 tsunami, Huppert & Sparks [3] suggested that 'It is likely that in the future, we will

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experience several disasters per year that kill more than 10 000 people'. Sadly for the world, this proved accurate, on average. The Great East Japan earthquake disaster on 11 March 2011 alone resulted in more than 20 000 casualties, while tsunamis and other natural disasters have killed over 200 000 since Boxing Day 2004, e.g. Hurricane Katrina in 2005 caused casualties exceeding 1200 [4], tropical cyclone Nargis in 2008 caused the worst natural disaster in Myanmar's recorded history with death toll estimates exceeding 138 000 [5] and Typhoon Haiyan killed more than 6000 people [6]. Earthquakes in Pakistan in 2005, in Eastern Sichuan, China in 2008 and in Haiti in 2010 caused more than 80 000, 87 000 and 160 000 casualties, respectively.

The 2004 Boxing Day tsunami was the motivation for the publication in these *Philosophical Transactions* of a theme issue [7] on extreme natural hazards, which followed an extraordinary meeting in the Royal Society in 2005. In the issue's introduction, Huppert & Sparks [3] speculated that a disaster with a million casualties might be a matter of time. Jackson [8] wrote then about the geohumanoid *fatal attraction*; earthquakes occur in places where they would likely cause more casualties compared to earlier times, because many rural communities have grown much larger with mostly poor building standards. The same is true for coastal communities which are now centres of substantial commercial activities. Tourism is now universal and usually concentrated along shorelines with sandy beaches, which are particularly vulnerable to tsunamis. The 1956 Amorgos tsunami [9] featured flooding elevations of over 5 m in several Aegean islands; it took place at a time when tourism was unknown in the Aegean. Had it happened today, during the summer, tens of thousands would be at risk. Worldwide, tens of millions of people live in high-risk coastal communities, and at any given time, hundreds of thousands of tourists are taking the sun on beaches, vulnerable to tsunamis and extreme weather events.

Tsunamis are generated by impulsive geophysical events of the seafloor and of the coastline, such as earthquakes [10,11], submarine or subaerial landslides [12] and meteorological events [13], and, less commonly, by volcanic eruptions [14], and even more rarely by asteroid impacts [15,16]. Tsunamis are long waves with small steepness that transform dramatically, through spatial and temporal spreading from their source region. The energy propagation maps of the 26 December 2004 [17] and 11 March 2011 [18] tsunamis are suggestive of abstract art as much as of great science (figure 1).

Tsunamis are high-impact, long-duration disasters, often with multiple waves attacking target coastlines, necessitating challenging rescue efforts. Even though secondary effects such as fire and debris flows [19] are common (figure 2), the insularity of ignorance in the design and in the evaluation of the safety of critical coastal structures and facilities can lead to catastrophic failures, as pointed out by Synolakis & Kânoğlu [20].

This contribution summarizes some key advances since the publication of Huppert & Sparks [7], as presented in the 13 papers, triggered by rapid developments in the science of tsunamis, but also from the forthcoming 5-year anniversary of the 2011 Great East Japan Earthquake Disaster. Tsunamis did become more known among most lay people around the world, after Boxing Day 2004, with snippets of eyewitness videos of the advancing tsunami dramatized in films such as 'The Impossible'. Yet, it was the dramatic footage, on occasion broadcast live, from the 2011 Japan tsunami which allowed most people to visualize tsunami inundation, far better than any of the few tsunami experts in the 1990s could. Then, only a few photos of advancing tsunamis existed, notably of the 1946 tsunami hitting Hilo, Hawaii, and of the 1995 Manzanillo tsunami [21], the latter resulting in the development of the theory of leading depression N-waves (LDN) [22,23], and the paradigm shift in the studies of tsunamis [24]. For the record, the first historical inference of coastal inundation by tsunamis was likely triggered for the eruption of the Thera volcano in the eastern Mediterranean, believed to have occurred around 1620 BC, which precipitated the demise of the Minoans on Crete [25]. Alexandria disappeared as one of the centres of the meta-ancient world following the AD 365 event [26], while the 1755 tsunami ended Portugal's imperial power and created the late eighteenth century fascination with natural hazards and their impacts on people, candidly portrayed in Voltaire's *Candide*.

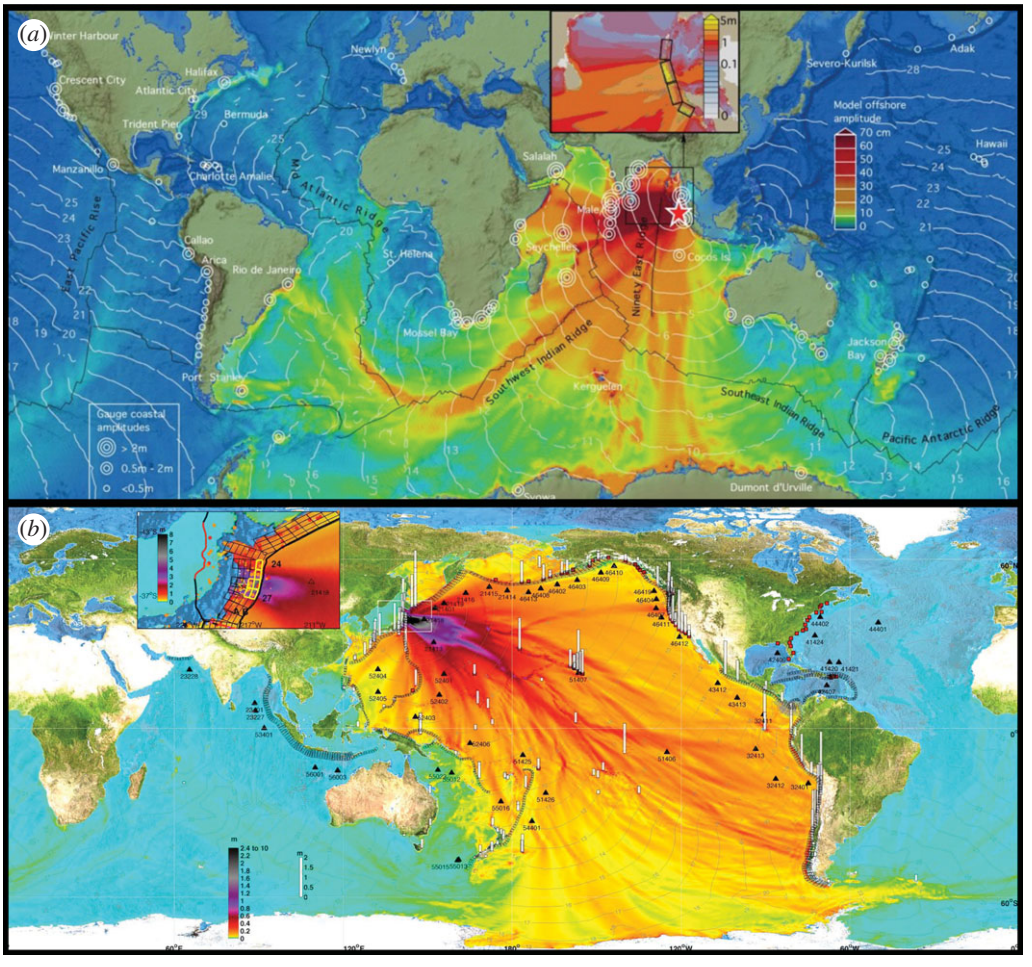

Figure 1. Global computed maximum tsunami heights of (*a*) the 26 December 2004 [17] and (*b*) the 11 March 2011 [18] tsunamis calculated from numerical model of Method of Splitting Tsunami (MOST). Contours show computed tsunami travel time. Colour-filled contours show predicted maximum tsunami amplitudes in deep water.

The scientific challenge for mitigating the effects of tsunami hazards is perhaps best articulated by Okal [27]. He writes that 'our quest for wisdom in the management of tsunami hazard shares some conceptual philosophy with Zeno of Elea's paradox: like Achilles, our communities seem well armed to constantly gain in *wisdom* and progress towards mitigation of a perceived level of tsunami hazard, but individual new events often bring an element of diversity which redefines the goal, and like the Tortoise, keeps pushing it forward, in an everlasting challenge'.

While our intent is to focus on substantial advances and challenges identified since the earlier theme issue [7], we will at first briefly discuss advances in the decade before the Boxing Day tsunami, to place the following decade in context. We note that Bernard & Robinson [28] published the first textbook documenting the use of deep-ocean tsunami measurements to forecast real-time flooding along the coastline, while recently, Kânoğlu & Synolakis [29] presented advances in validated and verified numerical codes for prediction of tsunami evolution and mitigation. To paraphrase Okal [27], our objective in what follows is to gain in wisdom and progress towards effective hazard mitigation, pursuing key recent events from which we learned, and which we think we understand better than earlier ones.

Figure 2. A picture from Kesennuma, Japan in the aftermath of the 2011 tsunami. The stranded ship was located about 750 m from the edge of the port. It is believed that the ship was floating somewhere in the middle of the bay, near the port.

2. Key advances between the 1992 Nicaraguan and the 2004 Indian Ocean tsunamis

A key advance in this decade was the development of two-dimensional numerical codes to estimate the inundation and overland flow depths of advancing tsunamis. Computing inundation in sufficient time to warn populations at risk and giving them enough time to evacuate to safer locales is a challenge for tsunami engineering. The development was made possible by examining detailed inundation and run-up measurements from tsunami surveys, and then determining what was the appropriate approximation of the parent equations of hydrodynamics, and what information was necessary to properly initialize computations.

Before 1992, there were no robust computational methodologies to even determine the one-dimensional inundation of idealized wave forms over simple bathymetries. The quest for better defining the initial conditions led to the development and deployment of tsunameters,[1] a key technological advance from the National Oceanic and Atmospheric Administration (NOAA) Center for Tsunami Research (NCTR) of the Pacific Marine Environmental Laboratory (PMEL) [31–33].

The 1 September 1992 Nicaraguan event remains a landmark tsunami, widely believed to have ushered the modern era in tsunami science. Contemporaneous calculations with existing models showed almost order-of-magnitude differences with measurements. More scientists participated in the subsequent field survey than in any other pre-2004 survey, most believing that this was to be the only event they would be able to study in detail in their professional careers. It was followed by the 12 December 1992 Flores tsunami, and by other tsunamis striking about once a year, on average, somewhere in the world. Most with run-up heights over 2 m were surveyed to measure inundation and run-up data, and allowing studies in detail of their parent earthquakes and tsunamis they triggered [27,34].

[1]The name *tsunamometer* was used in a relevant article in the science section of *The Economist*, in 2003 [30], where the technology was highlighted. It is also known as Deep-ocean Assessment of Tsunamis (DART) or as tsunamograph.

The Nicaraguan tsunami had three remarkable features. One, its triggering earthquake was not felt by eyewitnesses, hence there was no natural warning for coastal residents, and there was no warning from the Pacific Tsunami Warning Center. Subsequent analysis showed that it was a textbook *tsunami earthquake* or *slow earthquake* [35,36], which is a seism whose tsunami has far greater amplitude than expected from its conventional magnitude. The textbook on tsunami earthquakes, however, is yet to be written.

To wit, in 1993 Okal [36] asserted that the goal of tsunami research and warnings should be the understanding of tsunami earthquakes, there has been little progress in defining their causes, but more in characterizing them once they happen. Three more such slow earthquakes followed, the 17 July 2006 Java slow earthquake produced a tsunami with run-up reaching 21 m and with over 800 deaths [37], the 25 October 2010 Mentawais event with ∼16 m maximum run-up and causing 509 deaths [38], and the 27 August 2012 El Salvador event [39] with 6 m maximum run-up, but with no deaths.

Two, the run-up distribution in Nicaragua showed substantial alongshore variation, even over sub-kilometre distances, over what is largely an open and fairly straight coastline. Similar observations were made later during the field survey of 1994 East Java and 1996 Peruvian tsunamis. Extreme near-shore features were found to affect the run-up to first order, and this was confirmed in the analytical study by Kânoğlu & Synolakis [40]. The implication was that threshold models, i.e. wave evolution numerical models which interrupt the computation at some threshold offshore location, are inadequate to resolve these differences. Yet as reported by Synolakis & Kânoğlu [20], the pre-event analysis of the Fukushima nuclear power plant (NPP) does not seem to have considered overland inundation at the plant, as the computations published [41] by the operating utility appear to have stopped at a location offshore.

Three, the Nicaraguan tsunami manifested itself with an initial shoreline recession. Being a slow earthquake, this was the only precursor to the coastal residents, who, however, did not identify it as such. Tadepalli & Synolakis [23] presented analytical solutions for maximum run-up considering dipolar waves, which they named N-waves, as leading waves of tsunamis. They showed that LDN run up higher than their mirror images, leading elevation N-waves (LEN). This was a paradigm change from solitary waves to N-waves, which had been earlier considered unstable. Tens of descriptions from eyewitnesses of the 2004 Indian Ocean tsunami and mareogram records [42] confirmed both the N-wave hypothesis, and that subduction zone earthquakes typically generate LDN propagating towards the adjacent shoreline, while LEN propagate towards the open ocean [22]. Later, Kânoğlu *et al.* [43] showed that the amplification effect of N-waves in two-dimensional propagation can be even more dramatic, enhancing the run-up at specific locations along coastlines.

Three more defining events occurred in this 12-year period.

On 12 December 1992 in Flores, Indonesia another earthquake triggered a tsunami which devastated the northeast coast of Flores, with unusual run-up in the lee-side of the conical-shaped Babi Island located in between the epicentral region and Flores [44,45]. There was controversy as to whether the enhanced run-up was due to reflection of the tsunami off Flores or some unidentified hydrodynamic effect. This was resolved by the first large-scale laboratory visualization of a tsunami inundation, over a realistic two-dimensional bathymetry and topography [40,46,47] demonstrating that, once the wave hits the circular island, the crest splits into two waves propagating around the island and colliding behind it, in a spectacular demonstration of constructive interference. The analytical solutions developed [40] and the associated laboratory data have since been used extensively for benchmarking of tsunami numerical models [48], as described in [49].

The 12 July 1993 Nansei-oki earthquake generated a tsunami that devastated the island of Okushiri west of Hokkaido. The maximum height 11 m tsunami overflowed the 4.5 m seawall which, probably, was built based on the 1983 Japan Sea tsunami. In its aftermath, it was argued [50] that this should have raised serious concerns, since in several places along the Japanese Pacific coast, 6 m high seawalls had been constructed, based on the impact of the 1960 Chilean tsunami. The field measurements from the 1993 tsunami along with high-quality

bathymetric and topographic data eventually became a benchmark for validating numerical codes. For the record, the numerical model developed by Titov & Synolakis [48,51] now known as MOST was able to successfully model the extreme run-up value of 33 m at a river gully near the town of Monai [52].

In the context of the Fukushima disaster, one perplexing aspect of the Okushiri event is discussed in this issue [20]. In its aftermath, Japan spent over US$600M (in 1998 $) to build an 11 m high seawall to protect about 20 km of coastlines and rebuilt the main town of Aonae. Even so, population dwindled from 4679 in 1993 to 3160 in 2012 [53]. In essence, US$130K were spent per resident, with Japan thus expressing a commitment to tsunami hazard mitigation, which unfortunately the 11 March 2011 event underscored as not having been uniformly applied elsewhere.

On 17 July 1998, a moderate earthquake in Papua New Guinea (PNG) triggered a maximum run-up 15 m tsunami with over 2100 fatalities. The extent and depths of inundation could not possibly be explained by any known earthquake model. The subsequent field survey [54] hypothesized that the seism triggered a submarine landslide. A hydroacoustic record in Wake Island [55,56] identified beyond doubt the characteristic signature of the landslide through comparisons with the acoustic signatures at the same locale from the earthquake and its aftershocks [57,58]. The PNG event led to inclusion of landslide scenarios in inundation maps for civil preparedness [59,60].

Beyond the development of benchmarked computational codes such as MOST [48,51] which solve the shallow water wave equations, an approximation of the Navier–Stokes equations of hydrodynamics, in this period numerical simulations to higher order approximations of the equations of motion started being developed. One such was the solution of Euler's equations with the un-approximated dynamic free surface boundary condition [61], a numerical approach now known as fully nonlinear potential flow (FNPF). Grilli *et al.* [62] then applied it to the studies of the evolution of landslide waves. The comments of [20] regarding the futility of higher order numerical solutions in a physical problem where the uncertainties of the initial condition are far greater than differences in inundation estimates of different solution methods notwithstanding, FPNF represented a great step forward for routine application of nonlinear and dispersive long-wave models. We note that the first tsunami-relevant Large Eddy Simulation (LES) of the Navier–Stokes equations appears to have been that of Liu *et al.* [63] in the context of simulating underwater solid block landslides. Subsequent developments are discussed by Behrens & Dias [64].

Just before 2004, real-time tsunami forecasts based on the assimilation of measurements from tsunameters started happening. NCTR tested its real-time forecasting capability during the 2003 Rat Island tsunami [65,66] for the first time. Since then, this forecasting methodology has been tested in real time for each event in the Pacific and is discussed in the next section. It is important to note that the PMEL had deployed five tsunameters in the northern Pacific before 2004 to augment real-time forecasts and assist the tsunami warning centres (TWCs).

3. The development of real time forecasts since 2004

Since 2004, NOAA has been developing real-time tsunami flooding forecast capabilities for the US coastlines and its territories [18,67,68] in support of TWCs in Hawaii and Alaska operated by NOAA's National Weather Service [65] in addition to long-term forecasting capabilities and hazard assessment products for the US National Tsunami Hazard Mitigation Program. As Synolakis & Kânoğlu [29] describe, during an event, the NCTR methodology integrates real-time deep-ocean observations of evolving tsunamis from several tsunameters with a pre-computed basin-wide propagation database of wave amplitudes and flow velocities through an inversion algorithm to refine the tsunami source as combinations of tsunamigenic unit sources. Then, it uses high-resolution tsunami inundation models to provide accurate and timely forecasts for tsunami-prone coastal communities. After rigorous testing with all available data including laboratory tests, analytical benchmarks, historical tsunami data and, most importantly, tests in real time with

all tsunami events over the past decade, it has been accepted for operational use at the two TWCs in 2013, while remaining under continuous testing and development at NCTR.

Currently, there are over 1750 pre-computed unit source propagation model runs covering the world's oceans and they are maintained at NCTR [69]. This coverage provides capability of modelling any tsunami from all major subduction and known tsunamigenic zones. A similar concept is in use by the Bureau of Meteorology, Australia [70], but with a different approach. Rather than employing unit sources, the Bureau uses specific earthquakes—from M 7.5 to 9—at specified locations. The same kind of database is in the process of development for the Mediterranean and the Aegean Sea [71]. Synolakis & Kânoğlu [29] describe how for real-time forecasts, as the tsunami propagates across the ocean and is recorded at tsunameter observation sites, sea level time-series are ingested into an inversion algorithm [72] to produce an improved estimate of the tsunami source for a given earthquake, in real time. Then, given the offshore scenario based on this estimate, high-resolution MOST with three nested telescoping grids takes over to produce inundation predictions at a specific coastal site. The methodology and examples are presented in Tang *et al.* [18,67] and Wei *et al*. [68].

To date, this appears the only operational methodology to predict inundation and flooding for vulnerable coastal locations. Tsunami flooding forecast is a critical component of a robust tsunami warning system, as it clearly separates events that do not require evacuation. At the same time, predictions of the extent of tsunami flooding clearly convey the threat level, without requiring additional interpretation by civil defence.

NOAA's real-time forecasting methodology was tested with every event during the in-house development since the 2003 Rat Island tsunami. The success of the system relies on several factors. One, it is based on MOST which is continuously validated and verified starting from its development in the early 1990s. Two, a critical component of the forecast system is the real-time measurements from the network of tsunameters deployed at specific locations in the world's oceans to provide rapid measurements of a passing tsunami. These measurements allow one to constrain the initial source reasonably well. Tsunameter data for recorded tsunamis (over 40 tsunami events) carry a tremendous scientific value for further understanding of tsunami origin and propagation. Most recent publications on tsunami modelling reference and use tsunameter data. The data provide breakthrough information to identify and solve challenging problems in tsunami hydrodynamics. One application has been in documenting the effects of dispersion, which according to Løvholt *et al.* [12], An & Liu [73] and Okal & Synolakis [74], appear quite limited, as all tsunameter records appear to be modelled with linear or nonlinear shallow water wave theory, in the far field.

A thorough review of the development of tsunami warning systems is presented by Bernard & Titov [75], particularly NCTR's development of the Community Modelling Interface for Tsunamis (ComMIT) [76], a Web-based community computational model. The objective was to transfer tsunami modelling expertise and capability to the Indian Ocean countries, following the relevant recommendation from UNESCO's Intergovernmental Oceanographic Commission. ComMIT is NCTR's MOST with a user-friendly interface and is distributed through a free one-week training programme. Hundreds of scientists and engineers from nations at risk have been trained to develop inundation scenarios and hazard maps, sufficient for public education campaigns.

As an example of ComMIT's capabilities, the 15 July 2009 tsunami off the west coast of South Island, New Zealand was modelled remotely during the International Tsunami Symposium in Novosibirsk, Russia, in real time in a meeting urgently convened before many attendees [77]. In a ComMIT training course in Tanzania, NCTR modellers inverted the source for the Japan tsunami, as it was reaching the first tsunameter, and made the source available to ComMIT users around the world. As a result, scientists in the USA, in New Zealand and in Turkey were able to use this source and run forecasting models for far-field locales around the Pacific Rim. Now, ComMIT is rapidly becoming a cloud-capable Web-based forecasting tool, TsunamiCast. This holds promise for the development of a global warning system as envisioned by Synolakis & Bernard [24].

4. Other key advances since the 2004 Boxing Day tsunami

The 2004 Boxing Day tsunami was a watershed event killing approximately 1 in 25 000 of the world's population at the time. Given the large increases in the population of coastal areas, this was possibly the most lethal tsunami for humanity. The hydrodynamic observations are discussed in [1,78] and science and policy implications in [24]. Its parent earthquake was the largest to have hit since the era of long period instruments, and the accurate determination of its size involved the examination of the normal modes of oscillation of the Earth triggered by the earthquake [79].

A major advance since 2004 is now the wide acceptance of the coupling of the atmosphere (including the ionosphere) with the ocean. While there were hints before 2004 [80,81], the 2004, 2010 and 2011 events demonstrated that the ionosphere is coupled to the ocean, just as the ocean is to the solid Earth [82]. The latter coupling was first suggested in Ward's [83] now classical interpretation of tsunamis in the normal mode formalism, later explored by Okal [56,84].

The tsunami science community grew by close to an order of magnitude following this event, field surveys of most events followed, and more evolved tectonic models were developed to help better define the seafloor deformation. Before 2004, most events were modelled with uniform slip models, i.e. the entire deformation area was considered as one segment, and the distribution of the seafloor displacement calculated by standard elastic models.

One key observation in the aftermath of the Boxing Day tsunami which led to substantial progress in our understanding was made in the Salalah, Oman port in [85], wherein substantial currents and vortical motions were reported. Yet, the tsunami run-up along the open coastline was less than 40 cm, and suspected that this was not necessarily harbour resonance. Similar observations were made in ports in Réunion [86] and Madagascar [87].

The 2011 Japan tsunami provided one spectacular demonstration of this phenomenon. In the near field, in the Port of Oarai, rotational currents lasting approximately 3 h after the earthquake created a large offshore vortex—see fig. 4 of [88]. A similar observation was made in Guam, where two nuclear submarines broke their mooring lines and wandered out of control in the outer and inner basins in the local US naval base. On the other side of the Pacific, a fire-department boat returning from the tsunami alert faced substantial currents trying to re-enter the Port of Los Angeles. Strong currents were observed in many California ports. Crescent City, California is known to amplify far-field tsunami surges [89,90], and experienced significant damage following the 1964 Great Alaska [91] and the 2006 Kuril Island tsunamis [92]. It also had non-trivial local effects following the 2009 Samoa tsunami [93].

While by 2011 coastal inundation was being routinely modelled robustly, less attention had been paid to currents and far less to overland flow velocities. While computational estimates about the currents were available along with inundation projections, the synthesis of understanding that even small tsunamis can generate large vortices near breakwaters had not been made until recently [88,94]. It is now clear that currents can be modelled up to first-order accuracy with MOST and likely other shallow-water codes compared to current-meter data. Benchmark problems for currents have been suggested by the US National Tsunami Hazard Mitigation Program Mapping & Modeling Benchmarking Workshop for validation and verification of numerical models. Not accounting for the possible loss of life, the loss of harbour facilities, even for a short time, can result in substantial monetary losses. Borrero *et al.* [94] discuss the hydrodynamics of the generation of currents in ports.

Behrens & Dias [64] present developments in unstructured and adaptive grid techniques to bridge the gap of scales involved in tsunami propagation and inundation simulation. They argue that while computational acceleration by adaptive mesh refinement, hardware acceleration by GPU utilization, and parallelization make even real-time tsunami forecast for certain near-shore tsunamis technically feasible, all communities need to rely on more traditional approaches and a well-educated population. This is also the conclusion from the paradigm shift in Japan's civil defence, discussed in the next section.

Several unifying scientific paradigms have fallen victim to the large events of the past 12 years. Among them, the proposed control of maximum earthquake magnitude at subduction

by the combination of plate age and convergence rate [95] which the 2004 Boxing Day and later 2011 Tohoku events grossly violated [96]. The seismic moment, epicentre location and earthquake mechanism are routinely determined in real time through the centroid moment tensor solution, except when they are not, the 2004 and later the 2011 events being good examples [27,97]. In addition, seismic scaling laws, relating earthquake magnitude to fault length, width and duration of rupture (essentially reducing the characterization of the earthquake to a single parameter) have not been confirmed for subduction zone mega events, especially regarding the so-called *tsunami earthquakes*, whose rupture velocities are significantly deficient. Validation of these laws, in the context of the widely used dislocation models would require pre- and post-event bathymetric measurements at sufficient resolution to allow for resolving 1 m seafloor displacements in thousands of metres of water depth. At any rate, the 2011 earthquake, with its coseismic displacement locally reaching 60 m, violates any interpretation of scaling laws, however stretched [27].[2]

It is thus quite clear that seismic inversions are not sufficient for accurate real-time forecasts for the largest of earthquakes, likely to have the most impact. Possibly the greatest advance in terms of warnings has been the implementation of hydrodynamic inversions based on tsunameter measurements, as detailed by Bernard & Titov [75]. In these cases, normal mode analysis is needed, but this cannot happen in real time, yet. Yet, this is precisely the information needed to define the initial sea-state that accompanies tsunami-triggering earthquakes. Hence, the augmentation of the geophysical inversions with hydrodynamic measurements, now routine, allows for accurate far-field forecasts; for example, only one tsunameter recording was needed for a fairly realistic forecast, with a fairly accurate inversion possible with two [18], for the 2011 Japan event. Improvements in these combined seismic/hydrodynamic inversions are likely to help resolve the vexing issue with slow earthquakes, whose identification in real time remains problematic, if not outright impossible. Here, we note that progress is being made through GPS-based inversions [99] (figure 3).

As England *et al.* [10] claim, the dominant uncertainties in assessing tsunami hazards are attached to the location and size of the sources. As the development of the design tsunami for the Fukushima NPP demonstrated [20], when absence of evidence of historic tsunamis is interpreted as evidence of absence, the results can be devastating. Given that most of the relative plate motion in the eastern Mediterranean is aseismic, 'the modern record of seismicity provides little or no information about the faults that are likely to generate large earthquakes'. A similar conclusion is implicit in Satake's [11] analysis of the irregular nature of recurrent earthquakes in Japan.

Evidence of large earthquakes ($M > 8$) in the eastern Mediterranean is scarce and this delayed until recently the establishment of tsunami warning systems in the region [100]. There are two large events known, in AD 365 [26] and AD 1303 [101]. There is little known about the AD 1303 event, other than its tsunami also destroyed Alexandria, Egypt [102]. For the AD 365 event, it was unclear if the geological evidence of uplift was due to a single or a series of events. There is only a handful of on-land paleotsunami studies in the eastern Mediterranean, and most have focused on evidence from the Bronze Age eruption of the Thera volcano [25]. One reason is that the near-shore coastline is heavily populated, and thus the stratigraphy is mostly quite disturbed to have preserved sedimentologic evidence of past tsunamis.

To address, Rhodes *et al.* [103] wondered whether a record of paleotsunamis exists in the near offshore stratigraphic record. Significant attention was given to at a site off Caesarea, Israel, in which the shoreline to 30 m water depths was found to provide ample evidence that the near offshore record is an important tsunami deposit archive. Goodman-Tchernov *et al.* [104] and others [105,106] overcame some practical issues of collecting controlled stratigraphic sequences from sandy sequences, through the use of custom-built diver-operated pneumatic coring tools.

[2]We note that a landslide trigger has been proposed to explain this displacement, but we favour the McKenzie & Jackson's [98] wedge hypothesis.

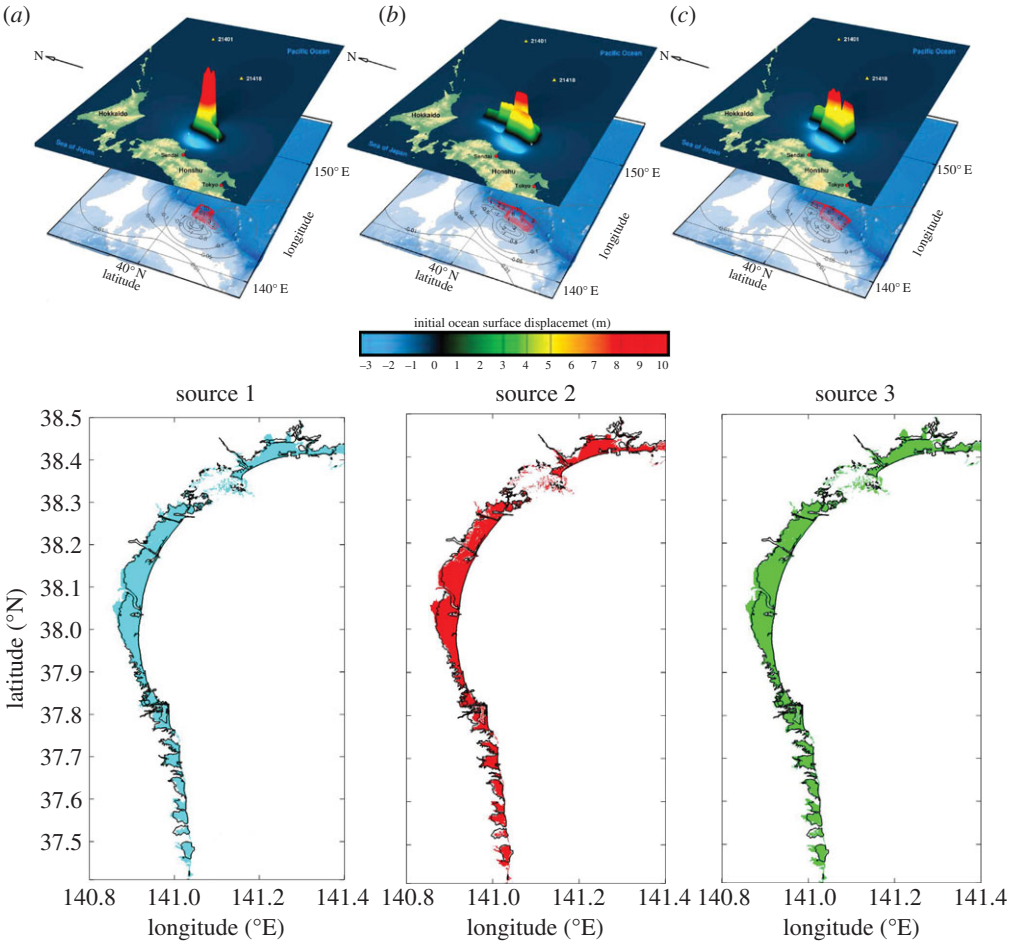

Figure 3. Run-up distribution along the Japan coast after the 2011 tsunami using MOST and inversion from one, two, and three tsunameter inversion. The timings of the inversions were approximately 40 min, 1.2 h, and 1.75 h after the event, respectively. The solid line is the field measurements.

A spectacular development since 2004 was the identification that the long-known AD 365 earthquake was due to a single event with an estimated $M \sim 8.5$. Shaw *et al.* [26] identified coral in rock holes left by petrophagea in several outcrops in southwest Crete; the key observation was that coral of the same geologic age was present in petrophagea holes along the same face at different elevations. This work led to subsequent re-evaluation of the hazard, as summarized by England *et al.* [10].

England *et al.* [10] identify candidate tsunami sources along the Hellenic plate boundary, which they show pose a significant hazard in North Africa and the eastern Mediterranean. One important finding is that given the lack of historic and geologic data, probabilistic assessment of the hazard is futile.

The unrest of the Thera volcano in the Aegean between 2011 and 2013 identified several shortcomings in local civil preparedness and basic science understanding. In terms of the former, the local community first attempted to appear to ignore the possibility of an eruption of the sort that occurs in Thera approximately every 50 years, but eventually understood the futility of this approach, and realized that the biggest problem in the case of the eruption was how to handle the tens of thousands of disaster spectators that might congregate to the island. An insular local science establishment in Greece had to eventually consider the advice of international experts,

in contrast to what was witnessed in Japan before 2011. Sadly, the opportunity to monitor the pre-paroxysm activity with ocean bottom seismometers (and thus better define the evolution of the magma chamber) was missed, both due to lack of interest from the US National Science Foundation and due to local science politics.

Paris [14] reviews the sources of tsunamis generated by eruptive processes, rapid ground deformation and slope instability at volcanoes. Volcanic tsunamis are characterized by short to moderate wave lengths. Their impact in the far field is often limited, but local impact is potentially disastrous. Mechanisms of tsunami generation by volcanic earthquakes, slope instabilities, pyroclastic flows, underwater explosions, shock waves and caldera collapse are discussed, based on observations of past events and results of numerical simulations. He argues that considering the diversity of source mechanisms, prevention of volcanic tsunamis through monitoring is challenging and needs to be coupled with population preparedness. Existing tsunami warning systems are not suited to deal with volcanic tsunamis. The challenging goal is to integrate all types of tsunami sources in tsunami hazard and warning systems remains.

Impacts of meteorites are potentially the most catastrophic of natural disasters [15,107]. When in the sea, they may affect wider areas through the generation of oceanic waves, compared to similar sized impacts on land. Wüennemann & Weiss [15] in this issue discuss how two different forms of oceanic waves form, an ejecta curtain spray and those generated by the collapse of the transient crater. The latter strongly depends on the ratio between water depth and the size of the transient crater. One basic conclusion is that the generation mechanism is quite different from that of submarine landslides, and that close to the generation region the initial wave can be of the same order as the water depth.

Numerical modelling of such tsunamis involves both understanding the hypervelocity impact and the cratering process. As suggested in Wüennemann & Weiss [15], there are very few codes capable of modelling the entire phenomenology, and they are commonly referred to hydrocodes, and thus the wave evolution can only be tracked to within about 100 times the diameter of the bolide object. They thus implement a multi-stage simulation of different spatio-temporal scales, to model the 2.5 million year old Eltanin event, possibly the only known deep ocean impact. Such models could be useful not just in producing more realistic special effects in Hollywood disaster movies, but also in assessing the inundation from future impacts, which are more likely to take place in the sea than on land.

High-end computational tools now allow for inundation predictions, even from submarine landslides, i.e. at least for those generated in a laboratory where initial condition is defined quite satisfactorily. New analytical results help explain the scaling of vexing tsunami evolution problems. For example, Kânoğlu *et al.* [43] recently identified a focusing mechanism, which might amplify tsunami run-up significantly. They introduced an exact analytical solution for propagation for a finite strip source over constant depth using linear shallow water wave theory, introducing realistic initial waveforms such as N-waves. They showed the existence of focusing points for N-wave-type initial displacements, i.e. points where unexpectedly large wave heights may be observed. Note that their analysis is different from Berry's [108], who considered focusing effects by underwater bathymetric diffractive lenses. In addition, Kânoğlu *et al.* [43] explored focusing phenomena analytically under linear dispersive, and numerically under nonlinear non-dispersive and weakly nonlinear weakly dispersive theories confirming focusing exists for four approximations of the parent Navier–Stokes equations. Geophysical implications of this solution [43] might help to explain high local run-up values observed for the July 1998 PNG [58] and the July 2006 Java [37], and even the 2011 Japan [109] tsunamis, which are otherwise not consistent with existing scaling relationships.

The 2010 Mentawai tsunami did provide a key new observation [38]; enhanced run-up was measured along the west coast of the Mentawais, behind small offshore islands. Common intuition would suggest that these islands would offer protection to the 'land' areas behind them. To test the hypothesis whether the run-up on coastal areas behind small islands was significantly higher than on neighbouring locations not affected by the presence of the islands. Stefanakis *et al.* [110] used active learning to vary parameters in the simplified geometry of a conical island

sitting on a flat seafloor in front of a uniform sloping beach. Their experiment was defined by five physical parameters, namely the island slope, the beach slope, the water depth, the distance between the island and the plane beach, and the incoming wavelength, while the wave height was kept fixed. If one attempted to find the maximum run-up in a brute force manner with massive computations, this would have required at least 100 000 simulations, even considering 10 possible values for each of their five parameters.

To achieve their goal, Stefanakis *et al*. [110] built an emulator based on Gaussian processes to guide the selection in the parameter space, thus reducing substantially the computations required to identify the run-up amplification; instead of 100 000, they found the maximum with about 200 simulations. Their results show that the island acts as a focusing lens for energy, and amplifies the run-up along the continental coastline behind its lee side, instead of protecting it, as popular beliefs suggest. This appears to be the first application of active learning in tsunami hydrodynamics, a methodology which could greatly reduce computations to identify local maxima among hundreds of possible scenarios.

5. Paradigm changes since 2011, in Japan and elsewhere

The accident at the Fukushima NPP had worldwide consequences for nuclear power, and substantial impact in Japan which is yet to be fully understood. We note that only on 9 August 2015 did the first Japanese NPP start operating again, after all reactors in Japan were shut down for safety evaluations.

Synolakis & Kânoğlu [20] discuss in this issue the perils of insularity, by describing the run-up to the accident in terms of engineering. They argue that neither the impact of the 2004 tsunami on an Indian NPP, nor the knowledge acquired since then about maximum earthquake size in subduction zones did anything to change the nuclear culture in Japan. After studying thousands of pages of government, agency and think-tank reports, they conclude that the Fukushima Dai-ichi plant owner, the Tokyo Electric Power Company, and its principal regulator, the Nuclear and Industrial Safety Agency, failed to take simple steps to give the plants a sporting chance to safely shut down, even though pre-2011 there had been mounting evidence that their design against tsunami flooding was inadequate.

The key culprit they identify is the location of the emergency diesel generators at basement level; they describe how, even after the event happened, had the diesel generators been located at 6 m higher elevation than where they were, the plant would likely have survived. They also discuss the substantial shortcomings in the last tsunami safety assessment of the utility, presented before the accident [41], an issue also explored by Okal [27] in this issue. Given the inherent uncertainties and the lack of context with which many engineering evaluations still appear to be performed, Synolakis & Kânoğlu wonder whether future tsunami safety studies for critical facilities should just consider the $M \sim 9.6$ maximum possible earthquake of Kagan & Jackson [111], located anywhere along subduction zones which may affect the facility.

According to Kânoğlu & Synolakis [29], the report of the National Diet of Japan [112] is appropriately critical and explicitly states that arrogance, ignorance and insularity helped create a regulatory climate not conducive to the pursuit of excellence in safety studies. In this regard, and compared with the rationalizations of post-event local industry reports (which, on occasion, state that their earlier tsunami designs which failed were conservative), the National Diet of Japan report represents a momentous paradigm change for Japan in addressing engineering failures.

Estimating the occurrence and frequency of tectonic tsunamis is only as good as estimates of triggering earthquakes. As Stein *et al.* [113] discuss in a review of probabilistic studies, the discovery of plate tectonics in the 1960s allowed arguing that steady plate motions load plate boundary faults at constant rates, and lead to what should be quasi-periodic cycles of stress buildup and release and this led to the concept of characteristic earthquakes closely located and of similar size. Segments of plate boundaries which had not produced a large earthquake in the recent past were ‘seismic gaps’, where a quake was considered due or overdue.

While estimates of the geometry and rates of plate motions have improved and advances in space-based geodesy and seismology have provided new knowledge, reliably assessing earthquake hazards remains, to say the least, difficult. Stein *et al.* [114] argue that the history of recorded seismicity is too short to establish spatio-temporal patterns of earthquakes. For the region where the 2011 event happened the recent Japanese hazard maps had estimated a lower probability of 0.1% (almost at the background level as elsewhere along the coast of Japan) compared to the Nanka-to-Tokai area where estimates reached close to 100% [115], and similar discrepancies have been observed elsewhere in the world, notably Haiti, China, Algeria and Italy [114,116]. Brooks *et al.* [117] show that uniform or randomized maps perform better than the Japanese National Hazard Maps, at least using the metric inherent in these maps.

How well the probabilistic approach used in most studies actually describes future shaking is unknown, primarily because such hazard maps have not been tested repeatedly with real data. This situation differs from familiar applications, such as coin-tossing, which in contrast to probabilistic maps, can be tested with human time scales [118]. Stein & Friedrich [116] conclude that while the uncertainty of events occurring on plate boundaries can be significantly reduced, the timing of the earthquakes cannot, while uncertainties on the size can only reduce significantly for the smaller events and not the very large ones.

Although maps may be improved by better estimating some parameters, the fact that others cannot be much better estimated limits how good maps can possibly be. Hence, Stein *et al.* [119] assert that it is better to recognize and communicate the uncertainties involved. They thus propose methods to assess how well a specific map performed and how to revise maps [120]. We note that estimating the probabilities distribution of tsunami on-land elevations at a given site involves the additional identification of the anomalous tsunami earthquakes, which as [27] discusses account for three of the 17 events in the past 11 years; predicting whether a given earthquake will be anomalous is impossible, before it happens. We thus hope that similar measures can be developed for testing probabilistic tsunami hazard maps, which have recently been promoted by national agencies and engineering consultants, often without an even glancing reference to how well these approaches have worked for earthquakes, much less for tsunamis.

A substantial paradigm shift in the estimation of earthquake hazard required for assessing tsunami potential is currently underway in Japan, as discussed by Satake [11]. Probabilities of future earthquakes had been traditionally calculated there using the characteristic earthquake model. Japan's Earthquake Research Committee has annually updated long-term forecasts of large earthquakes in Japan and published appropriate maps. As of 2010, the 30-year probability for a $M \sim 7.5$ event just west of where the 2011 event happened was 99%. The forecast failed as the 2011 event was much larger. Satake [11] compares limited historic records, recorded seismicity and palaeotsunami deposit studies and concludes that there is evidence of much larger earthquakes with longer recurrence intervals than documented in recent centuries. Most importantly, he finds that the sizes of recurrent earthquakes are highly variable.

Koshimura & Shuto [121] in this issue explain a paradigm shift in Japan in civil protection. The government of Japan realized that it cannot chase the last disaster, referring to designing coastal protection according to the impact of the latest tsunami that just occurred. As they write, even great seawalls can fail; hence seawalls need to be designed with the assumption that they will be overtopped, and coastal communities warned not to rely on coastal defenses alone. This is entirely consistent with recent developments in coastal resilience [122] explained and expanded into a comprehensive coastal community hazard protection resiliency index by Ewing [123].

Thus, seawalls will henceforth be designed in Japan so that they are not overtopped during tsunamis occurring every 150 years or less. For all others, which the Japanese government refers to as 'level 2 events', communities will rely on other forms of coastal protection, planning, evacuation and public education.

A spectacular measurement of the first tsunami hydrograph is shown in figure 4. Hydrographs are routinely used in flood management to predict the times and maximum water depths at specific on-land or river locations after large storms. Fritz *et al.* [124] did extensive measurements using lidar, and then with high-end particle tracking methodologies, they analysed eyewitness

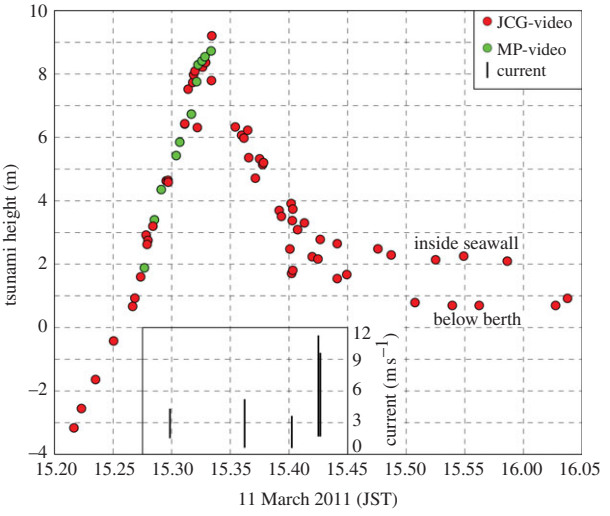

Figure 4. Hydrograph measurements using lidar, and then with high-end particle tracking methodologies, near a surviving coast guard building during the 2011 Japan tsunami. Adapted from Fritz *et al.* [124].

videos at a location near a surviving coast guard building from where the film was shot. They thus determined the time history of the tsunami flood at that location. Their tsunami hydrograph shows that the water level changed by 12 m within 10 min. Such measurements are incredibly useful to civil defence and education campaigns to help inform communities at risk of how quickly overland depths can change.

Okal [27] in this issue describes lessons learned from 17 tsunamis from 2004 to 2014 and changes in scientific paradigms. His entire discussion is focused towards identifying what has worked in the entire system—source characterization, warning, population response—and what has not.

In terms of science, he considers how the powerful new techniques to interpret early P wave arrival and the reverberations of P and SV waves in the upper mantle (known as the W phase) are revolutionizing our ability to obtain source information and counterbalancing the 'apparent setback' from the realizations of the limitations of scaling laws. The issue with identifying tsunami earthquakes remains vexing, and he explains developments in the identification of the slowness parameter in real time.

Okal [27] assigns a wisdom index for each event based on the warning issued and the population response, a provocative idea long overdue. Given that the characterization of all events is done by the same person, even though the index may be highly subjective, the trends are robust, and show that in the far field the science community has a good understanding of the warning and the phenomenology. Clearly, educating populations to self-evacuate remains the only option in the near field, even after more focused and accurate near-field warnings evolved. Okal [27] finds substantial cacophony between the scientific community and decision makers in industry and government.

6. Will climate change affect future tsunami impacts?

It would be unwise to write on the impact of any natural hazard without addressing how climate change will affect it. Little as we understand their triggers over hundreds of thousands of years, it is quite clear that the occurrence of earthquakes, volcanic eruptions and bolide impacts will not change, unless plate motions do, which seems highly unlikely. It is likely that the impact of meteotsunamis will change.

In terms of landslides, while back in 2004 it was asserted that, based on volume, 70% of slope failures in continental margins in the last 45 000 years occurred in periods of rapid sea-level rise [125], more recent analysis suggests that the evidence is inconclusive [126]. It is however possible that a warming ocean may trigger methane releases from the seafloor though gas hydrate dissociation; Urlaub *et al*. [126] argued that a bottom water temperature increase of even 1°C in water depths less than 600 m 'can cause the release of significant amounts of free gas and this can promote slope instability'. This implies an increase in the frequency of submarine landslides, but, again, we do not understand the basic physics well enough, and we have not had a recent event from which we can learn about the dynamics of seafloor methane releases. We note that substantial attention has been paid to the issue of whether massive submarine slope failures (triggered by other means) can have substantial impact in methane emissions, and a recent review [127] concluded that caution is needed before concluding that there is no link between large landslides and climate change.

One can imagine with a bit more certainty that increases in rain and storm patterns may accelerate erosion and change sediment loads, which may themselves increase the frequency of landslides, but given the scarce data on the incidence of such slides, this is just speculation. If anything, the evidence of slope sedimentation rates at low latitude margins does not implicate them as triggers [128].

Ever since the 1998 PNG tsunami [58], landslide tsunamis have been subject to extensive research efforts to understand their generation and kinematics. Before Boxing Day 2004 it had been widely asserted that a far greater proportion of tsunamis were due to landslides than believed only a decade earlier. It is now clear that they do not represent a sizeable fraction of high-impact tsunami events, although locally their near-field inundation can often exceed that of even large tectonic tsunamis. Whether landslide triggered waves can be modelled with shallow water codes or only with Boussinesq-type models continues to be debated.

Løvholt *et al.* [12] review the effects of submarine landslide kinematic parameters such as velocity, Froude number and acceleration on the tsunamigenesis. A novel aspect in their review is the distinction between translational landslides with slow acceleration and rapid slumps. Importantly, they show that retrogressive landslides with slow mass mobilization produce smaller waves than what some may have imagined. This is welcome, because the analysis of retrogressive failures has been a show-stopper, as the interaction of soil dynamics with multiple constitutive parameters and water motions remains not well understood. Equally importantly, they show that the landslide deformation processes that take place during the later stages of landslide motion have limited effect on the tsunami generation. This was suspected on the basis of Liu *et al.*'s [63] solid wedge experiments, but Løvholt *et al.* [12] provide a welcome confirmation, because, again, the deformation of an evolving slide is difficult to calculate, particularly before the landslide happens. Last, they demonstrate that depth-averaged models can model tsunamis induced by submarine landslides, even for landslides involving short horizontal scales, i.e. $kh \sim 2 * \pi$.

According to Pattiaratchi & Wijeratne's [13] review, meteotsunamis are multi-resonant phenomena, but primarily occurring when the speed of the atmospheric disturbance is close to equal the local shallow water wave celerity, then due to topographic resonance. All possible resonances depend in the bathymetry and geology of the coastline, while their timing with respect to tidal elevation or mean sea level (including storm surge) dramatically changes their impact. One cause of concern identified is that the 3 h intervals now standard in updating forecasts in atmospheric models are insufficient to resolve pressure changes of 0.3 hPa min^{-1}, required to trigger meteotsunamis.

Global warming will undoubtedly affect the incidence of meteotsunamis, as weather patterns change. While of course a single data point is not sufficient to draw general conclusions, it is noteworthy that the highest water level in 115 years from a meteotsunami was recorded in Fremantle, Western Australia. Pattiaratchi & Wijeratne [13] analysed weather and wave data from 25 events in 2014 and found that most occurred in winter, as cold fronts move onshore. The speculation is that, while the numbers may decrease as high-pressure belts expand during

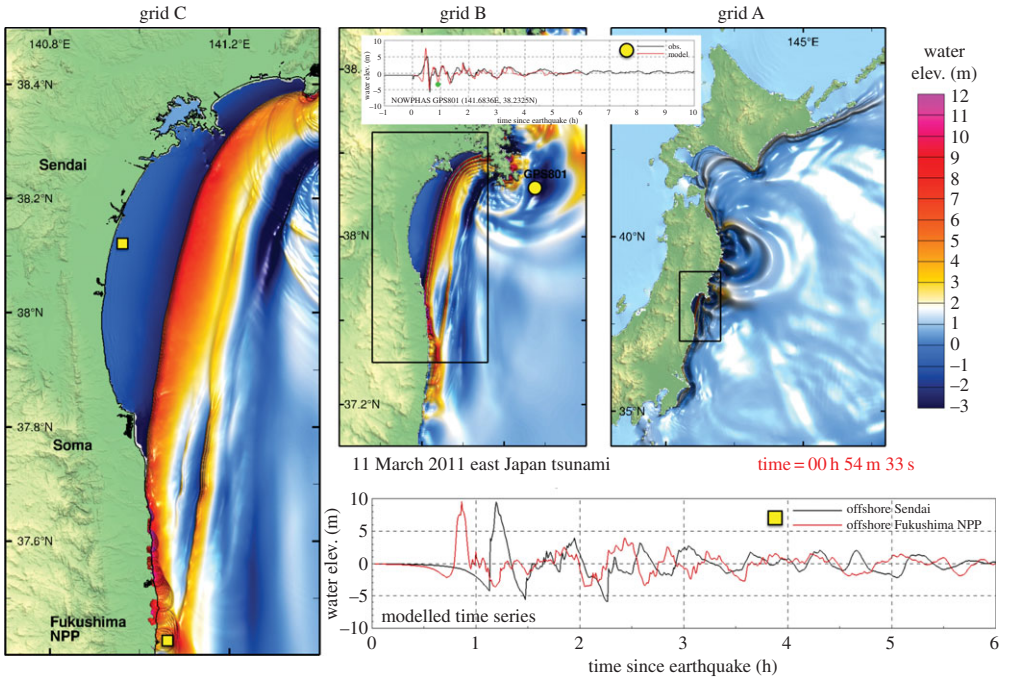

Figure 5. Results of numerical experiment that uses NOAA forecast methodology for modelling impact of the 2011 Tohoku tsunami at a portion of east coast of Japan, including the Sendai area and Fukushima NPP location. The model uses the tsunami source obtained from real-time assessment of DART data. Computations are done with MOST, using telescoping set of grids with high-resolution flooding simulation, the same method as in NOAA tsunami flooding forecast. The simulation shows up to 10 m amplitudes offshore Fukushima and Sendai, sufficient to flood a few miles into the Sendai Plain and produce over 13 m run-up at Fukushima. Modern computers with parallelized MOST can run such a model in only few minutes, potentially reducing the computations to seconds. The source definition depends entirely on the measurement data availability. The time of data inversion is negligible. Therefore, forecasts of this accuracy, even with existing data and computational capabilities, are possible within 1 h. With better measurements as planned along Japan coasts and faster computations, such forecast could be obtained in just a few minutes after an earthquake within a decade.

global warming, the resulting extreme wave heights due to meteotsunamis will increase. One mechanism may be the synergy with increased mean water levels, due to storm surges. It is our guess that the answer to the question of whether meteotsunamis are underrated is no, and this answer will likely be more emphatic in the coming decades.

What we know more about is the effects of small changes in near-shore bathymetry. A 1 m sea-level rise and the associated coastal erosion will move coastlines in many highly developed coastal areas hundreds of metres inland. Existing computational tools can be used to produce future generations of inundation maps. The existing warning methodology would be easily adapted to the evolving topographic and bathymetric conditions.

It is quite unlikely that the impact of giant tsunamis will be quite different along any coastline in 2100, unless coastal development changes. However, the impact of smaller events will be. Tsunamis with run-up less than 2 m occur on average about once a year, and they seldom have substantial impact. These tsunamis will need to be studied far more carefully and their interaction with coastal features analysed with computations of sub-metre resolution to understand differences in penetration (figure 5).

7. Conclusion

Despite substantial advances in tsunami science in the past decade and specifically after the 2004 Boxing Day tsunami, the 2011 Japan tsunami dramatically showed that substantial challenges remain for improved and effective hazard mitigation.

1. *Model standards*. There were no standards for the validation and verification of numerical models. After 2004, a number of numerical models have been used for evaluation of critical structures, etc., without validation and verification. In addition, even validated and verified models are used, in some cases, by professionals who are not trained in tsunami science. It could be claimed that the analysis for the safety of the Fukushima NPP which resulted the accident was primarily due to lack of experience in tsunami numerical models [20]. NCTR not only published the validation and verification standards of tsunami numerical models and accepted by and large by the community, but has also distributed ComMIT through training programmes. These trainings included not only usage of the models but also in education of tsunami science. However, this validation and verification process needs to be applied to other tsunami effects, i.e. validation and verification of tsunami numerical models for tsunami current estimates.

2. *Warnings*. The first extensively tested real-time forecasting methodology based on real-time data assimilation from measurements from tsunameters is now officially in use in TWCs. Most of the at-risk world oceans and seas are now covered with rapid warning procedures. Yet, there are no standards for forecasting methodologies and they do need to be urgently established for TWCs, as well as training procedures for the personnel. We note that none of the TWCs established in Europe has yet to issue a single a warning for an actual event. The situation is vexing, because tsunamis in the Mediterranean have near-field impact, the Achilles' heel this far of TWCs worldwide. We are concerned with several operational centres providing tsunami warnings may lead to substantial confusion and deterioration of the overall credibility of the European system. One such situation may arise if one TWC issues overly conservative warnings, or if the TWCs report the triggering earthquake magnitudes differently. While such diversity allows experienced professionals to gauge the underlying uncertainty, it is not helpful to operational civil defence centres, which have to make rapid evacuation decisions.

3. *Nuclear power plants*. Post 2004, there have been attempts to develop standards for the evaluation of NPPs against tsunami attack [129]. While there has been progress, there are no comprehensive guidelines on performing inundation analysis, or checking convergence of computations. In one example we know, a frequently used BT code showed landslide-triggered waves increasing in size as they propagated to deeper water. Not only does the safety of existing NPPs need to be re-evaluated, but also new ones have to be evaluated carefully, such as the one on the Mediterranean shoreline of Turkey. We should never again witness the kind of substandard hazard analysis and its negligent review which doomed the Fukushima NPP [20], primarily due to lack of familiarity with the context of numerical predictions and tsunami phenomenology. Standards are urgently needed for evaluating NPP tsunami safety studies and for the training and certification of engineers who perform them and of regulators who review them.

4. *Mitigation*. As the 2011 Japan tsunami amply demonstrated, even in very well-prepared nations, consequences can be underestimated in advance planning decisions. While research papers have catapulted the visibility of the field since Boxing Day 2004, perspectives and analyses of basic physical and social issues are needed to help motivate and acquaint the wider scientific community with the underlying challenges. Getting people to heed warning remains a formidable undertaking, particularly for smaller events.

As in Synolakis & Kânoğlu [20], it is clear that what is missing in contemporary hazard assessments are regulatory guidelines for the training of the scientists and engineers who work on estimating the maximum probable tsunami. The online free availability of computational tools has made it easy to model physical phenomena, sometimes with disastrous consequences. The outputs of different numerical methodologies may differ slightly, for the same initial conditions, but these differences dwarf the uncertainties in source characterization, or differences in results when convergence is not checked, or when inexperienced people use them. The latter requires context and experience. While likely hundreds of thousands have played with games such as 'flight simulator', rigorous training is required to allow the same to fly real airplanes, and in fact only a fraction do.

Ending, we are reminded of the tribal communities of the Indian Ocean and islands, such as in the Andamans or the Solomons, with no access to modern warning systems. The former fared

Figure 6. Pictures of a public outreach lecture during the 2009 Mentawais survey documented by [38]. Shown are Hermann Fritz and Costas Synolakis. A short clip of the survey and its outreach is at https://www.youtube.com/watch?v=6ES1o3zS1a4.

better during the 2004 Boxing Day tsunami than residents elsewhere in the Indian Ocean, while the latter routinely self-evacuated during several tsunamis in the past decade. They considered the unusual water motions as signs of impending disaster. Their instincts were 'perfected over centuries of kinship with the elements' [130]. While we in the rest of the world had a late start, we hope to acquire through education similar instincts within a generation (figure 6). We also hope to acquire technology that will make the availability and accuracy of tsunami warnings as ubiquitous and reliable as fire alarms.

Competing interests. We declare we have no competing interests.

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