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# The quest for wisdom: lessons from 17 tsunamis, 2004–2014

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Since the catastrophic Sumatra–Andaman tsunami took place in 2004, 16 other tsunamis have resulted in significant damage and 14 in casualties. We review the fundamental changes that have affected our command of tsunami issues as scientists, engineers and decision-makers, in the quest for improved wisdom in this respect. While several scientific paradigms have had to be altered or abandoned, new algorithms, e.g. the W seismic phase and real-time processing of fast-arriving seismic P waves, give us more powerful tools to estimate in real time the tsunamigenic character of an earthquake. We assign to each event a 'wisdom index' based on the warning issued (or not) during the event, and on the response of the population. While this approach is admittedly subjective, it clearly shows several robust trends: (i) we have made significant progress in our command of far-field warning, with only three casualties in the past 10 years; (ii) self-evacuation by educated populations in the near field is a key element of successful tsunami mitigation; (iii) there remains a significant cacophony between the scientific community and decision-makers in industry and government as documented during the 2010 Maule and 2011 Tohoku events; and (iv) the so-called 'tsunami earthquakes' generating larger tsunamis than expected from the size of their seismic source persist as a fundamental challenge, despite scientific progress towards characterizing these events in real time.

## 1. Introduction

It has now been 10 years since the Sumatra–Andaman earthquake of 26 December 2004 generated what was probably the most lethal tsunami in the history of mankind, with a death toll generally estimated at more than 225 000. A major cause of this horrific number was the total lack of preparedness, or even awareness

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of tsunami hazard, on the part of most of the populations at risk, and the absence of a warning system that could have helped mitigate its effects, especially in the far field, which accounted for as many as 50 000 dead, or one-fifth of the casualties. The scientific and operational community had been taken by surprise on Boxing Day (or Christmas Day depending on local time zones). In the wake of this disaster, major advances took place in the field of science, numerical simulation, mitigation and education, e.g. as summarized by Synolakis & Bernard [1].

Tsunami hazard dramatically returned to worldwide headlines on 11 March 2011, when the Tohoku disaster took place, with a death toll approaching 20 000. However, since the 2004 Indonesian event, and as of 10 June 2015, no fewer than 130 tsunamis have been detected, of which 103 gave rise to quantitative scientific measurements, and 14 resulted in casualties [2]. Notwithstanding the significant diversity in these events, notably in the size of their parent earthquakes, it comes as a legitimate question to assess whether we, as a community of scientists, engineers and decision-makers, have made any tangible progress in our understanding of tsunami hazard, in the development of effective mitigation, and, in real time when danger strikes, in the implementation of emergency warning and evacuation procedures. In other words, 'have we become wiser' in the decade following the Indonesian tsunami?

## 2. Scientific wisdom and know-how

### (a) The question of the regional maximum earthquake

On Boxing Day, 2004, the occurrence, along the Sumatra–Andaman subduction zone, of a mega-earthquake, which to this day remains the third-largest ever recorded [3], caught the scientific community by surprise, as a consensus then existed that such 'mega-events' should only take place at interfaces involving young lithosphere and fast convergence rates. This paradigm had been proposed by Ruff & Kanamori [4], based on Uyeda & Kanamori's [5] general concept that an older, and hence cooler and denser, plate would offer less resistance to subduction, thus leading to weaker coupling at the plate interface, and eventually to smaller earthquakes. Figure 1, adapted from fig. 2 in Ruff & Kanamori [4], suggests a linear relationship between the maximum moment magnitude expected at a subduction zone, $M_w = (\log_{10} M_0 - 16.1)/1.5$ (where $M_0$ is the maximum seismic moment in dyn cm), the age $A$ (in Myr) of the subducting lithosphere and the convergence rate $R$ (in cm yr$^{-1}$):

$$M_w = 0.136R - 0.0088A + 7.95. \tag{2.1}$$

Kanamori [6] later slightly adjusted the constants in (2.1):

$$M'_w = 0.141R - 0.0095A + 8.01, \tag{2.2}$$

to take into account differences in repeat times among subduction zones, the effect of this adjustment on the predicted maximum magnitudes remaining minor. Based on (2.1) or (2.2), the Sumatra subduction system should have supported an earthquake of at most $M_w = 8.2$, which could have generated a locally destructive tsunami, but could not have exported devastation and death across the Indian Ocean basin. As shown in figure 1, this situation was repeated during the 2011 Tohoku earthquake, and during the discovery and quantification of the 1700 Cascadia earthquake [7]. Similarly, the re-examination of historical seismicity in the Marianas (including pre-instrumental reports of tsunamis associated with strong local earthquakes) has suggested that the dataset of modern seismicity grossly undersamples the true seismic potential in the region [8]. In addition, Ruff & Kanamori's [4] dataset included a number of regions in clear violation of their model, such as Kamchatka and Alaska, where a recent modern reassessment of the 1964 earthquake has led to an even larger value of its size [9]. When regrouped in figure 1, these violators suggest that most regions in the original $[8.0 \leq M_w \leq 8.5]$ band actually supported earthquakes with $M_w \geq 9$, which makes it impossible to consider that each of them taken separately could be no more than an 'exception that confirms the rule'. This result is of paramount importance because the former range of magnitudes generally corresponds to

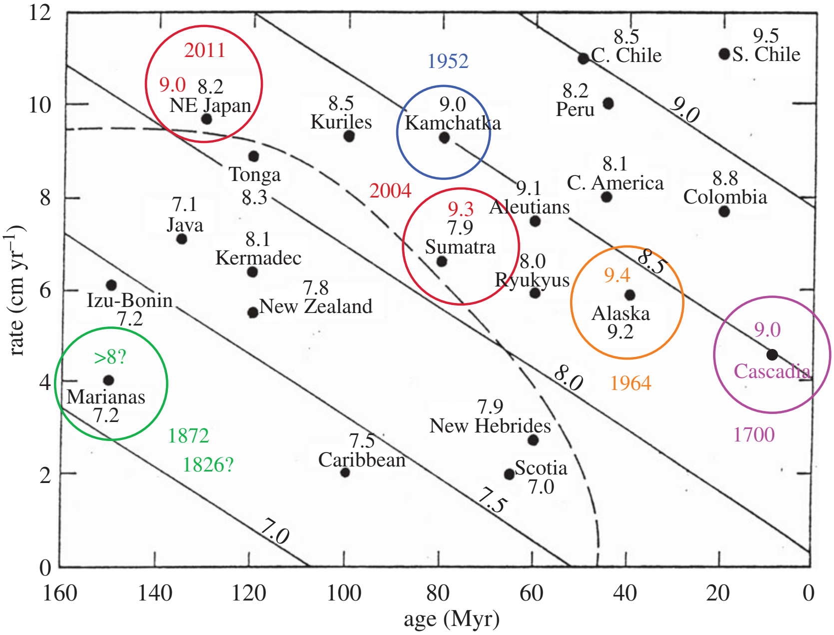


**Figure 1.** Adapted from Ruff & Kanamori [4, fig. 2]. In the authors' original figure, the oblique lines show the maximum moment magnitude $M_w$ expected according to (2.1) as a function of lithospheric age (in abscissa, increasing to the left) and convergence rate (in ordinate). Superimposed in red are the two recent earthquakes (2004 Sumatra and 2011 Tohoku) clearly violating the paradigm. The 1700 Cascadia earthquake, which became known since their study, is shown in purple, and the recently reassessed 1964 Alaskan event in orange. The blue circle refers to the 1952 Kamchatka earthquake, another violator in the original dataset. Finally, the green circle refers to the Mariana subduction zone where historical records suggest that the dataset of instrumental seismicity grossly undersamples the true seismic potential. See text for details. (Online version in colour.)

a tsunami potential restricted to the near field, whereas the latter can result in catastrophic transoceanic tsunamis.

In the aftermath of the shocking violation of Ruff & Kanamori's [4] model by the 2004 Sumatra event, and in a quest for improved wisdom in this respect, a considerable effort was made to find an alternative means of identifying which subduction zones could be prone to mega-earthquakes with transoceanic tsunami potential. In an attempt to save the model, Stein & Okal [10] used updated values of the plate tectonic parameters $A$ and $R$, as well as of moments of historical earthquakes, but concluded that the resulting dataset actually deteriorated the correlation between predicted and observed maximum magnitudes, from the value of 80% claimed by Ruff & Kanamori [4] to no more than 35%. At this point, their model could no longer be claimed to be supported by the available dataset.

Other attempts at correlating subduction seismicity with plate structural or kinematic parameters include the works of Jarrard [11] and Peterson & Seno [12], although these authors were concerned with cumulative seismic moment release, rather than with maximum earthquake magnitude. More recently, Schellart & Rawlison [13] have researched the correlation between maximum magnitude and a complex set of as many as 24 physical parameters of subduction zones. Most noteworthy is their inclusion of Java and Hikurangi as subduction zones capable of sustaining earthquakes with $M_w > 8.5$ ($M_0 > 7 \times 10^{28}$ dyn cm), in striking contrast to the maximum earthquakes known in those areas ($M_w = 7.7$ and 7.5, respectively).

If simple kinematic parameters cannot predict the occurrence of mega-earthquakes, local geological conditions may be controlling factors, notably as massive sedimentary structures would be expected to affect the mechanics of friction and stress release at subduction zones. In this framework, Ruff [14] proposed that subduction zones with excessive amounts of trench sediment generally supported earthquakes with $M_W \geq 8.0$. Writing at a time when the 1700 earthquake had not yet been documented, the author went as far as noting the anomalous behaviour of the Cascadia segment, then believed aseismic. However, his dataset does not help discriminate between large and truly great events ($M_W > 8.5$). This model was generally supported by further work on the subject by Scholl *et al.* [15,16], but significant exceptions where megathrust earthquakes are known in sediment-starved environments (Kamchatka, southern Peru, Sanriku) led Scholl *et al.* [17,18] to consider the possible role of ocean-floor smoothness as an additional contributor to the generation of megathrust earthquakes, and Heuret *et al.* [19] to explore a combination of sediment thickness and state of strain in the over-riding plate.

The conclusion of this section is that, while progress in this respect may take place in the forthcoming years, we have not yet replaced Ruff & Kanamori's [4] paradigm with a satisfactory alternative. As pointed out by Stein & Okal [3,10] and independently by McCaffrey [20], and in the context of tsunami mitigation, a precautionary attitude consists of assuming that all subduction zones (in principle, at least those with sufficiently long fault segments) could potentially entertain mega-earthquakes. The occurrence of the 2011 Tohoku earthquake certainly lent support to what could have appeared as a humble approach, sinning on the side of overcaution.

## (b) Scaling laws

Another relative victim of the past decade has been the concept of seismic similitude, or more generally of the scaling laws governing seismic sources. As discussed, for example, by Aki [21], Kanamori & Anderson [22] and Geller [23], it assumes that various extensive variables characterizing the earthquake source (e.g. fault length $L$, width $W$, seismic slip $\Delta u$, rise time $\tau_r$, rupture duration $T_R$) grow in a related fashion with its size, which amounts to saying that a number of intensive parameters, such as the rigidity $\mu$ of the medium hosting the source, the shape of the fault ($W/L$), the rupture velocity $V_R$ along the fault or the strain $\varepsilon$ (or stress drop $\Delta\sigma$) released by the earthquake, are all *invariants* of the seismic system. In lay words, this amounts to saying that 'all fault zones (perhaps, all rocks) are created equal', and that specific seismic source parameters, such as the amount of seismic slip $\Delta u$, should all be predictable from the knowledge of just one number, the source size, in physical terms its seismic moment $M_0$, which can be expressed under the concept of a moment magnitude $M_W$ [24].

This paradigm has been generally supported by a remarkable observational dataset covering more than 17 orders of magnitude in seismic moment [25], and has proven very seminal, as it can explain, for example, the frequency–magnitude distributions noticed empirically by Gutenberg & Richter [26], and explained in this context by Rundle [27]. However, the recognition of 'tsunami earthquakes' by Kanamori [28] pointed to an obvious diversity in strain release and hence to a violation of the concept of seismic similitude by this class of events, which are defined as triggering tsunamis of greater amplitude than expected from their magnitudes, especially conventional ones ('tsunami earthquakes' are characterized by source spectra displaced towards low frequencies [29,30]). That significant exceptions can exist to seismic similitude inevitably raises the question of its robustness, i.e. of how widespread these exceptions can be, notably among the very rare mega-events which bear the majority of tsunami potential and hazard. Nevertheless, in the context of tsunami forecasting, especially in real time, source scaling laws have been widely used to obtain source parameters ($L$, $W$, $\Delta u$) serving as input to hydrodynamic numerical simulations, once a centroid moment tensor (CMT) solution has been achieved.

The concept of seismic similitude, and hence of scaling laws, was dealt a stunning blow in the wake of the 2011 Tohoku earthquake. The numerous tomographic studies of its source revealed extreme seismic slip ($\Delta u \approx 50$ m) concentrated along a small patch of the fault plane with a width not exceeding 50 km, leading to an exceptional and hitherto unobserved level of strain release, locally approaching $\varepsilon = 5 \times 10^{-3}$. This model, in clear violation of scaling laws, was confirmed, in the range $\Delta u = 33$–$69$ m, by a multitude of independent studies, using inversion of seismic, geodetic and tsunami data (e.g. [31–34]). The slips obtained in these inversions are comparable with those (35–40 m) estimated for the 1960 Chilean earthquake [35,36], the largest ever recorded, featuring a seismic moment 5–12 times greater than the Tohoku event [37]. Note, however, that the geodetic data available in 1960 make it impossible to distinguish post-seismic from coseismic slips, and hence direct comparison with the 2011 earthquake may not be warranted. Incidentally, we recall that a variation of source parameters at constant moment can strongly affect tsunami amplitudes in the near field, while having essentially little effect in the far field, for which the mechanism of tsunami generation amounts to an integration of displacement over the source area, conceptually similar to the definition of seismic moment.

At any rate, the above studies of the 2011 Tohoku earthquake revealed beyond doubt released strains far in excess of those predicted under commonly accepted scaling laws. A possible scenario for their clear violation may be sought in rupture involving softer, possibly sedimentary, material in the shallowest portions of the subduction contact, where the greatest slips were inverted. More generally, this model has been invoked for certain classes of 'tsunami earthquakes' [38], but the 2011 Tohoku earthquake stands out as an extreme case of violation of scaling laws by a megathrust earthquake.

The documentation of an exceptional amplitude for the seismic slip released during the 2011 Tohoku earthquake reopens the case of controversial suggestions regarding historical earthquakes for which models had been proposed in what amounted to a similar violation of seismic scaling laws. A significant example is the great earthquake of 21 July AD 365 in western Crete, for which palaeoseismic data as modelled by Shaw [39] would require as much as 20 m of seismic slip on a fault zone not exceeding 100 km in length, although significant controversy exists as to whether or not this earthquake took place along the subduction interface (e.g. [40,41]). In this context, the slip distribution of the 2011 Tohoku earthquake removes a significant objection to the interpretation of the AD 365 Cretan earthquake along the lines of Shaw *et al.* [42]. Note that these authors had themselves justified the exceptional value of its strain release by comparing it with one of the asperities identified from source tomography in the source of the 2004 Sumatra earthquake [43].

Thus, the lesson learnt from the 2011 Tohoku earthquake is not that seismic scaling laws are a failed concept, but rather that they can suffer major exceptions, including during the mega-earthquakes expected to generate the most catastrophic tsunamis.

## (c) The W-phase

The development of the W-phase centroid moment tensor (WCMT) inversion represents the most important progress achieved in the past 10 years in the field of computational seismology, directly applicable to real-time tsunami warning. We recall that the concept of W-phase was introduced by Kanamori [44], who noticed the presence, in broadband seismograms of the 1992 Nicaragua 'tsunami earthquake', of an extremely long-period (100–1000 s) signal arriving at teleseismic stations between the P and Rayleigh phases. This energy can be modelled as the sum of numerous reverberations of P and SV waves in the upper mantle, hence the name 'W'-phase, by analogy with certain modes of acoustic propagation in whispering galleries, identified by Rayleigh [45]. Following a remark by Satô [46], Kanamori [44] proposed an alternative interpretation of the W-phase, namely a superposition of high-order spheroidal modes making up Rayleigh wave overtones (with overtone numbers typically in the range 2 to 8).

The two properties of the W-phase, namely its very long period and early arrival times (in the normal mode formalism, its group velocity is between 5 and 9 km s$^{-1}$), make it an ideal tool to retrieve in real time the ultra-low frequency of a seismic source, and hence its tsunamigenic potential. Despite early attempts at defining a magnitude scale based on a 'quick-and-dirty' calibration of the W-phase [47,48], its study and use were essentially abandoned in the next 10 years, presumably because of the lack of a sufficient observational dataset: there were few great earthquakes, and the Global Seismic Network of broadband instruments was still growing.

The 2004 Sumatra–Andaman earthquake changed this situation overnight, allowing Lockwood & Kanamori [49] to gather a superb dataset of W-phases and later Kanamori & Rivera [50] to develop a method for real-time WCMT inversion, which has been successfully implemented at a growing number of tsunami warning centres, e.g. Pacific Tsunami Warning

Center (PTWC) and CPPT (Tahiti) [51]. In particular, its use under an automatic procedure at the USGS National Earthquake Information Center (NEIC) in Golden provided an essentially final moment tensor solution of the 2011 Tohoku earthquake a mere 20 min after origin time [52,53].

The systematic and routine application of the WCMT algorithm can be said to have revolutionized real-time evaluation of tsunamigenic potential in the far field. As detailed in §4b, it should be noted, however, that in the case of the large intra-oceanic event of 11 April 2012 off the coast of Sumatra, the earlier WCMT solution differed significantly from the final one, achieved 22 min later [54], the two mechanisms being rotated 51° apart in the formalism of Kagan [55]. This difference of geometry was important in the context of tsunamigenesis, notably for the near field; however, its origin remains unclear.

## (d) Quantifiers and discriminants based on duration

One of the remarkable characteristics of the 2004 Sumatra earthquake turned out to be the long duration of its source, generally estimated to range between 7 and 10 min, based on a variety of measurement techniques (e.g. [56–59]). This long duration resulted from the combination of an exceptional length of rupture (1200 km), and of a relatively slow average rupture velocity ($V_R \approx 2.2\,\mathrm{km\,s^{-1}}$), which incidentally qualified the earthquake as a 'tsunami earthquake' [60]. A baffling aspect of this long source turned out to be that, at all distances where direct P waves could be observed, their wavetrain was not separated from later phases, notably PP and S. Taking advantage of the efficient attenuation of phases reflected in the mantle and of S waves in general, Ni *et al.* [61] used band-pass filtering in a high-frequency band ($2 \le f \le 4$ Hz) to isolate a P wavetrain whose duration could be easily measured in the time domain.

In the ensuing years, Ni *et al.*'s [61] work led to an emphasis on duration as an important characteristic of earthquake sources, in particular, in terms of tsunamigenesis, and opened up a new line of research, notably in the field of the quick identification of 'tsunami earthquakes'. We recall that Newman & Okal [62] had introduced an energy-to-moment parameter $\Theta$, allowing the robust recognition of such events from what amounted to a comparison of their high- and low-frequency characteristics. However, this approach, whose performance at the PTWC was reviewed by Weinstein & Okal [63], still required the knowledge of $M_0$, which these authors were deriving from mantle surface waves, an intrinsically slow process.

After the 2004 Sumatra event, the emphasis was put on extracting as much information as possible from the generalized P wavetrain, as this could provide a head start in the time-sensitive issue of tsunami warning. We recall that in the 1990s Tsuboi *et al.* [64] proposed the so-called $M_{wP}$ algorithm, which consisted of retrieving an estimate of $M_0$ from the time integral of the far-field seismic displacement of the generalized P wave (because the response of most 'broad-band' instruments is actually flat in ground velocity over the design frequency window, this amounts to a double integration). Although the $M_{wP}$ algorithm has been implemented at several warning centres, its performance is inherently deficient for the largest events, as documented for example by Lomax *et al.* [65]. In addition, it systematically underestimates the moment of 'tsunami earthquakes', and thus fails for those events most challenging in terms of tsunami warning: the exceptionally large or anomalously slow ones.

In this context, a number of investigators have attempted to build discriminants capable of identifying anomalous earthquakes (i.e. 'tsunami earthquakes') based on a fast and robust processing of teleseismic P waves. The most promising of these approaches is that of Newman *et al.* [66], who compare the high-frequency energy $E$ contained in the P wave (essentially the energy measurement contributed to the parameter $\Theta$) to an estimate $T_R$ of the duration of the source. Scaling laws would predict a constant value of the ratio $E/T_R^3$, while all known 'tsunami earthquakes' indeed feature significant deficiencies (of the order of 1–1.5 orders of magnitude) in that ratio. In this framework, Convers & Newman [67] have explored several strategies to define a source duration from P waves, including through an analysis of the evolution of the energy contained in a time window moving through the P wavetrain. As detailed in §4b, Newman *et al.*'s

[66] approach was able to identify the source slowness of the 2010 Mentawai earthquake as early as 17 min after origin, during the developmental stages of their algorithm.

Following a similar approach, Okal [68] has used an algorithm developed in the context of the discrimination of man-made explosions as recorded on hydroacoustic signals [69] to characterize source duration through a parameter $\tau_{1/3}$ expressing the time that the envelope of a teleseismic P wave filtered along Ni *et al.*'s [61] protocol is sustained at more than one-third its maximum amplitude. Then $E$ and $\tau_{1/3}$ can be compared through the parameter

$$\Phi = \log_{10} \tau_{1/3} - \tfrac{1}{3} \log_{10} E + 5.86 \tag{2.3}$$

($\tau_{1/3}$ in seconds, $E$ in ergs), which should be invariant under scaling laws and with the constant (5.86) adjusted to give it a zero average value. In the case of 'tsunami earthquakes', $\tau_{1/3}$ is expected to be anomalously long, while $E$ should be deficient, both properties resulting in an increase in $\Phi$, which reaches values in excess of 0.35 and as high as 1.5 [68], and can thus serve as an efficient discriminant for this class of events.

Finally, Lomax & Michelini [70] have used a somewhat more intricate approach in which they reconstruct an estimate of the earthquake's moment from $E$ and a duration $T_R$ from the square root of the product ($ET_R^3$), and then compare this energy-derived estimate to other determinations of the moment (presumably made at lower frequencies) to detect any anomalous behaviour in the source.

## (e) Other scientific developments

Because of its exceptional size, the 2004 Sumatra earthquake and tsunami generated perturbations in the Earth system, of large enough amplitudes to result in detectable coupling between subsystems (the solid Earth, the ocean, the atmosphere), which could otherwise be considered as very weakly, if at all, coupled. The availability of high technology then contributed significantly to the detection of these intriguing effects, and occasionally to their quantification; a full review is given in Okal [68], to which the reader is referred for details and references. They include: the recording of tsunamis by land-based seismometers, and of their high-frequency components by hydrophones of the International Monitoring System; the definitive recording of tsunamis by satellite altimeters, including the quantification of their effect on the spectrum of reflected radar, explaining the occurrence of 'tsunami shadows', which had long been considered an urban legend; the triggering of deep infrasound signals by tsunamis interacting with extended continental shelves; and the excitation of the ionosphere by the tsunami wave whose eigenfunction is prolonged upwards of the oceanic column, since the free surface of the ocean does not constitute *stricto sensu* a free boundary, but rather a fluid–fluid one, where densities merely vary by a factor of 1000.

In addition, we mention here two developments postdating Okal [68]. First, based on a suggestion by Tyler [71], Manoj *et al.* [72] identified the variation in the Earth's magnetic field induced by the 2010 Chilean tsunami, an observation later extended to the 2011 Tohoku event by Utada *et al.* [73]. Second, the perturbation, by a large earthquake, in the distribution of masses inside the Earth creates a static variation of its gravity field that can affect the orbits of artificial satellites. This effect was detected and modelled by Han *et al.* [74] in the wake of the 2004 Sumatra, 2005 Nias, 2010 Maule and 2011 Tohoku events, using satellite-to-satellite tracking as part of the GRACE experiment. While not directly related to tsunami issues, these observations are important, as they involve repeat passages on the same orbit, and thus can extend the investigation of the source spectrum (and of any anomaly therein) to periods of the order of one month, inaccessible to seismological investigations.

## (f) Summary

In summary, it is beyond doubt that our scientific view towards issues of tsunami generation and warning has evolved significantly over the past 10 years, as a direct consequence of the catastrophic nature of the 2004 Sumatra–Andaman tsunami, and of the more recent events. To the question whether the scientific community has become *wiser*, the arguments developed in §2a,b would suggest a rather ominous response, only reconcilable with a glint of optimism using an ounce of Socratian philosophy: 'The only thing we know ... is that we do not know' (what controls the distribution of mega-earthquakes at subduction zones; to what extent scaling relations can be trusted; etc.). By contrast, the development of the W-phase algorithms exposed in §2c has revolutionized our ability to explore the low-frequency spectrum of large earthquakes in real time, and represent the most obvious change in tooling in seismic source studies since the implementation of the CMT inversion program by Dziewonski *et al.* [75]. The works described in §2d (and to a lesser extent in §2e) are similarly pushing the envelope, under operational constraints, of our investigations of source parameters critical to robust improvements in tsunami warning and forecasting procedures. This unquestionably represents progress towards enhanced scientific *wisdom.*

## 3. Mitigation wisdom

This section will examine developments in tsunami mitigation which followed the 2004 Sumatra–Andaman disaster. Here, we define *mitigation* as efforts taken during the 'inter-tsunami' time window to reduce the hazard from the next event to be expected, including the development and deployment of relevant instrumentation. We discuss these issues only very briefly, as they have been widely detailed, e.g. by Bernard *et al.* [76], and are also covered in companion papers in this theme issue.

On a global scale, the most important consequence of the 2004 Sumatra–Andaman tsunami has been an immediate, worldwide increase in awareness for this hazard, 'tsunami' becoming overnight, and remaining to this day, a household word. This effort in educating populations at risk has taken many forms, the most visible of which include the material identification of hazardous coastal areas by an appropriate signage, including directions of evacuation. The effectiveness of such a programme was illustrated, e.g. as described in §4a below, during the 2009 Samoa tsunami, where a properly signed American Samoa suffered significantly fewer casualties than (Independent) Samoa, where no such programme had been carried out [77]. That such a programme may work by constantly exposing populations to evacuation signs posted along commuter routes is a simple illustration of the power of commercial advertising.

In the immediate aftermath of the 2004 disaster, the absence of warning systems outside of the Pacific basin was quickly palliated by temporarily increasing the domain of responsibility of existing centres: PTWC was chartered to cover the Indian Ocean, and the West Coast–Alaska Tsunami Warning Center (WCATWC; later US National Tsunami Warning Center) in Palmer, Alaska, was given responsibility over the Caribbean, pending the design and operation of appropriate regional centres. The latter came to life as the new awareness for tsunami hazard allowed, in many countries, the allocation of significant funding for mitigation efforts against future tsunamis. The principal developments in this respect were the operational launch of the Joint Australian Tsunami Warning Center (JATWC) in 2007, of the Indonesian TWC in 2008 and of French and Turkish TWCs covering the western and eastern Mediterranean, respectively, in 2012. The performance of these individually designed centres will have to be assessed during a real emergency, which for some of the new TWCs may not come for decades.

In the USA, the Tsunami Warning and Education Act (Public Law 109-424 of 20 December 2006) has provided US$135 million over 5 years for various aspects of tsunami mitigation, detection, forecast and warning. A significant effort under the Act has involved a substantial enhancement of the DART system of ocean-floor sensors [76,78], which grew from six stations in 2004 to 36 in 2015 (plus 25 similar instruments deployed by foreign programmes), streaming their data to the National Data Buoy Center in Mississippi. This is a remarkable development, since DART data constitute the critical input to the provision of realistic tsunami wave forecasts in real time under programmes such as SIFT [79]. However, a significant issue has become the maintenance of this network, subject to a hostile natural environment, vandalism on the high seas, and logistical and technological difficulties for repair or replacement: a random test on 4 February 2015 found 19 of 61 sensors (31%) not transmitting or misfunctioning. This figure is of particular concern when breakdowns affect areas with scarce sensor density, as it can significantly delay the assessment of the true size of the propagating tsunami, as occurred during the 2010 Maule event [80]. In this context, note the abandonment, in 2010, by the German-designed Indonesian tsunami warning system, of the use of bottom pressure units relayed by buoys, which had never reached an acceptable level of operational performance.

Another significant mitigation effort has been the systematic compilation of inundation maps for communities at risk, which can be used by civil defence decision-makers to design evacuation routes, or even to relocate critical facilities such as hospitals and schools out of harm's way. This is nothing short of a gargantuan task, as the response of the coast to an incoming tsunami has to be modelled on a very short scale, which requires the compilation of bathymetry and topography on an excruciatingly fine grid. In addition, the definition of the design scenario to be used in the preparation of inundation maps remains in itself a challenge, as we do not necessarily understand the maximum earthquake expectable in a particular seismic area (see §1). As an example, inundation mapping has been completed for the coastlines of California [81].

Finally, countless post-tsunami surveys in devastated areas have emphasized that an educated population stands a far better chance of survival than an ignorant one (and this will be a recurring theme of the case studies in §4). In this context, the post-Sumatra era has seen a concerted education effort especially in countries with little, or rare, direct exposure to tsunami hazard. Several programmes of regular, often yearly, tsunami drills, including full rehearsal of evacuation procedures, have been implemented in areas such as northern California [82] and Greece, where the 2011 drill in Crete was the first of its kind in the European Union [83].

In the USA, the combination of mitigation measures involving the computation of inundation maps, the development of societal resilience (including signage) and educational efforts (including tsunami drills) has been assessed by certifying the community as 'Tsunami Ready', an idea actually pre-dating the 2004 Sumatra disaster [84], and now being updated to the standard of 'Tsunami Resilient Community'. Over and beyond the tangible improvements in the resilience of the communities involved, this programme has gone a long way towards instilling awareness in the minds of the populations at risk.

This brief overview of a number of efforts undertaken since 2004 points to a genuine, worldwide commitment of society to mitigation of tsunami hazard. Unfortunately, their assessment in terms of a true increment in societal *wisdom* can be made only under live fire, i.e. during and after future large tsunamis. It is in this context that we examine in the next section the case of significant tsunamis that have taken place since the 2004 Sumatra disaster.

## 4. Operational and societal wisdom

In this section, we consider the 17 tsunamis listed in table 1, and assign to each of them a colour-coded 'wisdom index', based on our assessment of the success of the operational warning that was (or was not) issued by the relevant warning centre(s), and of the response of the population at risk. The wisdom index is simply colour-coded from 'black' (abysmal) through red (bad), yellow (average), blue (fair) and green (good). It was introduced in our previous publication [68], to which the reader is referred; however, here we simplify its concept by suppressing the intermediate orange colour between red and yellow, and the ultimate (gold) level, now combined with green. We further reclassify the lone 'olive' rating as 'blue', and we obviously extend the grading to the events postdating Okal [68], most notably to the 2011 Tohoku disaster. As detailed in Okal [68], we emphasize that the assignment of the index is based not on quantitative measurements (e.g. number of casualties or height of maximum run-up), but rather on the qualitative, and admittedly subjective, assessment of the performance of the warning centres (e.g. the evaluation of similar historical events, the recognition of a 'tsunami earthquake'), and of the response of the population.

**Table 1.** Recent tsunamis targeted in this study. For colour details of wisdom index, see text.

| date | epicentre | | | moment | maximum | | wisdom | |
|---|---|---|---|---|---|---|---|---|
| d m (j) y | °N | °E | region | ($10^{27}$ dyn cm) | run-up (m) | casualties | index | remarks |
| 26 Dec (361) 2004 | 3.1 | 94.3 | Sumatra–Andaman | 1200 | 50 | 225 000 | black | |
| 28 Mar (087) 2005 | 2.1 | 97.1 | Nias, Sumatra | 125 | 4.2 | 10 | blue | |
| 17 July (198) 2006 | −9.3 | 107.4 | Java | 4.6 | 21 | 802 | red | tsunami earthquake |
| 15 Nov (319) 2006 | 46.6 | 153.3 | Kuril Is. | 35 | 22 | 0 | yellow | |
| 1 Apr (091) 2007 | −8.5 | 157.0 | Solomon Is. | 16 | 12 | 52 | green | |
| 15 Aug (227) 2007 | −13.4 | −76.6 | Pisco, Peru | 11 | 10 | 3 | yellow | |
| 12 Sep (255) 2007 | −4.4 | 101.4 | Bengkulu, Sumatra | 43 | 5 | 0 | green | |
| 29 Sep (242) 2009 | −15.5 | −172.1 | Samoa | 17 | 22 | 192 | yellow | |
| 3 Jan (003) 2010 | −8.7 | 157.5 | Solomon Is. | 0.6 | 3 | 0 | green | |
| 27 Feb (058) 2010 | −36.1 | −72.9 | Maule, Chile | 187 | 29 | 156 | yellow | |
| 25 Oct (298) 2010 | −3.5 | 100.1 | Mentawai, Sumatra | 6.8 | 17 | 431 | red | tsunami earthquake |
| 11 Mar (070) 2011 | 38.3 | 142.4 | Tohoku, Japan | 395 | 39 | 18 500 | red | |
| 11 Apr (102) 2012 | 2.4 | 92.8 | Indian Ocean | 90 | 1.1 | 0 | blue | strike-slip intra-ocean; two events |
| 27 Aug (240) 2012 | 12.1 | −88.6 | El Salvador | 1.3 | 6 | 0 | yellow | tsunami earthquake |
| 28 Oct (302) 2012 | 52.8 | −132.1 | Haida Gwaii (Q.C.) Is. | 5.7 | 13 | 1 | blue | |
| 6 Feb (037) 2013 | −10.8 | 165.1 | Solomon Is. | 9 | 11 | 10 | green | |
| 1 Apr (091) 2014 | −19.6 | −70.8 | Iquique, Chile | 19 | 4 | 0 | green | |

### (a) Events from 2004 to 2010

We start by recapping the events of the years 2004–2010, which were covered in Okal [68], to which the reader is referred for a more detailed discussion:

- The 2004 Sumatra–Andaman event gets a *black*star, on account of the total absence of warning, especially for far-field shores, where many deaths could have been prevented. In addition, informal real-time warnings transmitted to government authorities in Thailand were not heeded, allegedly on account of their potentially negative impact on the large tourist community.
- By contrast, the 2005 Nias earthquake is ranked *blue* (almost perfect): the response of the population in the near field was exemplary, resulting in only 10 casualties, primarily on account of ancestral tradition among populations south of the 2004 rupture [85,86]. In the far-field, however, the issued warning was overcautious due to tsunami generation in shallow seas and under islands [87]. It resulted in evacuation for what eventually turned out to be a false alarm, generating panic, notably in Madagascar, where six people were killed in traffic accidents [88].
- The 2006 Java 'tsunami earthquake' receives a *red* card. It was only mildly felt in southern Java, but its tsunami reached 21 m of run-up at Pangandaran [89] and caused more than 800 deaths. Its anomalous properties had been noted almost immediately by the Indonesian BMKG, and 27 min after origin time by the Japan Meteorological Agency (JMA), but, by contrast, PTWC, which was then in charge of warning for the Indian Ocean, issued a statement of 'no warning', and failed to recognize its stunning similarity to the 1994 'tsunami earthquake', 600 km to the east. The *red* index expresses the combination of contradictory and insufficient warnings, and lack of preparedness in the wake of a similar event only 12 years earlier.
- We assign a *yellow* (average) index to the 2006 Kuril Islands earthquake. Even though no casualties were suffered from either the seismic event or the tsunami, this was due to the extreme remoteness of its unpopulated epicentral area, where the 21 m run-up was surveyed only nine months after the event [90]. In the far field, the handling of the warning was nothing short of a failure, with both PTWC and WCATWC repeatedly issuing statements of 'no warning' or even 'no watch', despite the significant moment of the earthquake ($M_0 = 3.5 \times 10^{28}$ dyn cm). The tsunami caused local damage in Hawaii, where a swimmer luckily escaped drowning, and an estimated US$26 million damage (the largest economic loss from a tsunami in the USA since 1964) in the marina at Crescent City, where two harbour personnel narrowly escaped death, while a proper advisory should have kept them out of harm's way.
- We assign a *green* (good) index to the Solomon Islands tsunami of 1 April 2007. While this event resulted in 52 deaths, it destroyed more than 6000 houses, suggesting a population at risk of more than 30 000. In this respect, it must be considered a success, resulting from immediate self-evacuation by a population with a strong awareness for hazard [91]. Remarkably, this situation was repeated during the smaller event of 3 January 2010 whose tsunami run-up reached 5 m on Rendova Island [92] but caused no deaths, and during the significant tsunami of 6 February 2013 in the Santa Cruz Islands, where only 10 lives were lost despite substantial damage and run-up reaching 11 m [93]. All three events are assigned *green* indices.
- We assign a *yellow* card (average) to the Pisco, Peru, tsunami of 15 August 2007. The earthquake inflicted substantial damage (and more than 500 deaths) in the city of Pisco, and the tsunami reached run-up values of 10 m on the nearby Paracas Peninsula. However, thanks to a grassroots programme of Coast Guard 'sergeants' who triggered an evacuation based on seismic shaking, most coastal communities were successfully evacuated [94]. But the programme had not been implemented in the village of Lagunilla,

where three people were killed. This unfortunate gap in an otherwise commendable programme remains unexplained and degrades the ranking of the event to *yellow*.

— The Bengkulu tsunami of 12 September 2007 earns a *green* index on account of the self-evacuation of a well-prepared community during this very large earthquake ($M_0 = 6.7 \times 10^{28}$ dyn cm; then third, now sixth, largest CMT), resulting in no casualties despite a significantly damaging tsunami [95]. As discussed below, this *green* ranking would carry a glint of hope in the context of future tsunamis along the coast of Sumatra.

— The 2009 Samoa tsunami earns a *yellow* card, which reflects the dichotomy between a largely successful self-evacuation by a well-educated and aware population on Tutuila (American Samoa) and a general lack of awareness and preparedness on Upolu (Independent, *ex*-Western, Samoa), which suffered five times as many casualties, despite a significantly smaller population at risk on its southern coast [77,96].

— The great 2010 Maule, Chile tsunami is assigned a *yellow* index, again reflecting an alarming diversity of responses. In the near field, the individual responses of coastal communities, based on self-evacuation following shaking of clearly exceptional intensity and duration, literally saved hundreds if not thousands of lives. Most of the tsunami fatalities involved individuals who became entrapped while camping on Orrego Island, in the estuary of the Maule River [97,98]. By contrast, the official governmental response was nothing short of inept: the President herself, on advice from the Chief of Staff of the Navy, issued a statement on national television barring any tsunami risk, about the time the first waves were reaching Valparaíso and after they had devastated the epicentral area; no warning was issued for the Juan Fernández Islands, 700 km west of the epicentre, when there would have been time to evacuate the village, later hit by waves running up 15 m, and causing 30 deaths [99].

In the far field, warnings and responses were also of a mixed character. In general, real-time simulations correctly predicted that the main lobe of the tsunami energy would transit between Hawaii and Polynesia, and falter before reaching Japan. Thanks to an orderly evacuation in Polynesia, there were no fatalities, despite structural damage in the Marquesas [80]. Hawaii wisely erred on the side of caution, but in southern California, and as detailed by Barberopoulou *et al.* [81], the response was erratic on at least three accounts: (i) some beaches were evacuated and others not; (ii) there was a general lack of perception, on the part of authorities, of the hazards due to currents as opposed to mere wave amplitudes; and (iii) there was no understanding of the duration of tsunami hazard in harbours prone to resonance under late-arriving high-frequency waves travelling outside the shallow-water approximation. All these significant shortcomings stress the need for serious education of emergency managers in these respects.

## (b) Events since 2010

In addition, we provide a more detailed description of the following events, which postdate the final write-up of Okal [68]; the discussion of the 2011 Tohoku tsunami is giving in a separate section, §4c.

— The 2010 Mentawai tsunami earns a *red* mark. This 'tsunami earthquake' occurred as an aftershock of the 2007 Bengkulu event in a framework reminiscent of the classical Kuril Islands examples first studied by Fukao [38]. The tsunami had run-up of 17 m on Pagai Island, with a death toll of more than 400 [100]. In a textbook example of the treacherous character of these events, the 2010 earthquake was felt only mildly on the Mentawai Islands, and in particular at lower intensities than the Padang earthquake only a year before. Unfortunately, the latter had been an intraplate event, occurring inside the subducting slab, under the island of Sumatra. While it inflicted considerable damage in Padang and killed more than 1100 people, it generated only a negligible tsunami, with a maximum reported run-up of 0.3 m. Tragically, this instilled at least informally in the islanders' minds the concept that tsunami danger during the next earthquake could be ignored if shaking did not reach the level of the 2009 Padang event. This implicit scaling between two events at the opposite ends of the spectrum of earthquake source slowness would of course prove scientifically wrong and socially tragic.

In a pattern shockingly reminiscent of the 2006 Java earthquake, PTWC, which was at the time charged with issuing tsunami warnings for the Indian Ocean, failed to recognize the anomalous character of the event. Its location significantly seawards of the bulk of aftershocks of the 2007 Bengkulu event should have provided a strong hint in this respect, as would have been the definitely deficient slowness parameter $\Theta = -6.22$. In addition, the earthquake's slow character was detected as early as 17 min after origin time by Newman *et al.* [66], whose algorithm was then in development and not available for operational purposes.

Finally, while a warning was issued by Indonesian authorities, it was relayed to the Mentawai Islands in the form of a message streamed at the bottom on television screens, while regular programming was not interrupted. Taking into account that most of the villages in the Mentawai Islands had no electricity in the first place, the choice of this communication system to relay an emergency (as opposed to, for example, battery-operated sirens, a widely used standard) can only be described as amateurish, if not simply irresponsible.

— We assign a *blue* rating to the twin events of 11 April 2012, which occurred at the diffuse boundary between the Indian and Australian plates [101], in the general context of stress transfer following the major 2004 Sumatra event [102]. With a moment of $9 \times 10^{28}$ dyn cm, the first event was by far the largest strike-slip earthquake ever recorded, and the second one, two hours later, was a distant second. Even though this geological province had been recognized as the focus of very large earthquakes for close to 35 years in what was then called the 'Indo-Australian plate' [103], the 2012 earthquakes caught the scientific community by total surprise, especially on account of their exceptional sizes.

Wang *et al.* [54] provide a detailed timeline of the forecasting efforts at PTWC, where, by default, the event was modelled as a thrust fault until a definitive solution was obtained by W-phase inversion a mere 44 min after origin time and an adequate estimate of wave heights obtained 53 min later. Interestingly, the earliest W-phase CMT solution yielded a hybrid mechanism, intermediate between pure thrust and strike-slip.

In hindsight, and given maximum waves eventually reaching barely over 1 m, basin-wide large-scale evacuation efforts certainly erred on the side of caution, but this can be understood in the wake of the terrifying experience in 2004, and given the unexpected, and at first scientifically bewildering, characteristics of the earthquake(s). However, the warning was not without glitches, as the earthquake caused power outages, which disabled emergency sirens in the province of Aceh, wasting minutes that would have been precious if not critical under the scenario of a major interplate thrust event generating a much stronger tsunami.

— The El Salvador event of 27 August 2012 is given a *yellow* ranking. Even though this tsunami resulted in no casualties and went largely unnoticed, its run-up reached 6 m [104]. We base our ranking on the failure, on the part of PTWC, to recognize it as a typical 'tsunami earthquake', despite a clearly deficient energy-to-moment ratio ($\Theta = -6.3$) and record deficiency in energy versus duration for its high-frequency P waves. Since no adequate warning was issued, no evacuation took place, and it must be considered miraculous that no coastal residents lost their lives, some of them owing their survival to clinging precariously to trees onto which they had been flung in the middle of the night [104].

— We assign a *blue* ranking to the Haida Gwaii (Queen Charlotte Islands) event of 28 October 2012. However, this grading is in itself a challenge: the tsunami inflicted no damage or local casualties, but this was due to the extreme remoteness of the affected shores. Indeed, this large event resulted in local run-up reaching 7 m, and perhaps 13 m

[105], which could have been lethal had the earthquake occurred during the summer, due to increased fishing and kayaking activities in the wilderness. The lone death was due to a car accident in Hawaii during the evacuation of more than 100 000 people.[1] In Hawaii, the decision to evacuate erred on the side of caution, since PTWC had correctly foreseen only 'small non-destructive sea-level changes' and the maximum waves in Hawaii reached only 0.8 m at Kahului, Maui. Note finally that the thrusting mechanism of the earthquake, which expressed slip partitioning, was itself unexpected along this boundary, which had largely been regarded as a pure transform fault, even though it involves a component of convergence [107]. This generated confusion on the US West Coast, where the warning was delayed until the nature of the mechanism had been realized by WCATWC, by which time waves were already approaching the coast of Oregon.

— The Iquique, Chile, tsunami of 1 April 2014 earns a *green* ranking on account of an orderly warning and evacuation, for this relatively minor tsunami, which featured run-ups of only 4.4 m [108] and inflicted no fatalities. As in the case of the 2011 trans-Pacific tsunami (see below), this responsible and efficient warning in Chile contrasted with the chaotic official situation during the 2010 Maule tsunami, suggesting that lessons had been learned in the meantime.

## (c) The case of the 2011 Tohoku disaster

The 2011 Tohoku earthquake and tsunami resulted in an unprecedented level of natural disaster, as a result of the destruction of the Dai-ichi nuclear power plant in Fukushima province. Over and beyond the approximately 18 500 casualties, it affected several million people, either directly in Japan or accounting for evacuation along the Pacific's distant shorelines. In this respect, it is difficult, if not impossible, to characterize the event with a single 'wisdom index'. In the end, we assign the event a *red* rating, representing a weighted average between the black star deserved by frivolous, if not inept and perhaps criminal, lack of advanced mitigation, the blue rating earned by the largely successful grassroots evacuation of the people of Japan, and the green one suggested in the far field by a successful and appropriate level of evacuation.

In the near field, and as expected in a country with a long tradition in this respect, tsunami warnings were issued promptly by JMA. However, the maximum magnitude used in this context was only 8.1, obtained about 2 min after nucleation time, and suggesting run-up heights of at most 3 m. The first correct estimate of the earthquake's size was NEIC's W-phase estimate of 9.0, 20 min after nucleation [109]. While the underestimation of the source by JMA is understandable at a time when the rupture had not ended (the source duration was later found to be at least 150 s), the broadcasting of clearly deficient wave amplitudes may have contributed to casualties among groups of people who evacuated to insufficient heights. In this context, one is led to question the wisdom of issuing premature estimates of earthquake sizes as the rupture is still propagating (e.g. 4.9, 7.2, 6.6 in that order, by JMA, in the first 10 s), since such values may elicit a false impression of safety if taken at face value.

We recall that tsunami walls along Japanese shorelines have traditionally been engineered to protect against 6 m waves (e.g. [110]). At the time when this infrastructure was deployed, in the 1960s and 1970s, the latest tsunami to significantly affect the country was the 1960 Chilean event whose maximum amplitude in Japan had reached 7 m, which led to the irrational situation of using a teleseismic event to define a worst-case hazard scenario when disaster could clearly originate in one's backyard. The widely publicized images of the 6 m wall at Miyako being overridden by the 2011 tsunami, endlessly broadcast on worldwide television and reprinted in countless publications, are a vivid if tragic reminder of the nonsensical nature of this insufficient engineering standard. Only in certain locations were taller walls erected at heights of 10–15 m even though the 1933 Sanriku tsunami had consistently reached run-up heights of more than

[1]The accident was caused by a drunken driver ramming his truck into a line of parked cars waiting for the all clear to the evacuation [106]. Under the circumstances, it is debatable whether this should be considered a tsunami fatality.

20 m (and a maximum of 29 m) along the eastern coast of Honshu [111]. Even smaller events, such as the 1993 Okushiri tsunami, resulted in a catastrophic overflow of the 6 m walls [112] and, in the later revision of the standard for mitigation and evacuation, to a locally amended height of 11 m.

On a long-term basis, the most catastrophic impact of the 2011 Tohoku tsunami will undoubtedly remain the flooding and destruction of the Dai-ichi nuclear plant. As discussed in more detail by Synolakis & Kânoğlu [113], the safety of the plant had been examined in two recent instances by scientific committees at the instigation of the plant's operator, the Tokyo Electric Power Company (TEPCO). As reported by the *Washington Post* [114] in the aftermath of the Tohoku disaster, during the first hearing in 2008–2009, a scientist had pointed out the so-called 'Jōgan' historical earthquake of AD 869 whose tsunami had inundated as much as 5 km into the Sendai plain [115], but his arguments had not been incorporated in the Committee's final report.

Following the 2010 Chilean tsunami, TEPCO ordered a series of new hydrodynamic simulations aimed at determining whether the plant would be adequately protected by its existing walls, under what had to be considered a worst-case scenario. The results of these simulations, available in the public domain [116], indicated perhaps not surprisingly that the maximum water level to be expected at the site was 5.7 m, and the plant was therefore safe as its wall was 30 cm taller. The whole exercise is nothing short of baffling to any reader with a minimum amount of scientific competence in the field and, most importantly, of common sense. The consultants hired by TEPCO performed a large number of simulations in which they varied such source parameters as the epicentral location, depth, strike, dip and slip of the earthquake source, but they do not provide any information on its *size* (the earthquake moment or magnitude), let alone did they let that size vary. In lay words, the most sophisticated numerical simulation will only produce a wave amplitude controlled first and foremost by the size of the initial input (in this case by the magnitude of the earthquake). A simple order-of-magnitude computation based on scaling laws [117] suggests that the maximum run-up envisioned (4.4 m before the influence of tide) would correspond to source slips $\leq$2.5 m, or magnitudes $\leq$7.5, which clearly underestimates the seismicity off eastern Honshu, even before the occurrence of the 2011 Tohoku earthquake.

In addition, it defies common sense that the maximum wave height presented under an alleged worst-case scenario (6 m) would be *five to six times less* than the waves documented a few hundred kilometres to the north during the 1896 Sanriku tsunami (38 m) or, even more recently, the 1933 normal faulting event (29 m). While it could be argued that the latter was not part of the subduction cycle expected to produce the majority of great earthquakes in the region, an engineer working to protect a critical structure such as a nuclear plant should not be driven by the details of the geological nature of a hazard, but merely by the fact that its occurrence in the past proves that it will happen again in the future. Finally, it is also against common sense that the hazard from an alleged worst-case scenario for a local source would be comparable with that from a far-field source at the other end of the Pacific basin.

In summary, the simulations performed by the TEPCO committee were certainly not computationally wrong, but their initial conditions were grossly inadequate to represent the worst-case scenario that the protection of a nuclear plant should require. The selection of source parameters led to a verdict of safety for the plant by inexplicably ignoring aspects of Japanese seismicity notorious not only in the scientific community, but also within the most senior fragment of Japanese population, i.e. survivors of the 1933 event. It is hard to believe that educated 'experts' would not have been familiar with this evidence, and thus the motivation behind their use of deficient parameters as 'design sources' is at best obscure, at worst suspect.

Despite a death toll of more than 18 000 people, some aspects of the 2011 Tohoku tsunami can be regarded as a definitive success in evacuation. Most importantly, it has been estimated that 200 000 people were present in the zone devastated by the tsunami [118]. Notwithstanding tragic occurrences, such as regrouping of evacuees at shelters located at heights that proved insufficient given the exceptional amplitudes of the waves, as well as an average delay of 20 min in reaching safe ground, this estimate means, in rough numbers, that nine out of ten of these residents managed to save their lives through various evacuation procedures. This success is largely due to the high level of education to tsunami hazard instilled in the local population through the combination of ancestral tradition, formal education and regular exercises in preparedness.

In the far field, warnings and evacuations were largely successful. An important role was undoubtedly played by the occurrence of the earthquake in broad daylight at its source, so that, in contrast to the case of the Maule tsunami a year before, horrific pictures of devastation were immediately broadcast on worldwide television, contributing a sense of approaching disaster to coastal populations all around the Pacific basin. Evacuations in Hawaii, Polynesia, California and Chile were largely orderly and successful. Despite considerable damage in Hawaii, California and Chile (reaching a combined US$100 million), and as far as Antarctica, where the tsunami triggered the calving of an ice shelf [119], only two deaths were reported in the far field (one in Crescent City, California, and one near Jayapura, Papua, Indonesia), both in violation of evacuation orders. This can be directly contrasted with the 1960 Chilean tsunami, which killed more than 200 people in the far field, principally in Hawaii and Japan. Evacuating to the protection of deep water thousands of ocean-going vessels of all sizes across the distant shores of the Pacific Ocean easily saved tens if not hundreds of millions of dollars. In these respects, the far-field warnings and evacuations would deserve a *green* ranking.

In conclusion, the 2011 Tohoku tsunami stands out as an example of catastrophic disaster, made significantly worse by inadequate, if not simply inept, mismanagement of its before-the-fact mitigation in the near field [113], and should earn a *black* star in this respect. However, in the midst of this despicable record, several glints of hope can be recognized. First, the death toll in Japan could have been much worse, had it not been for a largely successful evacuation. The daytime occurrence of the tsunami certainly played a role in this context, but the major cause of this success can be traced to the awareness of the population, itself a result of the education of the Japanese people to tsunami hazards. Second, the warnings and evacuation were successfully carried out in the far field. While these developments were certainly positive and remain encouraging, they cannot help raise the 'wisdom index' for the 2011 Tohoku tsunami to better than a *red* rating.

## (d) The wisdom plots and their discussion

Our 'grades' reported for the 17 tsunamis examined above are summarized in figures 2–4. Figure 2 summarizes the death tolls of the events, colour-coded by the wisdom index (note the logarithmic scale). As explained in the introduction to this section, the wisdom index is not supposed to be linked directly to the death toll. However, it is apparent both from figure 2 and from the formal computation of a correlation of 73% between the index and the logarithm of death toll (taken as −0.5 for events without casualties) that the less satisfactory rankings (black, red) correspond to events that have resulted in significant fatalities. After all, the primary purpose of exercising wisdom during an emergency should be to save lives.

In figure 3, we similarly examine the influence of earthquake size (expressed as logarithm of seismic moment $M_0$ (lower scale) or moment magnitude $M_w$ (upper scale)) on the wisdom index. This time the correlation is weak (37%). In general, and again somewhat expectedly, we are doing poorly with the very largest events (Tohoku and Sumatra), but the poor marks given to the Java and Mentawai events (and to a lesser extent to the El Salvador one) underscore our failure to properly mitigate the treacherous 'tsunami earthquakes' which can occur even at reduced moment values. We discuss this situation in more detail below.

Next, in figure 4, we plot a timeline of wisdom indices. Formal correlation coefficients are 33% for the 17 events, and only 16% if the 2004 Sumatra tsunami is excluded. These numbers mean that, while we have not repeated the black rating of 2004, which expressed a total lack of preparedness in both the near and far fields, any progress made since then may not be sustained with time and the level of wisdom achieved during later events has been at best irregular, at worst random.

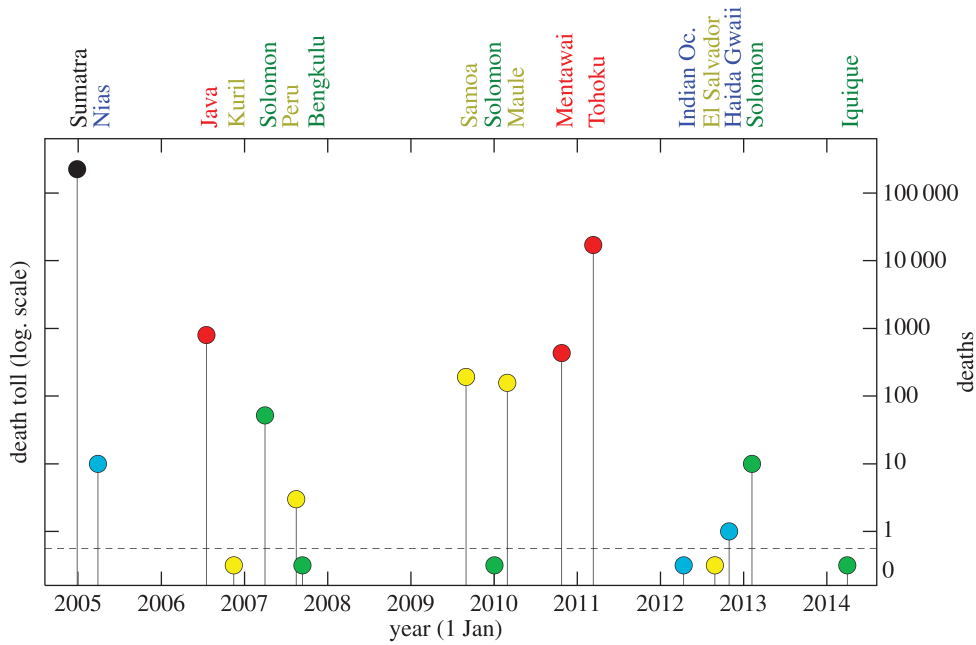


**Figure 2.** Tsunami deaths colour-coded by wisdom index for the 17 tsunamis considered in this study. The vertical scale is logarithmic above the dashed line, the value 0 being plotted symbolically below it. (Online version in colour.)

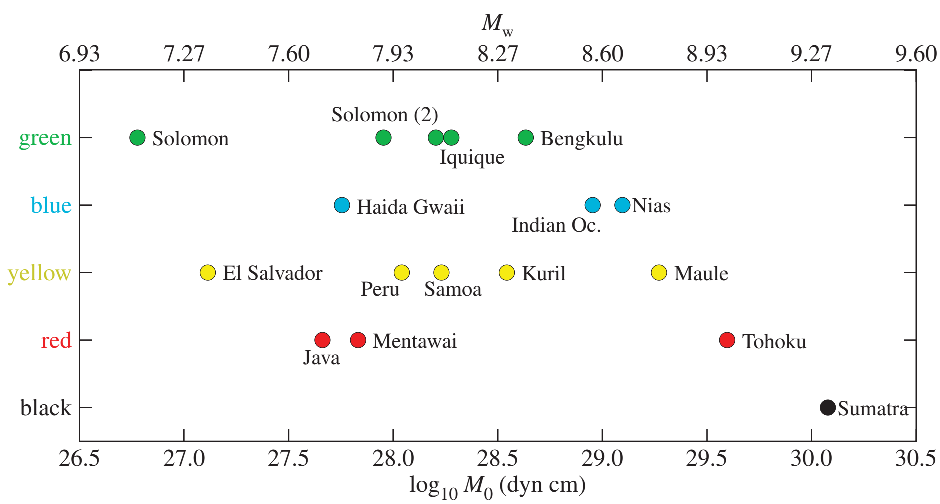


**Figure 3.** Colour-coded wisdom indices of 17 tsunamis since 2004, as a function of seismic moment $M_0$ (lower scale) or moment magnitude $M_w$ (upper scale). (Online version in colour.)

Finally, the wisdom indices are mapped geographically in figure 5. It is difficult to draw general conclusions from this map because of the irregular repartition of the earthquake foci, with the line extending from Sumatra to Samoa contributing 10 of the 17 events. In addition, when tsunami hazard and death are exported across an ocean basin, the mapping of the event at its source may be somewhat deceptive. In this general context, two conclusions may be drawn. First, the three remarkable green rankings given to events in the Solomon Islands. All of them involve self-evacuation by the coastal population upon feeling the strong shaking from the earthquake.

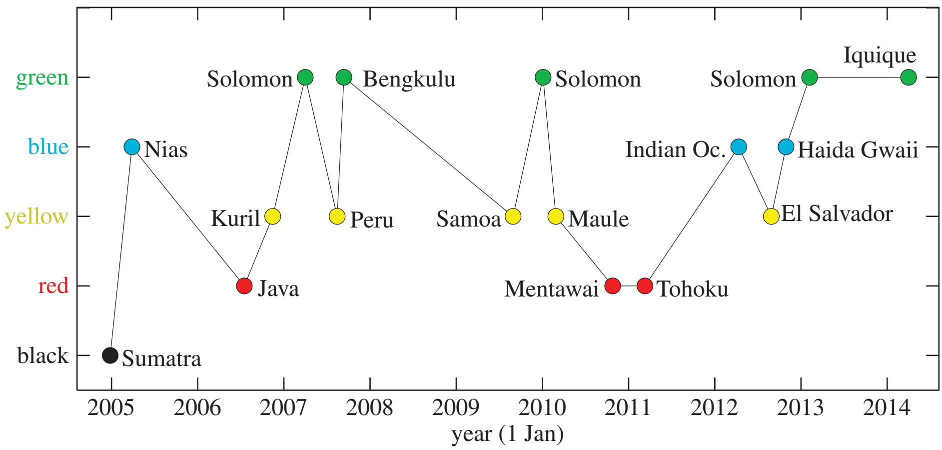


**Figure 4.** Colour-coded wisdom index as a function of time for 17 tsunamis since 2004. Note the erratic character of the evolution of the index. (Online version in colour.)

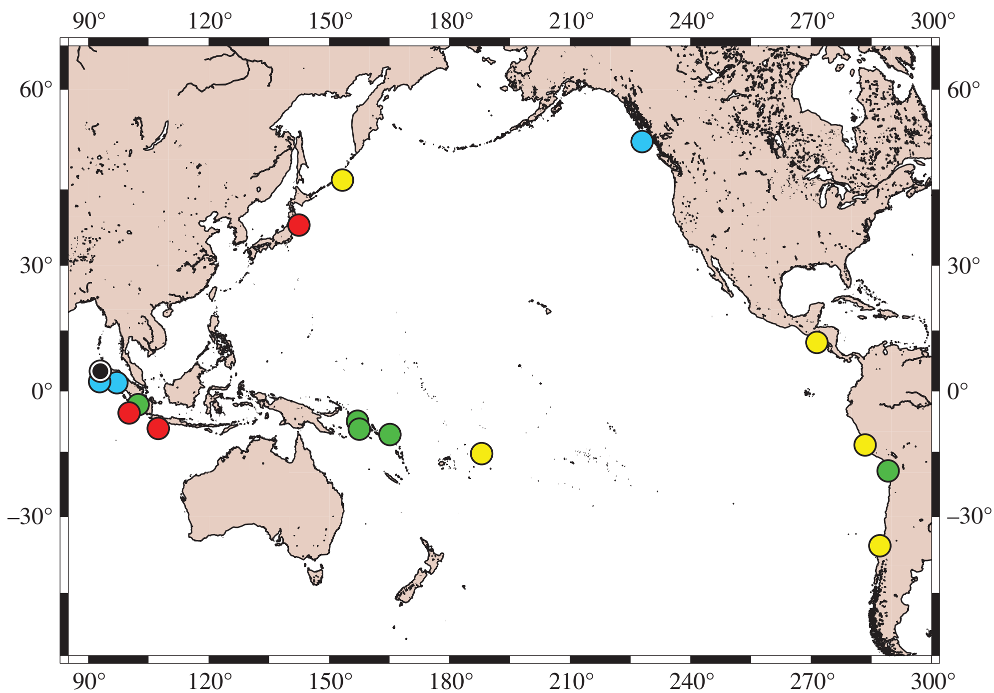


**Figure 5.** Colour-coded wisdom indices for 17 tsunamis, 2004–2014, mapped at the epicentres of the parent earthquakes (the latter have occasionally been slightly displaced to enhance clarity). (Online version in colour.)

While the 52 casualties of the 2007 event are obviously regrettable, they represent much less than 1% of the population at risk, and as such the evacuation must be considered successful. The repeat of this pattern of evacuation in 2010 and 2013 illustrates once more, and if need be, the value of education (taken in its broadest sense) as a fundamental ingredient of tsunami mitigation.

Second, and by contrast, the results concerning Indonesia are very significantly scattered. On the one hand, the 2005 Nias and 2007 Bengkulu events constituted success stories, as also did the orderly and largely successful evacuation in Jayapura, Papua, during the 2011 Tohoku event

[120]. On the other hand, the 2006 Java and 2010 Mentawai 'tsunami earthquakes' were not, or not sufficiently, recognized as such, and turned into tragic disasters. The disparity in colours along the Sunda arc in figure 5 is of particular concern given that, to the south of the 2005 Nias rupture, the 2007 Bengkulu sequence has failed to release the full strain accumulated since the great 1833 earthquake [95], resulting in a seismic gap that is widely expected to rupture through a great earthquake in the next years to decades, bearing catastrophic tsunami hazard, especially for the city of Padang with a population of 1 million [121,122].

## (e) Summary

At least one positive conclusion can be drawn from the examination of the 16 post-Sumatra tsunamis. The considerable progress in science, instrumentation and simulation capabilities, as well as in hazard awareness, over the past 10 years has led to a much better control of the far field: this is best illustrated by the fact that, to our knowledge, tsunamis have inflicted only three casualties in the far field (generally defined as beyond 1000 km of the epicentre), two of the victims having deliberately violated an evacuation order. From the scientific point of view, our command of the far field is similarly expressed by the often spectacular quantitative agreement between wave amplitudes forecast in real time and eventually recorded at distant maregraphs located across oceanic basins [79]. From the operational standpoint, the catastrophic nature of the 2004 Sumatra and 2011 Tohoku tsunamis, as well as the smaller intervening events, have raised and helped maintain the awareness of decision-makers.

Our main area of repeated failure remains the problem of 'tsunami earthquakes'. Because of their extreme low-frequency spectrum, these events are weakly, if at all, felt by the populations at risk, thus negating the concept of 'the shaking is the warning', which otherwise stands out as a most efficient means of saving lives. In this respect, we must accept that we did not fare better in 2010 (Mentawai) or 2012 (El Salvador) than in 1992 (Nicaragua) or 1994 (Java). This is highly regrettable, as significant progress has been and continues to be made in developing methods aimed at the real-time detection of 'tsunami earthquakes'. Newman *et al.*'s [66] discriminant based on comparing the energy of P waves to their duration proved its potential in real time during the 2010 Mentawai earthquake and its systematic implementation at local national warning centres stands as a critical priority. In this context, the survey report by Hill *et al.* [100] mentions that 'residents described (the shaking) as a gentle, slow, rocking earthquake that lasted several minutes'. It is nothing short of remarkable that this statement, opposing the weak amplitude of the shaking to its long duration, has the ingredients of a human, qualitative version of Newman *et al.*'s [66] discriminant. This suggests that it may be possible to sensitize lay populations to the importance of the *duration* of shaking, especially under conditions when its intensity remains weak, and, indeed, some US West Coast communities are adapting their outreach towards emphasizing the importance of length (as opposed to strength) of shaking as a tsunami harbinger. This remains, however, a formidable task, as the human perception of time without a quantitative measurement is even more inaccurate than that of distance, especially under scenarios of emergency.

Finally, we stress once again the value of education as a major contributor to saving lives. For the record, we recall the successful evacuation, during the 2004 Sumatra disaster, by diverse communities in devastated areas, from the native Sentenelese tribes of the Andaman Islands to the groups of Japanese tourists and the young English schoolgirl at Thai resorts: all shared the benefits of education, be it from ancestral tradition, regular exposure to tsunami hazards or formal schooling. This should be contrasted to the fates of, for example, Swedish tourists at the same resorts, who perished in alarming numbers, as they were totally unaware of tsunami hazard (with 428 fatalities, the 2004 Sumatra tsunami turned out to be the most lethal natural disaster in the history of Sweden). Similarly, the consistently high wisdom indices achieved in the Solomon Islands illustrate the awareness of a population educated by a high level of recurrence of local tsunamis.

## 5. General conclusion

We have examined some of the major developments following the 2004 Sumatra–Andaman disaster and the other tsunamis which took place in the past 10 years, from the standpoint of science, mitigation and real-time operations. On all fronts, our outlook on significant or critical issues has evolved appreciably, and this form of new acquired knowledge must be regarded as a progress in our *wisdom* towards our general command of tsunami hazard.

On the scientific front, we have had to question, qualify or abandon a couple of paradigms which had guided our scientific models for tsunami hazard, but this apparent setback has been more than made up by the development of powerful techniques mostly based on the interpretation of early-arriving P waves, which are revolutionizing our ability to obtain critical source information in a timeframe useful for tsunami forecasting and warning. In this respect, there can be no doubt that, by acquiring a more profound command of those scientific matters, our community has indeed become *wiser*.

Regarding mitigation, considerable efforts continue to be made in various fields, including the development of regional warning centres, the preparation of sophisticated inundation maps, which allow local decision-makers to prepare adequate strategies of evacuation, and the general education of populations at risk, including through grassroots exercises such as drills. A fundamental aspect of these activities is that they contribute to raising and maintaining the awareness of these communities, and thus to making them 'tsunami aware', and eventually lead them to achieve their formal status as 'Tsunami Ready'. Writing as a teacher himself, the author is obviously biased to thinking that education and *wisdom* go hand in hand.

However, the ultimate verdict comes only during an emergency, namely when a new tsunami strikes a coastline with the potential for disaster. In this respect, the examination of the 'wisdom indices' developed in §4 leaves a mixed result. It is clear that some lessons have been learned; for example, in Chile, where, following the poor official handling of the 2010 Maule event, the warning and evacuation were exemplary during the 2011 (teleseismic) and 2014 (local) events. The value of education is regularly stressed, notably by the high percentage of residents escaping devastated areas in countries which can be as diverse as Japan and the Solomon Islands, but which share a long heritage of sensitization to tsunami hazard, constantly maintained by a mixture of ancestral tradition, formal education and exposure to recurring events. The main challenge presently remains to build awareness for specific situations, such as the treacherous 'tsunami earthquakes' for which advances in scientific and operational wisdom are hard to transfer to the coastal communities at risk.

In conclusion, 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.

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