Tsunami Processes: Reflections and Prospects from Sumatra and Other Events

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We analyze some fundamental aspects of tsunami generation, propagation and coastal interaction in the framework of the systematic study of the catastrophic 2004 Sumatra events, and of other recent tsunamis.

Processes generating tsunamis have traditionally included Earthquakes (most common); Landslides (many examples documented and reproducible in the laboratory); Volcanic Eruptions at Sea (a handful documented); and Bolide Impacts (speculated). Theoretical studies of such parent phenomena, principally in the case of earthquakes and landslides, have led to the concept of scaling laws, allowing a simpler representation of the source, some predictability of their recurrence rates, as well as the definition of specific invariants in observable properties of the relevant tsunamis. In the near field, one such invariant for seismic tsunamis can be the aspect ratio of the distribution of run-up along a linear beach, which because it is directly related to the strain released by the seismic source, must remain under 10**(-4). In the far field, we show from numerical simulations that transoceanic tsunami amplitudes are primarily controlled by the earthquake's seismic moment, the only other significant parameters being source water depth and to a lesser extent fault dip. In particular, arguments based on source scaling indicate that the 2004 tsunami was anomalous neither in the near nor in the far fields, once the exceptional size of the earthquake was recognized.

A major problem which contributed to the deficiency of initial estimates of the Sumatra-Andaman earthquake was that routine seismological algorithms were not designed for such a large event; in lay words, the earthquake exceeded the measuring rod. In this respect, it is necessary to consider new directions of research holding promise for reliable real-time assessment of very large earthquakes. They include the use of large-scale local or regional GPS arrays, and the development of seismological techniques emphasizing the duration of the seismic source, such as the computation of integrated short-period magnitude, or the formal quantification of source duration from high-frequency P waves, an algorithm for which we provide preliminary results. Such techniques also help recognize in real time anomalous behavior such as slow ruptures during the so-called "tsunami earthquakes" (e.g., Java, 2006). In addition, the question of the maximum potential earthquake sustainable by a given subduction zone must be reopened in the wake of the Sumatra-Andaman disaster, with the contribution of non-subduction events, such as the great 1933 Sanriku earthquake, carefully addressed.

Despite spectacular progress in the development of "tsunameters" (bottom sensors coupled to surface buoys), the question of the direct detection of tsunamis on the high seas remains a challenge. In this respect, the catastrophic 2004 Sumatra tsunami was recorded by many "ancillary" technologies which were never designed to detect it in the first place. Such observations provide significant insight into the coupling, in the presence of the tsunami, between physical media as diverse as the ocean, the atmosphere, the ionosphere, and the solid Earth, with in many cases the suggestion that such observations can be reasonably quantified in terms of tsunami surface amplitude or even earthquake source. For example, the detection of tsunami waves by coastal seismological stations worldwide opens the possibility of supplementing at much reduced cost a network of tsunameters, while the recording of tsunami waves by CTBT hydrophones provides unique insight into their high-frequency components, strongly dispersed under the deep-water approximation, yet capable of non-linear, delayed and highly hazardous interactions with distant harbors. The mechanism by which the Sumatra tsunami gave rise to infra-sound signals detected a teleseismic distances points to a significant level of energy loss to the atmosphere along the Burmese coast, incidentally a region which was spared major destruction. Finally, the 3-D seismic recording of the Sumatra tsunami by seismometers deployed on large icebergs floating off the shores of Antarctica suggests the possibility of detectin tsunamis using GPS navigation on large vessels encountering the wavefront on the high seas.