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What is a mega-tsunami?

James Goff [a,*], James P. Terry [b,1], Catherine Chagué-Goff [a,c,2], Kazuhisa Goto [d,3]

[a] School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, NSW 2052, Australia
[b] Department of Geography, National University of Singapore, AS2, 1 Arts Link, Kent Ridge 117570, Singapore
[c] Institute for Environmental Research, Australian Nuclear and Science Technology Organisation, Locked Bag 2001, Kirrawee DC, NSW 2232, Australia
[d] International Research Institute of Disaster Science (IRIDeS), Tohoku University, Aoba 6-6-40-102, Aramaki, Aoba-ku, Sendai 980-8579, Japan

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ABSTRACT

No unambiguous and widely accepted definition currently exists for the term 'mega-tsunami'. This is in spite of the rapidly growing popularity of the expression in the scientific literature, especially in recent years following the devastation wrought by the 2004 Indian Ocean and 2011 Tohoku-oki tsunamis. A comprehensive literature search is revealing. We find that although there have been several previous attempts at a definition, the term mega-tsunami has generally been applied in a rather arbitrary fashion to a number of tsunami characteristics, such as wave height or amplitude at both source and distant locations, run-up height, geographical extent and impact. This haphazard situation is undesirable. In response we propose a stricter definition for mega-tsunami that is based solely on initial wave height/amplitude at source exceeding 100 m/50 m respectively. A source-related definition conveniently avoids any difficulties associated with the potential influence of coastal physical attributes (e.g. configuration, bathymetry, geomorphology) on tsunami parameters at affected locations. Using this definition, it becomes apparent that mega-tsunamis can only include those rare events on geological time-scales generated by large bolide impacts, violent volcanic activity or oceanic island flank collapse, and possibly extreme tsunamigenic submarine earthquakes. Most seismically-triggered events instead fall into the group of *souteigai*-tsunamis, i.e. 'unexpected' tsunamis, which are considered exceptional according to historical experience and local perspectives.

1. Introduction

According to Darbyshire and Ishiguro (1957) the traditional term *tsunami* means harbour wave (*tsu*: harbour, *nami*: wave). The original Japanese definition includes any form of wave that would be unusually large inside a harbour, although this may not be quite as simple an explanation as it sounds (Darbyshire and Ishiguro, 1957). Alternatively, in the Tsunami Glossary produced by the United Nations Educational, Scientific and Cultural Organization–Intergovernmental Oceanographic Commission (UNESCO/IOC) (2013), a tsunami is specifically described as "a series of travelling waves of extremely long length and period, usually generated by disturbances associated with earthquakes occurring below or near the ocean floor… Volcanic eruptions, submarine landslides, and coastal rock falls can also generate tsunamis, as can a large meteorite impacting the ocean". The Tsunami Glossary (UNESCO/IOC, 2013) also mentions that a tsunami has no connection with tides and that the term 'tidal wave' is misleading. Although the latter observation is indeed correct under the Anglicised use of the word tsunami (UNESCO/IOC, 2013), it is technically incorrect under the traditional Japanese version (Darbyshire and Ishiguro, 1957).

It appears that the first use of the term tsunami in popular scientific literature was in an 1896 National Geographic article (Scidmore, 2013). However, according to Shuto et al. (2007) it was probably Platania (1909) writing in the journal, *Bollettino della Societa Sismologica Italiana*, who first used the term tsunami in the peer-reviewed literature outside Japan, but it was Darbyshire and Ishiguro (1957) who fully explained the word *tsunami* and its derivation to the international community. Darbyshire and Ishiguro (1957) entitled their paper 'Tsunamis', thus adopting the Anglicised plural usage (n.b. the lack of italics also recognises the Anglicisation of the term).

While the confusion concerning the precise definition of *tsunami*/tsunami may be a moot point, it is indicative of the problems faced by researchers working in earth science and related disciplines. With this in mind, it is noteworthy that the expression 'mega-tsunami' is becoming increasingly common in the peer-reviewed literature and yet its definition is far from clear. Indeed, it is not even mentioned in the latest

* Coresponding author. Tel.: +61 2 9385 8431; fax: +61 2 9385 1558.
E-mail addresses: j.goff@unsw.edu.au (J. Goff), geojpt@nus.edu.sg (J.P. Terry), c.chague-goff@unsw.edu.au, ccg@ansto.gov.au (C. Chagué-Goff), goto@irides.tohoku.ac.jp (K. Goto).
[1] Tel.: +65 6516 7144; fax: +65 6777 3091.
[2] Tel.: +61 2 9385 8921, +61 2 9717 9354; fax: +61 2 9385 1558, +61 2 9717 9270.
[3] Tel./fax: +81 22 395 7201.

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Tsunami Glossary (UNESCO/IOC, 2013). Among the wider research community, the term mega-tsunami is generally considered to be a media-driven descriptor (McGuire, 2006), created for a television documentary entitled "Mega-tsunami: Wave of destruction" first aired in 2000 (BBC, 2000). Upon closer scrutiny, however, the term actually appears to have been coined first in the scientific literature by Bourgeois (1990), appearing again a year later in two further publications (Bourgeois, 1991; Paskoff, 1991). Over a decade later, usage of the term then gained significant traction in the period following the 2004 Indian Ocean Tsunami (IOT).

Recent years have seen the term mega-tsunami being used increasingly in association with waves generated by ocean-island flank collapse and the emplacement of high elevation coastal boulder deposits (e.g. Ward and Day, 2003; Dawson and Stewart, 2007; refer to Table 1 for further examples). Yet much of this work has either ignored the need for any definition or offered only an arbitrary one to fit the specific discussion at hand. Clearly, the lack of an accepted definition for mega-tsunami combined with the potentially sensational nature of the term itself is undesirable. Furthermore, this situation has also led (in part) to a growing number of reports correlating unsubstantiated bolide impacts with hypothetical 'mega-tsunami' events during the past 10,000 years (e.g. Bryant, 2001; Blakeslee, 2006; Pinter and Ishman, 2008; Scheffers et al., 2008; refer to Table 1 for further examples). Unfortunately, these uncorroborated associations have served to obfuscate a term that nonetheless has value in tsunami research.

It is important to emphasise that the aim of this paper is not to develop a new scale for tsunami magnitude or intensity, such as those summarised by Lekkas et al. (2013), but rather to address the somewhat arbitrary use of the term mega-tsunami. Indeed, Lekkas et al. (2013) use the term "megatsunamis" to describe the 2004 IOT and 2011 Tohoku-oki tsunami, but at no point do they define it.

2. A definition for mega-tsunami

A clear and agreed definition for mega-tsunami has become an even more pressing issue since the Japanese government is now instructing its scientists to "verify the occurrence of mega tsunamis over a time scale of several thousand years" (Central Disaster Management Council, 2011). While the point may be debatable, it appears that as opposed to searching for mega-tsunamis in Japan, the Japanese government is really tasking its scientists with finding evidence for *souteigai* (meaning "unexpected" or "beyond expectations" [*soutei*: expect, *gai*: outside]) tsunamis (hereafter we use the term "*souteigai*-tsunamis"), in other words — unexpectedly large waves such as those generated by large subduction zone earthquakes.

The Tokyo Electric Power Company (TEPCO) indeed used the word "*souteigai*" to describe the 2011 Tohoku-oki tsunami which destroyed the Fukushima Daiichi nuclear power plant (Aoki and Rothwell, 2011) resulting in such devastating consequences. This raises the question as to whether the 2011 Tohoku-oki event was a mega-tsunami or a *souteigai*-tsunami? Both expressions have been used to describe this event, which presents us with a dilemma when attempting to provide a coherent definition for the term mega-tsunami.

A mega-tsunami could undoubtedly be characterised as an 'unexpected' or *souteigai*-tsunami, but the perception is that it should also be an exceptionally large event, and as such warrants a unique definition. There have been many large tsunamis over the geological timescale with the oldest, an undoubted mega-tsunami, occurring around 3.47 Ga in what is now the Australian continent (Byerly et al., 2002). However, the original use of the term mega-tsunami referred to the almost iconic event associated with the Chicxulub asteroid impact at the Cretaceous–Tertiary boundary (Bourgeois, 1990; Campbell et al., 2008). Geological evidence and numerical modelling outputs tend to suggest that such a tsunami would be the archetypal event for a mega-tsunami, with extreme wave heights at source (~100 m wave height/50 m wave amplitude or more) and extensive inundation of local (and distant?) coastlines by large waves. While there is still controversy surrounding much of the geological evidence used to corroborate the purportedly widespread inundation caused by the Chicxulub asteroid impact (e.g. Keller, 2012; Gertsch et al., 2013), it is this type of shallow to deep water bolide impact that could be responsible for generating such mega-tsunami events.

From a geological timescale perspective, events such as the 2004 IOT and 2011 Tohoku-oki tsunamis are by no means large, but in the modern era they have attained mega-tsunami status almost by default since they are the largest ones observed in recent human history and have had catastrophic implications for coastal populations. What then of *souteigai*-tsunamis, the 'unexpected' large waves? Do events generated by large fault ruptures such as the 2004 IOT (e.g. Gupta, 2005; Synolakis, 2006; Mörner et al., 2008; Wickramaratne et al., 2011), the 2011 Tohoku-oki event (e.g. Udo et al., 2012; Hein, 2014), and even the 1755 Lisbon tsunami (e.g. Jelinek et al., 2012) represent mega-tsunamis or not?

The work of Naranjo et al. (2009) may provide an answer. According to these authors, the term mega-tsunami should indicate a tsunami that has an initial wave amplitude or height of several tens or hundreds of metres, much larger than a 'normal' one. They state that most mega-tsunamis therefore originate from large scale events such as landslides, devastating volcanic eruptions, and bolide impacts, whereas 'normal' tsunamis originate from tectonic activity and the subsequent raising or lowering of the sea floor. If this definition for a mega-tsunami is to be accepted, notwithstanding the more variable use of the term by many researchers in the past (Table 1), then it is evidently the case that numerous (on a geological timescale) large earthquake-related events cannot trigger mega-tsunamis. Equally, in general terms, initial tsunami wave heights/amplitudes induced by submarine landslides are typically fairly small, around 10 m/5 m or so, while those for volcanic flank collapses can be an order of magnitude larger (Harbitz et al., in press). Thus, events such as the giant Storegga submarine landslides on the continental slope west of Norway may be able to remobilise enormous volumes of debris but may not actually produce especially large initial waves (Masson et al., 2006). In other words, perhaps this indicates that the term mega-tsunami should best be reserved to define those rare, extreme events, recorded in the geological record that were generated by volcanic flank collapses or bolide impacts.

Before drawing out this line of argument further, it is important to highlight another difficulty stemming from the absence of an agreed mega-tsunami definition. This has been the seemingly arbitrary use of the expression in a variety of settings. Table 1 reveals how the term mega-tsunami has been employed to mean not only large waves at the source of the event (with a minimum wave height >40 m; refer to Alexander and Neall, 2007), or on land in both local and distant coastal settings, but also to imply geographically extensive tsunamis (i.e. ocean basin scale) that may or may not have large wave heights (or amplitudes) at source or distal locations. With this array of arbitrary designations, the generating mechanisms appear all-encompassing and could arguably be bolide impact, landslide (subaerial or submarine), fault rupture and volcanic-related activity. Consequently, any event with either large wave heights (or amplitudes) and/or covering an extensive area seems to satisfy the requirements for it to be deemed a mega-tsunami under existing terminology. Following this model, with the advent of increasingly sophisticated instrumental records, even relatively small events such as the 2009 South Pacific tsunami could plausibly be called mega-tsunamis because their effects can be traced across ocean basins (e.g. Richmond et al., 2011). This is confusing.

Returning to the first time that the term was quantified, and arguably the most appropriate interpretation of a mega-tsunami, is more helpful. Bourgeois (1991) refers back to Bourgeois et al. (1988), in which the authors stated that the geological evidence is "most consistent with the occurrence of a tsunami about 50 to 100 m high." This probably refers to the tsunami height above sea level, most likely resulting from a bolide impact in a mid- to outer-shelf location, i.e. in