The nature of tsunami energy decay with epicentral distance in the open ocean for two large trans-Pacific tsunamis

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**Abstract.** The dynamics of a tsunami wave in a zone of propagation in the open ocean includes examination of time evolution of tsunami amplitude whilst propagating over a large distance. In this study, we used NOAA Center for Tsunami Research database from field measurements of vertical displacement of sea surface elevation referred here to tsunami maximum amplitudes for two trans-Pacific tsunamis, namely the 2011 Tohoku, Japan and 2014 Iquique, Chili events. The data were all recorded by DART buoys located at various geographical positions across the Pacific and were analyzed to examine tsunami energy decay in terms of tsunami amplitude decrease with increasing epicentral distance, defined here as tsunami travel distance measured from the epicenter. The results show that the amplitude decreases dramatically in a near-field region of observation and decreases gradually in distant propagation before advancing with relatively constant energy. Extracted from the amplitude decay curve, this finding suggests that different mechanisms of energy conversion and conservation are responsible for energy release in the propagation zone. This is of significance for the development of tsunami early warning as accurate prediction of tsunami run-up in a zone of mitigation requires knowledge of tsunami wave height when the wave approaches shorelines.

1. Introduction

Knowledge of the nature of tsunami energy decay hence tsunami amplitude variation with travel time and distance while propagating away from the source in the open ocean is of primary importance for tsunami early warning [1]. This knowledge is required for prediction of tsunami wave height or run-up when the wave approaches coastal areas [2]. In this context, tsunami hazard analysis and assessment involve comprehensive knowledge about two tsunami zones, namely a zone of tsunami propagation in the open ocean and a following zone of hazard mitigation in the near coastlines. During propagation over great distances, tsunami energy may only be lost with limited amount [3] but field and numerical work of [4] confirmed a dependence of the energy upon water depth along its pathways. Analysis of tsunami waveforms has also indicated a decrease in tsunami amplitude with epicentral distance [5, 6], providing further supports for temporal and spatial variations of tsunami energy.

Much attention has since then been given to the problem of tsunami energy decay. One of crucial questions is that whether mechanisms responsible for the energy decay hence amplitude attenuation are independent of the event. For this reason, two trans-oceanic tsunamis, that is, the 2011 Tohoku and 2014 Iquique, Chili, were chosen to consider in the present work. These tsunamis were generated by
the source from separate regions in the same Pacific Ocean basin with corresponding wave energies were mostly confined to the Pacific. Hence, we could expect that a large part of tsunami energy decays when the wave propagates over great distances across the Pacific, enabling us to analyze the decay process in the same ocean basin. In addition to the limited tsunami energy spread, field records were obtained from a number of Deep-ocean Assessment Reports of Tsunamis (DART) stations positioned throughout the Pacific. Instead of tide gauges or other coastal instruments, these DART buoys provide reliable tsunami data that are not largely influenced by local effects of bathymetric and topographic distortions. Thus, the main aim of this study is to examine the nature of tsunami energy decay problem in terms of direct observations of tsunami maximum amplitude attenuation with increasing epicentral distance for the 2011 Tohoku, Japan and 2014 Iquique, Chili tsunamis. We focus upon mechanisms responsible for the energy decay and examine whether there is a trend in the amplitude attenuation with distance for the trans-Pacific tsunamis.

2. Experimental Methods
Two major trans-oceanic tsunamis, namely the 2011 Tohoku and 2014 Iquique, Chili were considered here as case studies to be reported. The Tohoku event was generated by a large earthquake of $M_w$ 9.0, with its hypocenter was at 30 km deep below the seafloor, off the northeastern-coast of Honshu, Japan and the epicenter was predicted at 38.3° N and 142.4° E. The catastrophe occurred on March 11, 2011 with earthquake origin time (OT) was widely reported at 05:46:24 Universal Time Coordinate (UTC). The Iquique event was induced by a large earthquake of $M_w$ 8.2, hypocentered at a depth of 25 km below the seafloor, off the Chilean northwestern-coast of Iquique and the epicenter was measured at 19.6° S and 70.8° W. This destructive tsunami occurred on April 1, 2014, where the OT was found at 23:46:46 UTC.

2.1. Data collection
We used field data records of sea surface elevation recorded on DARTs distributed across the Pacific and officially managed by National Oceanic and Atmospheric Administration (NOAA). All of the data used were freely accessed from NOAA Center for Tsunami Research at https://nctr.pmel.noaa.gov and for direct comparison we also used those available at http://www.ngdc.noaa officialy operated by National Geophysical Data Center (NGDC) as part NOAA. The DARTs considered for each event were those positioned nearby the source from about hundreds kilometer to about 3,000 km away from the epicenter in near-field regions to regions of distant observation of more than 17,000 km away from the epicenter.

2.2. Data analysis
The data of tsunami maximum amplitude attenuation with respect to corresponding epicentral distance for each event were extracted from the observed waveforms. The maximum amplitude was associated with tsunami wavefront that transported the highest wave energy into places where the DARTs exist. We assumed effects of bathymetry and topography on the maximum amplitude were relatively small, making tsunami data reliable for examination. Therefore, analysis of this quantity over time and space during propagation provides insight into tsunami energy decay hence tsunami amplitude attenuation with travel distance.

3. Results and discussions
The results for the two trans-oceanic tsunamis studied here are given in two tables for separate tsunami events and the resulting plots follow. Table 1 provides a total of 20 DART buoys with different codes, located at various positions across the Pacific for monitoring the Tohoku event. Each position of these DARTs is completed with its epicentral distance away from the source and the observed maximum amplitude measured from the undisturbed water level of sea surface. Notice that particular DARTs operated as near-field observatories for the Tohoku are considered to be far-field ones for the Iquique.
The opposite situation comes true in the sense that some DARTs are near-field stations for the Tohoku but are far-field stations for the Iquique.

Table 1. Data of tsunami amplitude variation with distance for the 2011 Tohoku event.

| DART code | Latitude position | Longitude position | Epicentral distance (km) | Observed amplitude (m) |
|-----------|-------------------|--------------------|--------------------------|------------------------|
| 21418     | 38.69° N          | 148.77° E          | 552                      | 1.639                  |
| 21401     | 42.62° N          | 152.58° E          | 987                      | 0.511                  |
| 21413     | 30.52° N          | 152.12° E          | 1,246                    | 0.763                  |
| 21415     | 50.18° N          | 171.85° E          | 2,670                    | 0.253                  |
| 52402     | 11.88° N          | 154.12° E          | 3,165                    | 0.222                  |
| 46408     | 49.63° N          | -169.87° E         | 3,952                    | 0.158                  |
| 46403     | 52.65° N          | -156.94° E         | 4,837                    | 0.117                  |
| 46409     | 55.30° N          | -148.52° E         | 5,344                    | 0.200                  |
| 52406     | -5.29° N          | 165.00° E          | 5,388                    | 0.192                  |
| 51425     | -9.51° N          | -176.24° E         | 6,839                    | 0.100                  |
| 51407     | 19.59° N          | -156.59° E         | 7,023                    | 0.175                  |
| 46411     | 39.35° N          | -127.02° E         | 7,486                    | 0.168                  |
| 46412     | 32.46° N          | -120.57° E         | 8,398                    | 0.067                  |
| 43412     | 16.07° N          | -107.00° E         | 10,619                   | 0.122                  |
| 51406     | -8.48° N          | -125.03° E         | 11,241                   | 0.149                  |
| 43413     | 11.07° N          | -99.85° E          | 11,563                   | 0.131                  |
| 32411     | 5.01° N           | -90.84° E          | 12,741                   | 0.111                  |
| 32413     | -7.40° N          | -93.50° E          | 13,479                   | 0.106                  |
| 32412     | -17.98° N         | -86.34° E          | 14,816                   | 0.100                  |
| 32401     | -20.47° N         | -73.43° E          | 17,028                   | 0.072                  |

Similar to the previous event, table 2 provides a lesser number of DARTs (also in different codes) covering ocean-wide positions of the DARTs across the Pacific for the 2014 Iquique, Chilean tsunami. Each geographical location of the DARTs is also completed with the associated epicentral distance and the observed tsunami maximum amplitude.
Table 2. Data of tsunami amplitude variation with distance for the 2014 Iquique event.

| DART code | Latitude position | Longitude position | Epicentral distance (km) | Observed amplitude (m) |
|-----------|--------------------|--------------------|--------------------------|------------------------|
| 32401     | -20.47° N          | -73.43° E          | 288                      | 0.215                  |
| 32402     | -26.74° N          | -73.98° E          | 853                      | 0.044                  |
| 32412     | -17.98° N          | -86.34° E          | 1,644                    | 0.051                  |
| 32413     | -7.40° N           | -93.50° E          | 2,800                    | 0.030                  |
| 32411     | 5.01° N            | -90.84° E          | 3,510                    | 0.010                  |
| 43412     | 16.07° N           | -107.00° E         | 5,606                    | 0.013                  |
| 46412     | 32.46° N           | -120.57° E         | 7,847                    | 0.013                  |
| 46411     | 39.35° N           | -127.02° E         | 8,779                    | 0.012                  |
| 51426     | -23.30° N          | -168.29° E         | 9,880                    | 0.019                  |
| 51407     | 19.59° N           | -156.59° E         | 10,331                   | 0.019                  |
| 46409     | 55.30° N           | -148.52° E         | 11,048                   | 0.010                  |
| 46402     | 51.07° N           | -164.02° E         | 11,916                   | 0.009                  |
| 21414     | 48.95° N           | 178.26° E          | 13,160                   | 0.010                  |
| 52406     | -5.29° N           | 165.00° E          | 13,317                   | 0.014                  |
| 21419     | 38.69° N           | 148.77° E          | 14,932                   | 0.009                  |
| 52402     | 11.87° N           | 154.04° E          | 15,156                   | 0.005                  |
| 21418     | 38.69° N           | 148.77° E          | 15,679                   | 0.006                  |
| 52405     | 12.99° N           | 132.18° E          | 17,459                   | 0.005                  |

From the data listed in table 1 for the 2011 Tohoku event and table 2 for the 2014 Iquique event, we then plot tsunami maximum amplitude against epicentral distance for each event in figure 1.

Figure 1. Plots of the observed maximum amplitude (in meter) as a function of epicentral distance (in kilometer) for the 2011 Tohoku event (left panel) and the 2014 Iquique event (right panel).

The data points for both plots in figure 1 clearly indicate at least two possible mechanisms associated with tsunami energy decay and its corresponding amplitude attenuation in the open ocean. These mechanisms are here speculated to be responsible for energy release in the zone of propagation. The first mechanism by which energy conversion from available gravitational potential energy into kinetic energy in the initial stage of tsunami generation takes place may extent to a maximum period of 4 hours calculated from tsunami origin time for each event. This time period is directly estimated from
both plots, where the initial stages of energy decay hence maximum amplitude attenuation are characterized by a rapid drop in the amplitudes from initial values of the amplitudes to the values that correspond to a travel distance of about 3200 km away from the source (equivalent to a travel time of 4 hours with the speed on the order of 800 km/h) for each devastating catastrophe. In the initial stage, the energy release is arguably sourced on mechanical energy available for tsunami wave generation, dominated by the gravitational collapse of the initial potential energy after which it is converted into kinetic energy of the wave during an initial phase of tsunami propagation in the near field. This feature is supported by [7], prompting that there is a significant, rapid decrease in the total energy just within a couple of hours in the initial stage.

Following the first mechanism, the second stage of tsunami passage in the open ocean was started from the time when the wave reached a quasi-steady state at the upper end of the near field about 3,200 km to more than 17,000 km away from the epicenter, equal to a total time of about 20 hours traveling across the Pacific. This wider range of observation is categorized into intermediate zone [8] to distant observations [6, 9, 10]. In this stage, the energy decay rate hence the amplitude attenuation varies slowly with time and distance, showing that the wave advances with relatively constant energy. It follows that the second mechanism is mainly characterized by energy conservation, where potential and kinetic energies change to one another during wave energy propagation in the distant observation, as again supported by [7]. Another interesting feature in figure 1 is a similarity of the plots that reflects the same decay time for both catastrophes. A decay time is defined here as the time taken by a tsunami wave to travel from the source to a particular location across the Pacific, where the amplitude is measured about 5% or less compared to the initial value in the amplitude measurements. With this definition, we could argue that the decay time for the 2011 Tohoku case is roughly calculated from the data in the first and last rows in table 1, given by DART 21418 in the near field at 552 km and DART 32401 in the far field at 17,028 km away from the epicenter. From these DARTs, we can conclude that the wave has traveled more than 17,000 km with the amplitude is reduced to 5% or less, compared to the initial value before the attenuation begins. Therefore, the decay time for this event is estimated to be 21.5 hours, based on the long wave speed on the order of 800 km/h. Although the decay time for the Tohoku estimated here is about 3 hours shorter than that averaged from the data reported by [1] for the same event, we argue that the difference in the values of decay time is justifiable due to differences in decay time definition.

Applying the same definition of the decay time as in the previous case to the 2014 Iquique event but using different DARTs, that is, DART 32401 located at 288 km in the near field and DART 52405 positioned at 17,459 km in the far field, we estimate the decay time for this event to be 22.0 hours, slightly longer than that of the Tohoku case. However, the decay times for the two trans-Pacific events considered in this study are comparable to 24.7 hours for the 2010 Maule, Chili event discussed in [1] and 24.6 hours for the 2011 Tohoku tsunami previously reported by [1, 7, 11]. The remarkable point to note here is that the decay time for the Tohoku is slightly shorter than that for the Iquique event, indicating that the former is more dispersive than the latter. This is consistent with the work of [1] based on the tsunami frequency content analysis, but this argument is outside the scope of this study.

The similarity of the 2011 Tohoku and 2014 Iquique tsunamis in the amplitude attenuation curve leads to approximately the same decay time for both events. This results in a simple conclusion that the way in which the energy of trans-Pacific tsunamis decays hence the corresponding amplitude attenuates is independent of the event, as long as the separate sources are centered at positions across the Pacific.

In the context of minimizing hazard risks, tsunami alerts are important not only for people living at near-field regions from the source but also for safety issues at remote areas in tens kilometer away from the source. These alerts include accurate prediction of tsunami heights or run-ups in the zone of mitigation that requires improved understanding of the behaviors of tsunami wave energy decay and tsunami wave amplitude attenuation during tsunami propagation in the open ocean.
4. Conclusions
The nature of tsunami energy decay has been examined in terms of tsunami amplitude attenuation with increasing tsunami travel distance in the open ocean. The data of the observed maximum amplitudes with respect to the epicentral distance s for the 2011 Tohoku, Japan and the 2014 Iquique, Chili cases were extracted from field records by a number of DART surface buoys, across the Pacific-wide basin. The results for the two trans-Pacific tsunamis examined in this study demonstrate a rapid decrease in the maximum amplitude during propagation from the zero point to a travel distance of about 3,200 km away from the source in the near field and a slowly varying amplitude with distance in the far field before advancing to places across the Pacific, equivalent to a travel distance of more than 17,000 km away from the source with relatively constant energy. Two basic mechanisms likely to be responsible for the energy decay hence maximum amplitude attenuation are mechanical energy conversion from the available potential energy to the kinetic energy and vice versa and total energy conservation, where conversion between potential and kinetic energies is minimal.

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6. References

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