Could satellite altimetry have improved early detection and warning of the 2011 Tohoku tsunami?

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[1] The 2011 Tohoku tsunami devastated Japan and affected coastal populations all around the Pacific Ocean. Accurate early warning of an impending tsunami requires the detection of the tsunami in the open ocean. While the lead-time was not sufficient for use in warning coastal populations in Japan, satellite altimetry observations of the tsunami could have been used to improve predictions and warnings for other affected areas. By comparing to both model results and historical satellite altimeter data, we use near-real-time satellite altimeter measurements to demonstrate the potential for detecting the 2011 Tohoku tsunami within a few hours of the tsunami being generated. We show how satellite altimeter data could be used to both directly detect tsunamis in the open ocean and also improve predictions made by models. **Citation:** Hamlington, B. D., R. R. Leben, O. A. Godin, E. Gica, V. V. Titov, B. J. Haines, and S. D. Desai (2012), Could satellite altimetry have improved early detection and warning of the 2011 Tohoku tsunami?, *Geophys. Res. Lett.*, *39*, L15605, doi:10.1029/2012GL052386.

1. Introduction

[2] Early warning of an impending tsunami threat is heavily dependent on the detection of the tsunami in the open ocean away from the shore [e.g., *Bernard et al.*, 2006]. The wave amplitude, however, in the open ocean is small (generally much less than one meter), making it difficult to distinguish the tsunami signal from other ocean variability until the tsunami approaches the shore and grows rapidly in amplitude. Detection must occur with enough lead-time to allow coastal populations to move to safety. Furthermore, detection and warnings must be accurate, since if coastal populations go to great lengths to move to safe areas only to find out later such an evacuation was unnecessary, they may be less likely to heed warnings in the future. In recent tsunami events, models have been used to provide an early assessment of an impending tsunami threat. Without actual observations of the open ocean, however, it is difficult to immediately determine the presence of a tsunami in the ocean. Any open ocean observations of the tsunami could be used to adjust and hone model predictions and improve the representation of the earthquake source in order to provide more accurate and reliable warnings to coastal inhabitants [e.g., *Geist et al.*, 2007; *Yamazaki et al.*, 2011]. Furthermore, such open ocean observations could potentially be used directly to warn coastal populations.

[3] In recent years, tsunami detection has been demonstrated in the open ocean using measurements from satellite altimeters. *Okal et al.* [1999] first used satellite altimeter measurements to identify the 1992 Nicaraguan and 1995 Chilean tsunami from changes in sea surface height (SSH). However, it was not until the Sumatra-Andaman earthquake in 2004 that a tsunami signal was unambiguously detected in the open ocean using satellite altimeters. SSH measurements were used by a number of authors to study the properties of the Sumatra-Andaman tsunami (see auxiliary material).[1] More recently, the comparatively weaker 2010 Chilean tsunami has been positively detected in SSH measurements [*Hamlington et al.*, 2011]. Studies have also shown that the tsunami signal can be detected in the open ocean from satellite altimeter measurements of sea surface roughness [*Godin et al.*, 2009; *Hamlington et al.*, 2011].

[4] While the previous studies mentioned above have demonstrated the ability to retroactively detect a tsunami in satellite altimetry data, there has been little discussion regarding whether such measurements could be used to assist in the near real time (NRT) detection and assessment of tsunamis in the open ocean. In this paper, we examine the devastating 2011 Tohoku tsunami, which caused over 19,000 casualties in northeastern Japan and affected more than 57 cities [*Ando et al.*, 2011], and discuss the extent to which satellite altimetry data could have been used to improve the far-field estimates and warnings provided to coastal inhabitants potentially affected by the impending tsunami. It should be emphasized that satellite altimeters could not have helped for the warning of near-field coastal populations of Japan, since the time between the earthquake and arrival of the tsunami was measured in minutes rather than hours. The quickest and perhaps best warning for coastal populations in such close proximity to the location where the tsunami is

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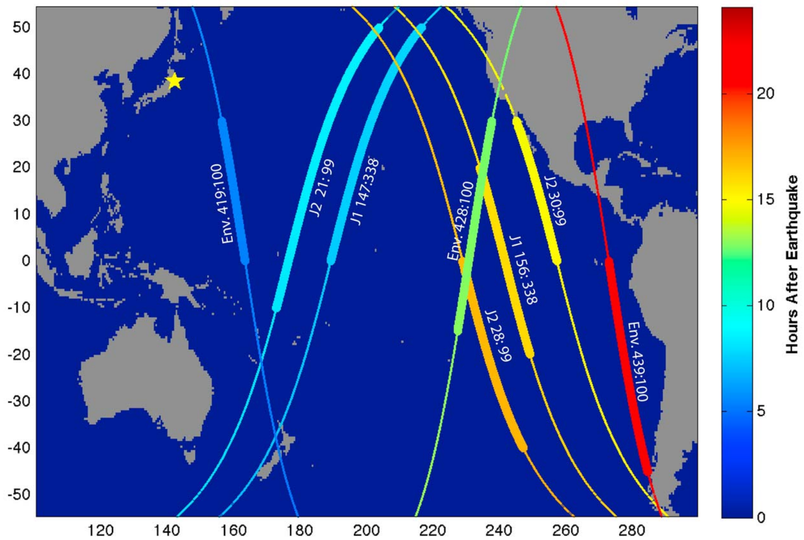

Figure 1. Satellite altimeter passes of Jason-1, Jason-2 and Envisat that overflew the tsunami wave field on March 11th, 2011. The colorbar indicates the time in hours after the earthquake that each pass took place. The bolded portion of each pass indicates the segment approximately coincident with the tsunami wave field.

generated is the earthquake itself. The improvement of estimates and warnings for more distant regions, however, is still important given the destruction caused in the far-field by recent tsunami events.

2. Data and Methods

2.1. Satellite Altimetry Data

[5] The Tohoku tsunami was generated by a Mw 9.0 earthquake at 5:46 UTC on March 11th, 2011 approximately 130 km east of Sendai, Honshu, Japan. Several studies characterizing the rupture process have already been produced [e.g., *Yamazaki et al.*, 2011]. Multiple satellite altimeters overflew the Pacific basin-wide tsunami after the tsunamigenic earthquake, but most of these passes did not occur until several hours after the generation of the tsunami. Envisat was the first to sample the tsunami on ascending pass 419 of cycle 100 approximately 5.5 hours after the earthquake (Figure 1). Envisat sampled the tsunami again during cycle 100 on passes 428 and 439, approximately 13 and 22 hours, respectively, after the generation of the tsunami. Jason-1 first sampled the wave field on ascending pass 147 of cycle 338 (Figure 1) approximately 7.5 hours after the earthquake, and then again on pass 156 roughly 16 hours after the earthquake. Finally, Jason-2 sampled the tsunami wave field on ascending pass 21, and again on passes 28 and 30 of cycle 99, approximately 8.5, 15, and 17 hours after the generation of the tsunami. In the interest of brevity and since these passes occurred closest to the time of the earthquake, we focus on Envisat pass 419 of cycle 100 and Jason-1 pass 147 of cycle 338, with analysis of Jason-2 pass 21 of cycle 99 included in the auxiliary material.

[6] Jason-1 and Jason-2 NRT SSH anomaly data was obtained from the Physical Oceanography Distributed Archive Center (PO.DAAC) at the NASA Jet Propulsion Laboratory [*Desai and Haines*, 2010]. For Envisat data and for historical data from Jason-1 cycles prior to cycle 292, SSH and sea surface roughness measurements were obtained from the Radar Altimeter Database System (RADS). While NRT data for Envisat is now provided through PO.DAAC, the data is only available since cycle 105. Jason-1 and Envisat NRT SSH data currently have average latency of roughly 7 hours with Jason-2 having latency closer to 4 hours.

[7] For comparison and to verify the time and location of the tsunami leading edge, we also used the Method of Splitting Tsunami (MOST) model SSH data produced by the NOAA Center for Tsunami Research (NCTR) [*Titov et al.*, 2005]. The two-dimensional SSH data produced by MOST were interpolated at the times and locations of each altimeter ground-track of interest and compared to the satellite altimetry SSH data. Additional details on the MOST model are included in the auxiliary material.

2.2. Statistical Analysis of SSH and Sea Surface Roughness

[8] Satellite altimeters provide the opportunity to study the effect of a tsunami on both SSH and sea surface roughness. To determine the feasibility of detecting the 2011 Tohoku tsunami in NRT from satellite altimeter measurements, we use statistical tests to compare the tsunami-affected data to both model data and historical altimeter measurements when a tsunami is not present.

[9] To extract the tsunami signal from the background ocean variability in the SSH measurements, the filtering technique introduced in *Hamlington et al.* [2011] is implemented. This filtering technique is based on the method developed by *Gower* [2007] consisting of subtracting a smoothed average (9-second boxcar filter) of SSH measured on the same pass of the cycles before and after the tsunami cycle. Since the focus here is on the NRT detection of the tsunami signal, only the cycles before the tsunami cycle are used to remove the variability not related to the tsunami. Once filtered, we can compare the SSH data to the MOST model output in an attempt to confirm the presence of a tsunami and subsequently provide information capable of improving the model result.

[10] Additionally, recent studies have demonstrated the ability to detect a tsunami in the open ocean through changes in the sea surface characterized by the radar backscattering

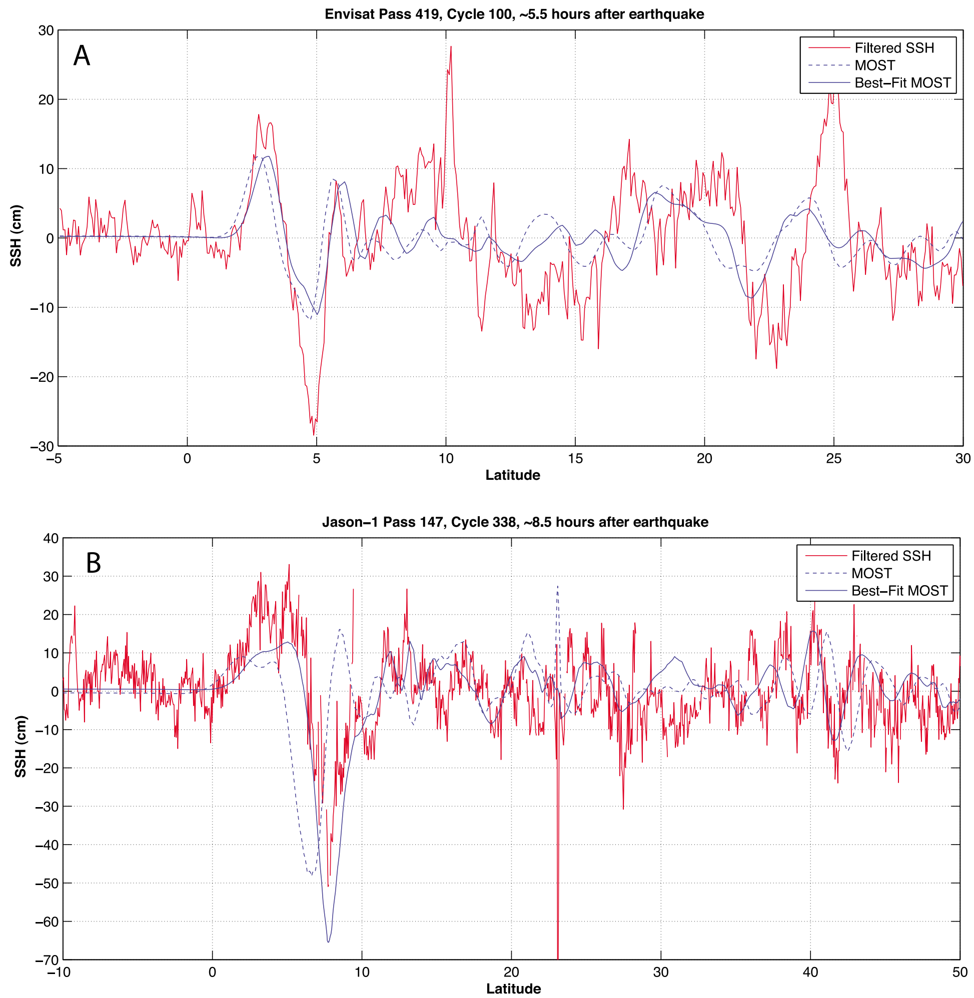

Figure 2. Comparison of filtered SSH data (red) with the MOST (blue dashed) model results for (a) Envisat pass 419 of cycle 100, and (b) Jason-1 pass 147 of cycle 338. The best fit of the MOST model (blue solid) to the observations is also shown.

strength at nadir, σ_0 [*Godin et al.*, 2009; *Hamlington et al.*, 2011]. To determine if σ_0 variations were induced by the 2011 Tohoku tsunami, we perform statistical randomization tests to compare data with and without the tsunami present. Further details of these randomization tests are included in *Hamlington et al.* [2011] and section 3 of the auxiliary material.

3. Results

[11] The SSH data from Envisat pass 419 of cycle 100 is filtered by removing the smoothed SSH data from pass 419 of the previous cycles, as described in section 2. By sampling the results produced by the MOST model along this pass, we can compare the filtered SSH data to the model output. Figure 2a shows the filtered SSH data with the MOST model results overlaid. Envisat enters the tsunami wave field near the equator with the leading edge contained in a window between 3°N and 7°N. The comparison with the MOST model shows an apparent time discrepancy between the observations and model results. To test for the presence of a time lag between the satellite altimetry observations and MOST model estimates, the time of the MOST model is adjusted in increments of one minute and the correlation between the filtered satellite altimetry SSH measurements and the lagged MOST model estimates is computed. The best fit of the MOST model to the Envisat observations occurs with a small lag of 3 minutes (Figure 2a). Here, lag time is given as the number of minutes that the arrival estimate provided by the MOST model was early relative to reality.. Jason-1 first sampled the leading edge of the tsunami near the equator on pass 147 over seven hours after the earthquake. As seen in Figure 2b, the amplitude was approximately 40–50 cm in the filtered satellite altimetry SSH and a comparatively large amplitude of 30–40 cm was seen in the MOST model data. The best fit between the model and observations was found with a lag of 5 minutes. In addition to yielding a higher correlation, the amplitude of the tsunami computed using the MOST model more closely matches the observed amplitude with a lag of 5 minutes. Jason-2 pass 21 of cycle 99 provided an arrival time that was two minutes later than predicted by the model (Figure S2a), although the amplitude of the leading edge near 10°S was found to be only 10 cm.

[12] Using the historical data from Envisat and Jason-1, it is possible to determine if the correlation and amplitude

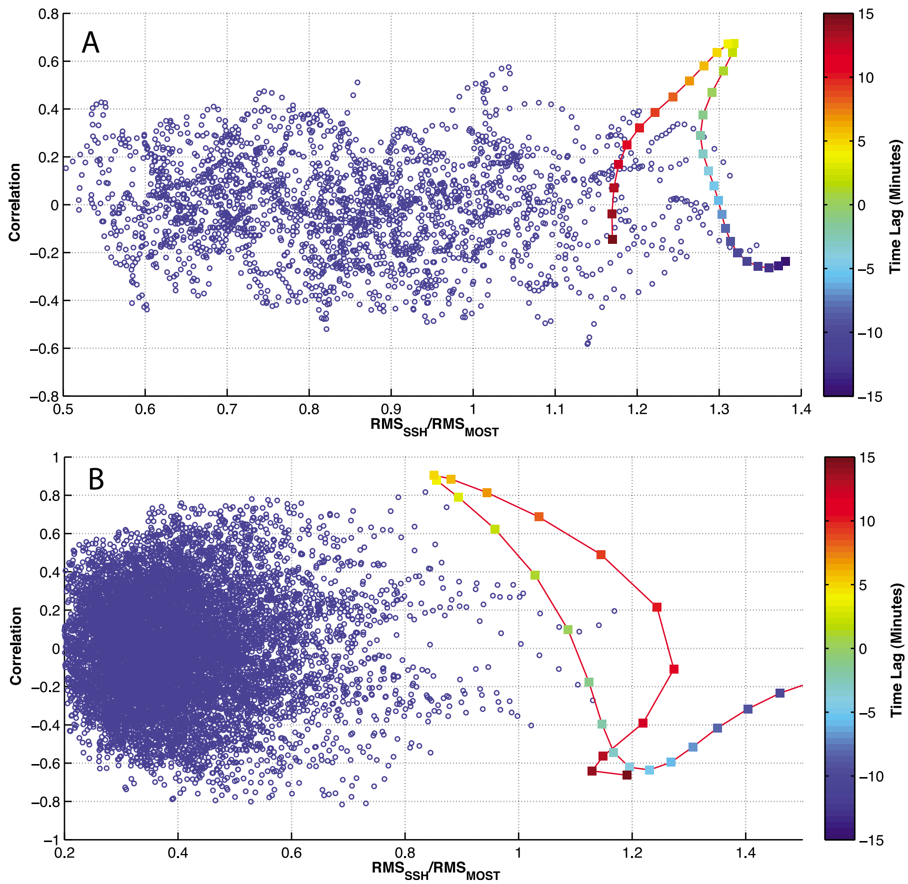

Figure 3. Correlation of the Tohoku tsunami model predictions and satellite altimeter observations. Correlation between MOST model and filtered SSH data and ratio of RMS values of SSH data and MOST model are shown for observations during the Tohoku tsunami (squares) and historical observations (circles). Each point represents a time lagged MOST model of +/−15 minutes and a cycle of (a) Envisat pass 419, and (b) Jason-1 pass 147. This leads to 31 points for each cycle of Envisat and Jason-1. Color of the squares indicates the time lag of the MOST model. In the ideal case of noise-free observations and a perfect tsunami model, correlation equal to unity with RMS ratio of one would be found at zero time lag.

agreement between the observations and model data for a given pass are exceptional. Pass 419 from every Envisat cycle in the past is collected using RADS, and the correlation between the MOST model and filtered SSH data is computed. Additionally, the RMS value of the filtered SSH data is computed and compared to the RMS value of the MOST model data. These computations are done for the MOST model with time lags of +/−15 minutes, leading to 31 data points for each cycle. Figure 3a shows the results for Envisat pass 419 using the data in the window between the equator and 15°N, relating the correlation with the MOST model to the ratio of the RMS values from the model and observations. The square points show the results for cycle 100 (containing the Tohoku tsunami) with the color indicating the lag time. For perfect agreement between model and observation, there would be a point with a correlation of one, RMS ratio of one and lag time of zero. In this case, the peak correlation is found to be 0.72 with a lag of 3 minutes and an RMS ratio of 1.28. In cycles other than cycle 100, no correlation greater than 0.6 is found. The same test is applied to Jason-1 pass 147, again using the data from pass 147 of every available Jason-1 cycle. The greatest correlation in the window containing the leading edge during the tsunami cycle is found to be 0.89 with a lag of 5 minutes and an RMS ratio of 0.85 (Figure 3b). From the historical Jason-1 data, there is no other data point from a cycle other than cycle 338 with a correlation greater than 0.8 and a RMS ratio closer to one. The importance of improving the arrival time with respect to amplitude estimates of the MOST model is also apparent from these randomization tests. The amplitude found at a lag of zero minutes is almost 30% greater than the amplitude found when using a lag of 3 minutes. Both underestimation and overestimation of the tsunami amplitude by model estimates could have significant negative consequences with regards to issuing a warning. Results for Jason-2 pass 21 of cycle 99 also show that the highest correlation with the MOST model was found during the tsunami pass (Figure S2b).

[13] Detailed Results for the randomization tests on sea surface roughness are included in the auxiliary material section 3 and Figures S1 and S2. Through the randomization tests, it is found that the variations in the sea surface roughness for Envisat pass 419 cycle 100 on the day of the tsunami were not significantly different from the variations present at other times. Applying the same randomization tests to Jason-1, however, shows that there is less than 1% chance that the observed sea surface roughness variations on the day of the tsunami in the region between 5°N and 10°N would occur at any other time. The roughness variations

induced by the tsunami are much more pronounced, leading to the positive identification from the randomization tests on the sea surface roughness measurements.

4. Near Real Time Tsunami Monitoring Using Satellite Altimetry

[14] When compared to Deep-Ocean Assessment and Reporting of Tsunamis (DART) buoy data, which can be obtained and processed within an hour after the tsunami arrival, there is currently greater latency between the sampling of the tsunami by a satellite altimeter and the time at which the data is available for analysis. Recent advances in the processing of Envisat, Jason-1, and Jason-2, however, have opened up the possibility of using satellite altimetry measurements to improve assessments of a propagating tsunami. The latencies described in section 2 could be reduced by an additional 1–2 hours by using slightly less accurate orbit altitude estimates, which does not have a substantial impact on the analyses done here. An even greater reduction in the latencies would be obtained from the use of additional ground terminals for reception of telemetry from the satellites. Jason-2, for example, has only three ground stations, but with the appropriate distribution of additional terminals, current latencies could potentially be reduced by half or more by allowing for more frequent downloads of data from the satellite altimeters. Envisat provided the first measurements of the tsunami approximately 5.5 hours after the earthquake. Assuming a delay of roughly 5 hours, this data could have been available to improve warnings for the coastal populations in Central and South America with several hours of lead-time. A pass of Jason-2 within 5.5 hours of the earthquake could potentially have been used to improve estimates and provide warnings for Hawaii. Furthermore, using a simple randomization test (see auxiliary material, section 5), it is determined that given the satellite altimeters available during the time of the tsunami, a first over-flight of the tsunami 5.5 hours after its generation is larger than should generally be expected. With both Envisat and Jason-1 available during the 2011 tsunami, one would have expected, on average, altimeter sampling of the tsunami within 3.4 hours.

[15] Similar to the system employed by NCTR, one could pre-compute statistics for both the historical SSH and σ_0 variations over segments of each altimeter pass. With the output from the MOST model available in a relatively short time after the generation of a tsunami, the corresponding statistics of a possible observation of a tsunami could be quickly computed and evaluated against both the historical values and MOST model, as demonstrated in section 3. Both agreement and discrepancy between the filtered satellite altimeter measurement and MOST model results would be useful in improving the estimates and predictions obtained from the model, while also confirming the existence of a tsunami in the open ocean. Furthermore, along-track measurements made by satellite altimetry provide a larger, near-synoptic cross-sectional view of the propagating tsunami wave in the open ocean, giving information that can not be obtained from DART buoys, which do, however, have advantages in separating the tsunami signal from background ocean variability. The use of satellite altimetry data with the MOST model has been done for the Sumatra 2004 tsunami as published by *Geist et al.* [2007], and a similar incorporation of the satellite altimeter data could be done in NRT.

5. Conclusion

[16] In addition to demonstrating positive detection of the 2011 Tohoku tsunami in the open ocean, we have extended our analysis to determine how these results and satellite altimetry data in general can be used to aid in the near real time detection of a tsunami in the open ocean and subsequent warning of populations in the far-field. Comparisons between the MOST model and satellite altimeter SSH measurements serve two purposes related to the early warning and detection of tsunamis. First, such tests on the differences between model and observations could lead to better projections from MOST and an improvement in the estimation of source parameters. Currently DART buoy data are used to adjust and improve estimates from the MOST model. DART buoys, while allowing for easier separation of the tsunami signal from the background variability, are located sparsely across the ocean and provide measurements at only a single location. By using the near real time satellite altimetry provided by NASA/JPL PO.DAAC for such a comparison to the MOST model data, the tsunami signal can be definitively detected in the open ocean and the observations can potentially be used to improve MOST model estimates. Secondly, such comparisons could be used to aid in near real time to determine the presence of the tsunami signal in the satellite altimetry data.

[17] In recent literature, the statement has frequently been made that there is only a small chance of observing a tsunami with the along-track measurement system of satellite altimetry. The study of recent tsunamis, however, shows that for large, basin-wide events, there is a high probability that satellite altimeters will sample the tsunami at least once within a few hours of its generation. The latency of the satellite altimetry data has improved considerably in recent years, with some data being available less than two hours after the altimeter makes the measurement. Furthermore, this latency could be reduced even further with the addition of new ground terminals and an adjustment in the precise orbit determination computation. This opens up the possibility of using the satellite altimeter measurements directly to detect the tsunami in near real time. Considering the excellent sampling of the 2004 Sumatra-Andaman tsunami, 2010 Chilean tsunami and 2011 Tohoku tsunami, satellite altimetry should now be regarded not just as a source of data to retroactively study the characteristics of a tsunami and improve future model estimates, but also as a system for the near real time detection of tsunamis in the open ocean and source of measurements upon which far-field warnings could be issued. The methods for objective and quantifiable detection presented here will pave the way for such a system and represent an improvement over the detection techniques used in previous studies. Furthermore, while providing detection of the tsunami directly through SSH and sea surface roughness measurements, satellite altimetry measurements will complement models like MOST by providing additional observations for adjusting and tuning tsunami simulations.

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