EFFECTS OF TIDE AND WAVE DIRECTIONALITY ON LOCALIZED TSUNAMI-INDUCED CURRENTS IN PORT AND HARBORS

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Here, we present the results of a numerical modeling study to investigate how the maxima of the tsunami-induced currents vary due to dynamic effects of tides and wave directivity. A sensitivity analyses was conducted in three harbors by coupling the tsunami with the tide signal at twelve different tide levels. We find that tsunami-tide interaction can change the maximum current speed experienced in a harbor by up to 25% for the events and harbors studied, and that this effect is highly site-specific. To evaluate the effect of wave directionality on maximum currents, three earthquakes with different magnitudes were devised along the Pacific, which were also tuned to create the same maximum near-harbor amplitude. Our analysis also shows that, for the harbor and sources examined, the effect of offshore directionality and tsunami frequency content has a very weak effect on the maximum currents experienced in the harbor. The much more important dependency on maximum currents is on the near-harbor amplitude of the wave, indicating that currents in a harbor from a tsunami generated by a large far-field earthquake may be reasonably well predicted with only information about the predicted local tsunami amplitude. This study was motivated by the hope of constructing a basis for understanding the dynamic effects of tides and wave directivity on current-based tsunami hazards in a coastal zone by the application of numerical simulation tools for hazard mapping purposes. The consideration of these aspects is crucial and yet challenging in the modeling of tsunami currents.

Keywords: tsunami currents, tides, wave directivity, numerical modeling

INTRODUCTION

Until recently, the focus of tsunami hazard studies has mostly been overland flooding, inundation, and/or damage to coastal infrastructure due to the waves. However, the latest transoceanic tsunamis have shown that even when there is no or little inundation, the currents generated by tsunami surges can potentially cause significant damage to maritime facilities (Lynett et al., 2014). Over the past few years, the adverse nearshore effects of tsunami-induced currents from far-field sources have been reported from many locations around the world, as well as maritime communities along the U.S. West Coast (Dengler et al., 2008, Wilson et al., 2012, 2013). The largest of the recent tsunamis was the 2011 Tohoku tsunami. It caused adverse effects on every maritime facility along the U.S. West Coast, ranging from interruptions of harbor operations to the complete destruction of port infrastructure. The strongest effects and most severe damage occurred in the Crescent City and Santa Cruz Harbors (Wilson et al., 2012, 2013). Tsunami surges created very strong currents in Crescent City's inner harbor, which caused extreme damage or completely destroyed the docks and boats moored at the time of the tsunami.

There are several factors that can influence the variability of the maximum tsunami-induced currents in harbors, including the tsunami's source, distance to the target area, and nearshore features. In addition, other key considerations for obtaining a detailed and accurate description of the maximum tsunami currents are the tide levels and their interaction with the tsunami. Only a few studies have investigated tide–tsunami interactions, with a focus on understanding their influence on the maximum wave heights, runup, and inundation limits. This has mainly been because, until recently, the context of tsunami hazards has been limited to overland flooding and inundation. However, recent studies of Lee et al. (2015), where they mainly focus on effects of dynamic tides on tsunami propagation, and Shelby et al. (2016), in which they study tide-tsunami interaction in Hudson River Estuary, also briefly investigate the effects of tide-tsunami interaction on flow velocities, but only for limited number of tide phases. Nonetheless, their results clearly reveal that large differences can be observed in maximum current speeds due to nonlinear interaction between tsunamis and tides.

In this study, we seek to place another missing piece of this puzzle, and explore how the dynamic effects of tides influence the tsunami-induced currents inside harbors and bays. It is anticipated that the tidal influence on the maximum currents in a harbor or port during a tsunami could be significant when the tidal elevation and currents are similar in magnitude to those of the tsunami, and the interaction between the tides and tsunami-induced currents can be non-linear. Therefore, an adequate demonstration of the physics of this problem has paramount importance.

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The next aim of this paper is to examine the influence of the source location of the tsunami. Here, we attempt to determine whether the source location of the tsunami plays a major role in the predicted maximum currents inside a harbor for a specific predicted local wave height, i.e. if two different sources produce the same local wave height, do they also produce similar currents? The motivation for testing this hypothesis is the expectation that decisions about advisories or warnings from a distant source are based primarily on the local height predictions from National Oceanic and Atmospheric Administration (NOAA), which already take into account the open ocean propagation. This is important in issuing advisories/warnings for harbors regarding maximum expected currents, in order to take necessary mitigation measures and to continue harbor operations if possible, especially when the direct relation between the current speeds and the observed damage is considered (Lynett et al., 2014). Here, we present a foundation for understanding the dynamic effects of tides and wave directivity on current-based tsunami hazards in a coastal zone by the application of numerical simulation tools for hazard mapping purposes.

METHODOLOGY

In this section, we will provide information about the numerical model that we used and the methodology followed in this study.

Tsunami Hydrodynamic Model

The hydrodynamic modeling results presented here come from the application of the "method of splitting tsunami" (MOST) numerical model (Titov and Synolakis, 1995 and 1998). The MOST model has been used extensively for tsunami hazard assessments in the United States and is currently used for operational tsunami forecasting at the NOAA Pacific Marine Environmental Laboratory (PMEL). Variants of the MOST model have been in constant use for tsunami hazard assessments in California since the mid-1990s. The MOST solves the classical 2+1 nonlinear shallow water (NSW) equations using a finite difference scheme. More thorough information about the theoretical background and the validation of MOST was provided by Titov and Synolakis (1998). Thus, we will not provide more technical details of the model here because of its extensive previous usage. In this study, MOST was used to propagate tsunami waves from their source to a nearshore region through nested grids. The model propagated the tsunami waves to the shore, computing the wave amplitude, velocity, and overland inundation and captures the non-linearity of the waves as they reach shallow water. Computations were stopped at the 5-m-depth contour in all the parent grids, at which depth waves were reflected back (a solid wall boundary condition was imposed). Runup and inundation computations were only performed in the innermost grid, in which a bottom friction term was included in the momentum equations. For all the simulations presented here, the Mannings "n" friction factor was 0.03.

The outermost grid at the 4-arcmin resolution covered the entire Pacific basin. Three additional grids of increasingly finer resolution were derived from data obtained from NOAA's freely available National Geophysical Data Center (ngdc.noaa.gov/mgg/inundation/tsunami/), specifically for tsunami forecasting and modeling efforts. The innermost nearshore grid with the highest resolution was at the 1/3 arcsec grid, with boundary inputs for free surface elevation and velocities from the previous MOST nested layer.

Tidal Time Series

To investigate the effects of tides on tsunami currents, sensitivity analysis results were compiled from selected study areas: San Diego Bay, Crescent City Harbor, and Pillar Point Harbor located inside Half Moon Bay. These harbors are located in Northern, Central, and Southern California, where the tidal characteristics are modestly different. Also, the physical characteristics of individual harbors or bays can play major roles in amplifying the effects of tides. In this regard, San Diego Bay and Pillar Point Harbor represent different types of basins. San Diego Bay is a large, long, and narrow bay, which contains different oscillatory modes, whereas Pillar Point Harbor is a small rectangular-shaped boat harbor with less complex internal hydrodynamics. Crescent City Harbor on the other hand, was a natural candidate for this study, because the most severe effects of the recent tsunamis were observed there (Dengler et al., 2008, Wilson et al., 2012, 2013). The tide data used for each study area were collected from the NOAA Tides and Currents database, where 1-min (or 6-min, depending on the type of tide station) water level data recorded during the 2011 Tohoku tsunami by local tide stations are available for download.

Figure 1a shows the tidal time series used in this study to force the innermost grids, which were recorded between March 11, 2011 and March 15, 2011, during the Tohoku-Oki Tsunami. The very first step in the analysis part of this work was to reproduce the tide signal numerically using MOST at the location of the tide gauge station. For this purpose, the innermost grid was only forced by tides from the boundaries, and these input files were modified and re-run until the numerically predicted tides matched the data measured at the tide gauge station. Once this was achieved, the tsunami (Figure 1b) and tidal time series (Figure 1a) obtained numerically from the MOST simulations were linearly superimposed. Then, the tsunami signal is shifted in time to see how the tsunami currents would have been affected if the tsunami had arrived at the maximum tide, minimum tide, or any other intermediate tide level. For each study area, tsunamis were superimposed at 12 different tide phases over a tide cycle. This illustrated the influence of the tidal currents on the maximum tsunami currents for various tsunami arrival times.

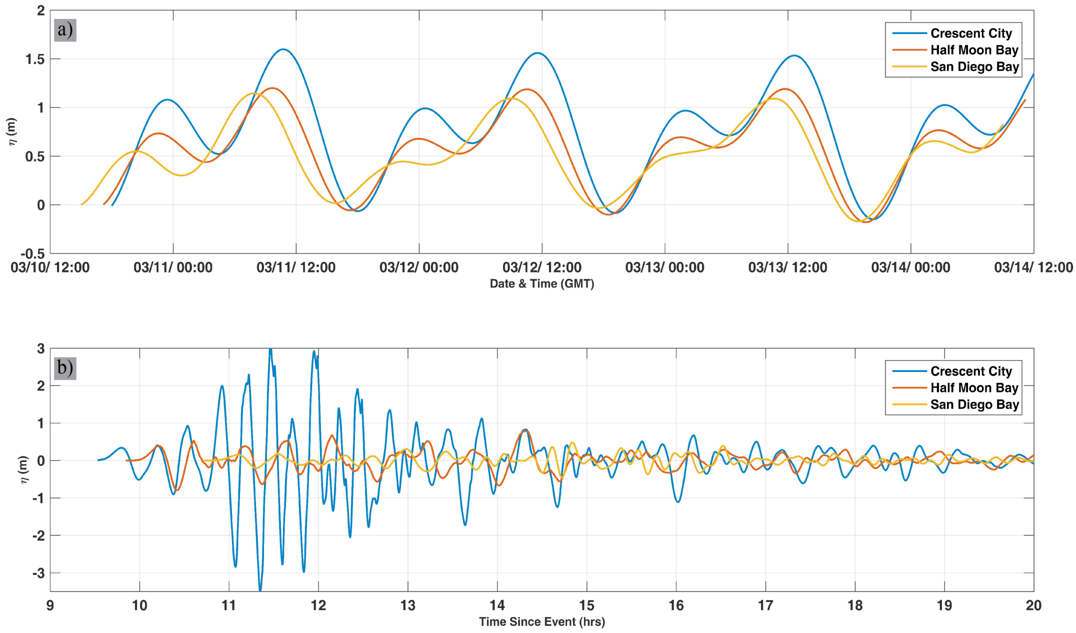

Figure 1. a) Input time series of tides for each location extracted from tide gauge station measurements tides with respect to mean low water (MLW) level. b) Tsunami time series from Tohoku 2011 tsunami, predicted by MOST at each location.

Wave Directivity Analysis

The approach for this analysis was to run hypothetical tsunami scenarios from three different source regions along the Pacific, and tune them in a way to ensure that they would create the same maximum offshore wave amplitude near the selected study area. Then, the resulting maximum current fields could be compared. Furthermore, it is well known that when examining wave-driven free surface flows, small changes (or errors) in the sea surface amplitude can lead to large changes (or errors) in the fluid speed (Lynett et al., 2012, Borrero et al., 2015). Therefore, it was crucial in this study to obtain the same offshore maximum free surface elevation within ±1% precision near the study area for all three sources, so that their resulting maximum current fields can be comparable.

Pillar Point Harbor, located inside Half Moon Bay, was picked as the pilot study area. Pillar Point is a south-facing harbor located along the central coast of California, and is exposed to the effects of tsunamis from all over the Pacific Rim. The harbor, with its south-facing orientation, should represent a difficult location to demonstrate that wave directionality is not an influential parameter. The sources devised for this study were assumed to arise from the Alaskan–Aleutians Subduction Zone, the Chile Subduction Zone, and the Mariana Subduction Zone. It must be noted that these sources are completely hypothetical, or, in other words they have no physical basis. We presumed these sources and tuned them to yield the maximum free surface elevation of 1 m offshore Pillar Point Harbor.

RESULTS AND DISCUSSION

To understand the effects of tides on maximum tsunami-induced currents, Figures 2 and 3 provide useful information in which the model results are presented. When interpreting these results, the following should be kept in mind: the results presented here were de-tided, which means the velocity time series of the tide-only simulations were subtracted from the time series obtained from the tsunami-plus-tide simulations. This provides a time series that includes the tsunami signal and any alteration of this signal from tide-tsunami interaction. In Figure 2, we plot the maximum current speeds at Crescent City, predicted from the 2011 Tohoku tsunami source, superimposed with the tide signals for high, low, and mid-high tides, along with the results for the tsunami-only case. Although it is difficult to quantify the effects of the tides on the maximum currents from Figure 2, the differences in the overall current fields compared to the tsunami-only and various tsunami-plus-tide cases is evident.

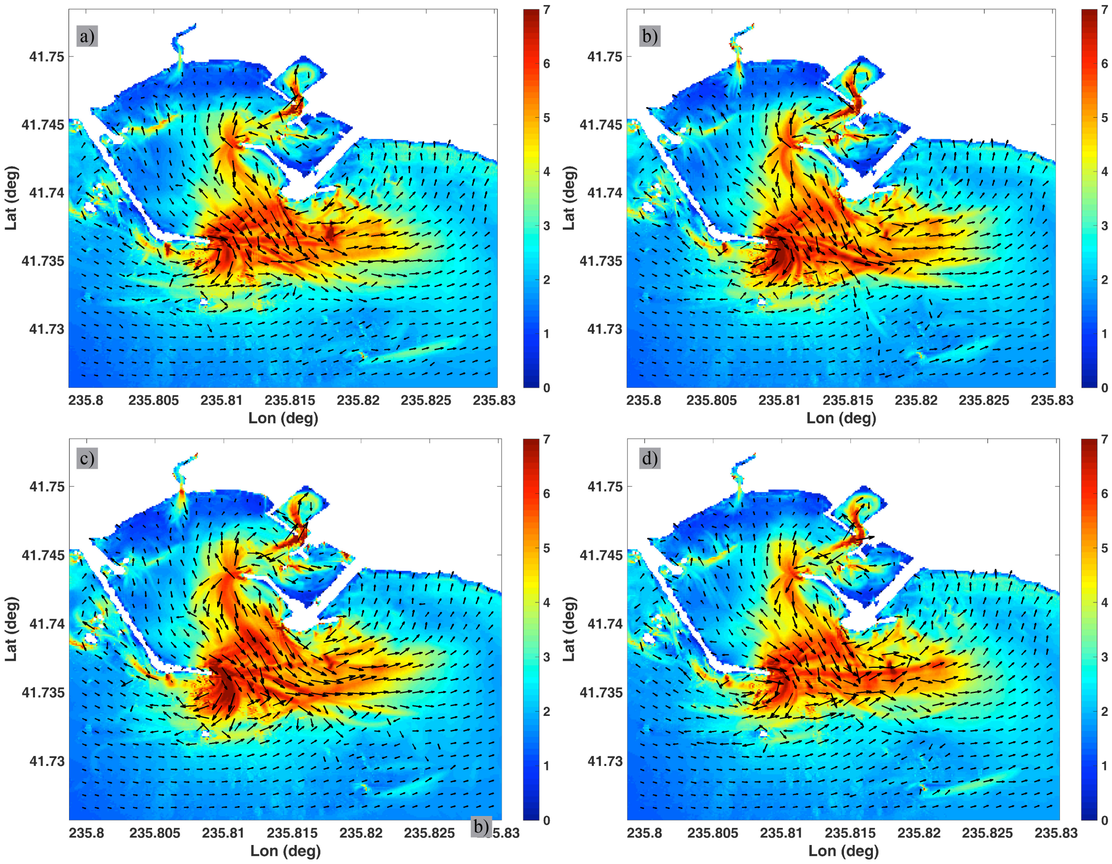

Figure 2. Maximum current speeds predicted by MOST for a) Tsunami only, b) when tsunami arrives at high tide, c) when tsunami arrives at low tide, and d) when tsunami arrives at mid-high tide. The vectors show the direction of the maximum detided currents.

In terms of quantification of the tide effects on maximum currents, we refer to Figure 3, in which the normalized means of the predicted maximum currents at each location are plotted against the corresponding tide level. The mean of the maximum currents is the spatial average of the maximum detided currents calculated at each grid node. Subsequently, they were normalized by the mean maximum currents obtained from tsunami + max tide case. For example, the value corresponding to "Max" in Figure 3 shows the mean of the maximum currents estimated in that particular bay or harbor, if the tsunami would arrive during the high tide. The same logic applies for "Min," "Mid-High," "Mid-Low," or for any other intermediate tide level. This metric makes it possible to estimate the scale of the tidal effects on tsunami currents.

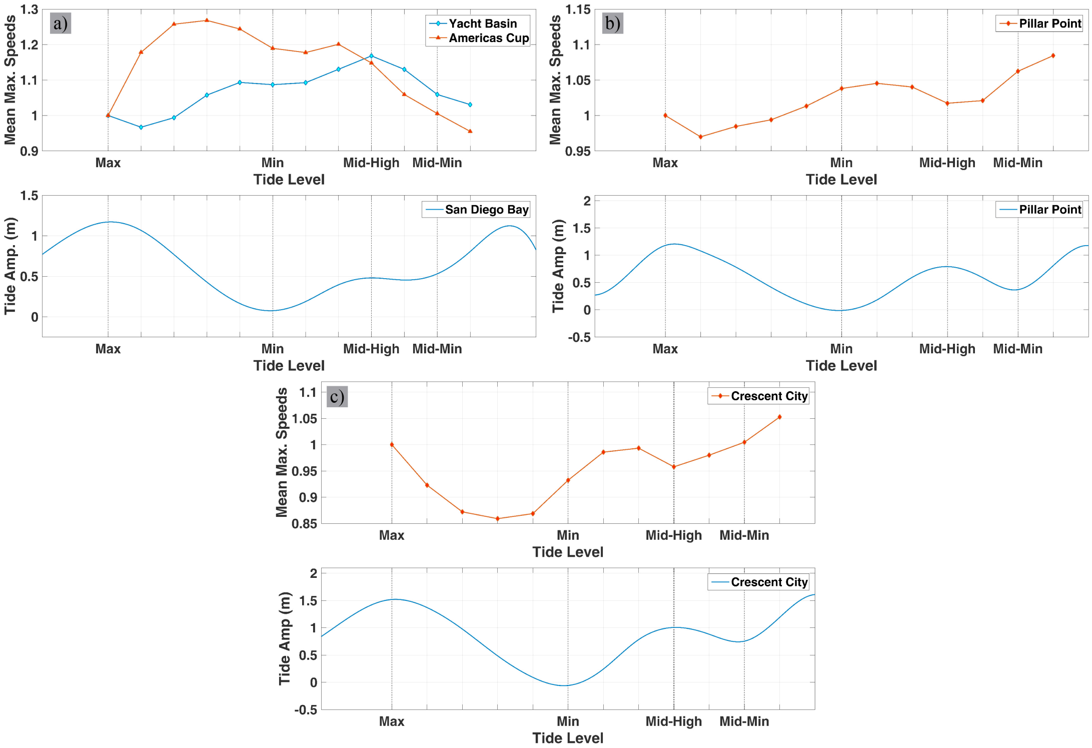

Figure 3. Top plots show the ormalized maximum mean currents plotted against tide level at a) San Diego Bay, b) Half Moon Bay, and c) Crescent City Harbor.

Figure 3a shows a plot of the variation in the mean of the maximum speeds in San Diego Bay. We focused on two harbors: the America's Cup Harbor located in the north, and the Yacht Basin in the south of Shelter Island, in which the strongest currents were witnessed during the 2011 Tohoku tsunami (Wilson et al., 2013). The highest modulation in the mean-maximum currents due to tides was estimated in the America's Cup Harbor, where the difference between the lowest and highest mean-maximum currents was over 25%, with the same metric showing a 15% change in the Yacht Basin. However, these maximum tide-tsunami interaction effects in the two harbors occur at very different tidal phases, indicating that the effect is highly localized, even with two harbors in close proximity within the same bay system. Similarly, Figure 3b, in Pillar Point Harbor, this margin from largest to smallest is around 10%, as shown in, which agrees well with our a priori considerations about the scale of the tidal effects on the currents in Pillar Point. Last but not least, in Crescent City Harbor, the difference between the smallest and largest mean-maximum currents is on the order of 20% (Figure 3c). It could be expected that greater effects from tides would be observed here, as the tidal range is larger; however, the tsunami amplitude is also larger, and these two scales compete against each other. What this comparison does show rather clearly is that for a tsunami with height on the order of the tidal range, the variability of tsunami arrival time with respect to the tidal phase is likely to impact the maximum currents with uncertainty in the range of +/- 25% or less.

The results obtained in Pillar Point Harbor are given in Figures 4 to 5, obtained from the hypothetical tsunami simulations to assess the influence of wave directivity on tsunami-induced currents. The probability distribution of the maximum speeds given in Figure 4a suggests a good agreement between all three cases. The peaks of the curves lie at around 0.7 m/s, and all three distribution shapes are similar and are characterized by slowly decaying tails at the high velocity end. On the other hand, the probability distributions of the free surface elevations display arguably more source-dependent variability, with peaks in the range of 0.6–0.8 m. However, it must be reiterated that the velocity distributions contain statistically significant probability values extending beyond seven times the peak value of 0.7 m/s, while free surface elevation distributions only extend 0.5-1.0 beyond the peak. The velocity distribution for a tsunami event is expected to be much broader, in a scaled sense, than its free surface elevation distribution. This has clear implications for uncertainty quantification in tsunami speed predictions.

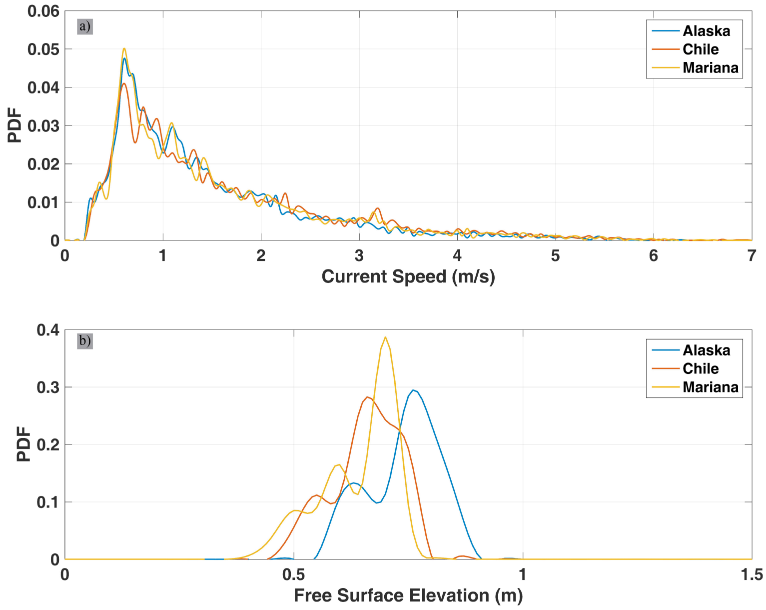

Figure 4. Probability distributions from all three sources of a) maximum current speeds and b) free surface elevations.

The differences in the predicted maximum current speeds for each scenario are examined further in Figure 5. In this figure, the simulated maximum currents from the Alaska and Chile scenarios are plotted against Mariana scenario for every grid point in the computation domain. The figure reveals that the correlation between the maximum current speeds gets higher as the observed speed increases. For both Alaska and Chile scenarios, the more than 98% of the grid points fall within +/- 1 m/s/ of the current speeds observed in Mariana scenario, for all current speeds.

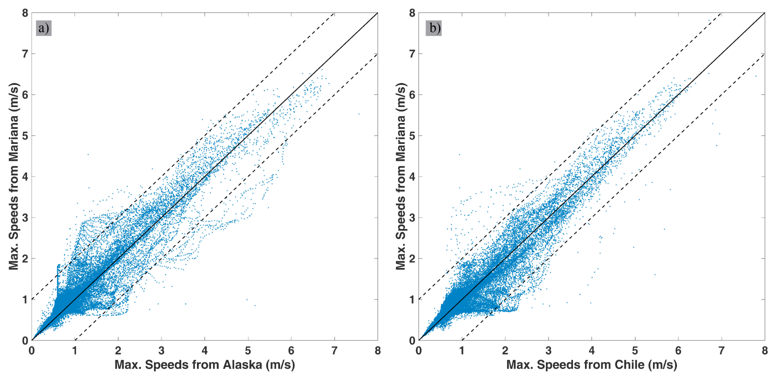

Figure 5. Maximum currents speeds of Mariana scenario versus maximum current speeds from a) Alaska scenario and b) Chile scenario. The solid line indicates the 1:1 relation, and the two dashed lines indicate 1 m/s error bounds.

Figure 6a shows the maximum current speeds from all three hypothetical cases predicted by MOST. The model results suggest that high current speeds driven by eddies formed both within and outside of the Pillar Point harbor near the entrance, as a result of the strong advection. At the entrance to the inner harbor, however, the maxima plot shows relatively slower current speeds. Although the maximum current plots give an idea about the spatial variability of the current patterns, it is not easy to perceive localized scenario-based differences. To refine the local variations in the maximum speeds from different sources, Figure 6b and 6c show the absolute and relative differences in the Alaska and Chile scenarios with respect to the Mariana case. The largest deviations are observed outside of the harbor, which can be attributed to energetic eddies following different paths. Nevertheless, the error patterns inside both harbors show a great similarity. In the vicinity of the entrance of the outer harbor, the relative error is around 20% for both the Alaska and Chile scenarios where the maximum speeds occur, and 10%–15% in the inner harbor. This analysis clearly shows that, for the harbor and sources examined, the effect of offshore directionality and tsunami frequency content has a very weak effect on the maximum currents experienced in the harbor. The much more important dependency on maximum currents is on the near-harbor amplitude of the wave, indicating that currents in a harbor from a tsunami generated by a large far-field earthquake may be reasonably predicted with only information about the predicted tsunami amplitude. Secondary effects, such as the duration of the maximum current and the persistence of currents in the harbor, are likely to have a stronger source dependence.

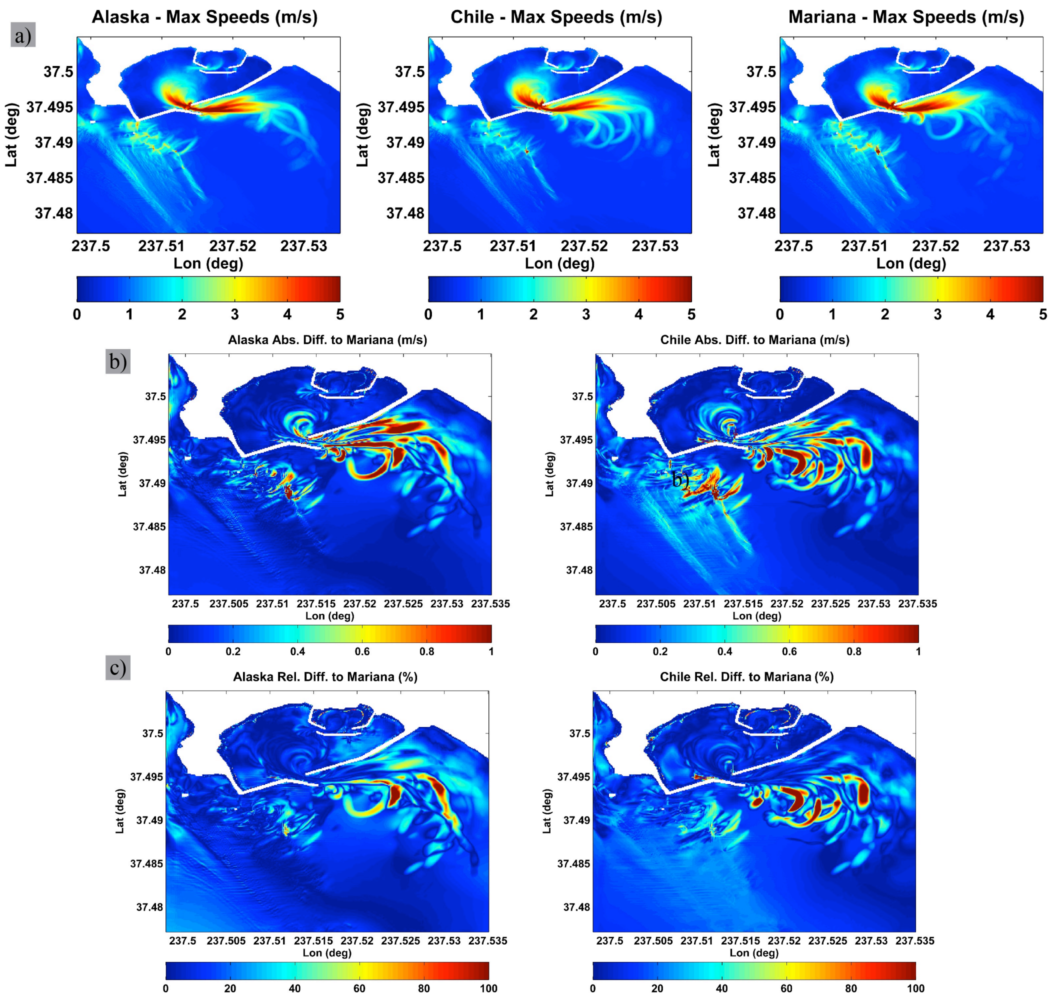

Figure 6. a) Maximum current speeds estimated by model in Pillar Point Harbor, b) absolute difference in maximum current speeds from Alaska and Chile cases with respect to Mariana case, and c) relative (%) difference in maximum current speeds from Alaska and Chile cases with respect to Mariana case.

CONCLUSIONS

Observations after recent transoceanic events in California revealed that even though tsunamis from distant sources do not cause significant inundation and overland flow, they can still induce strong currents with erratic flow patterns, which can be damaging to infrastructure and vessels in ports and harbors. In this study, we conducted a sensitivity analysis focused on understanding the effects of tides and wave directionality on localized tsunami-induced currents. To this end, we addressed the fundamental question of whether the inclusion of tides in tsunami simulations has any significant impact on the tsunami-generated currents. We find that tide-induced variability in the maximum tsunami currents ranged from 10% to 25%, which is a variability that is, currently, lower than a typical forecast accuracy.

However, it should be kept in mind that these results do not provide a general rule in quantifying the specific tide effects on tsunami currents for a generic location. For the same tsunami event and tide signal, two neighboring harbors in San Diego Bay reacted dissimilarly. Likewise, the pattern of tide effects for Pillar Point Harbor and Crescent City Harbor also did not agree, which showed the influence of the physical characteristics of individual harbors, such as the bathymetric features or existing infrastructure, as well as the strength of the tsunami and tide signals, on these types of analyses. Therefore, to better accommodate the significance of tides in a particular area of interest in relation to tsunami currents, we strongly recommend that similar analyses be conducted and assessed on a site-specific basis, which will give the most accurate results. Finally, we summarized our findings regarding the role of the wave source region on the localized maximum tsunami currents, with the hope of determining whether decisions about maritime advisories or warnings might be made based only on the local wave height predictions. We find that statistically, the source location does not play a significant role in the prediction of maximum speeds, and that spatial variability in maximum currents is dominated by the presence of eddies, for which deterministic simulation is of limited use.

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