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Precise Prediction of Coastal and Overland Flow Dynamics: A Grand Challenge or a Fool's Errand

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In this paper, the challenges in simulation of tsunami-induced currents are reviewed. Examples of tsunami dynamics in harbors, overland flow, and through urban environments are presented, with a focus on the numerical and natural variability in speed predictions. The discussion is largely aimed to show that high-confidence prediction of location-specific currents with a deterministic approach should not be possible in many cases. It is recommended that the tsunami community should look to some type of stochastic approach for current hazard modeling, whether that be a community-wide ensemble approach or a stochastic re-formation of our hydrodynamic theories. Until such tools are available, existing deterministic simulations of tsunami-induced currents require a high level of expert judgement in the analysis, presentation, and usage of model output.

Keywords: tsunami currents, numerical modeling, uncertainty

1. Introduction and Background

As interest in developing tsunami loading specifications increases (e.g. Yeh et al., 2005 [38]; Chock, 2016 [6]; Tokimatsu et al., 2016 [32]), the need for high-confidence predictions of tsunami-induced currents becomes paramount. Furthermore, as the structure under consideration exists (or will exist) at a unique location, the engineer must have confidence that the tsunami speed prediction at that specific location is accurate. While many numerical models have been tested for overland flow and runup, very few have been validated for complex currents. A primary reason for this is that very little experimental or field speed data exists. Note that is this paper, the terms "currents," "speed," and "velocity" refer to the fluid particle speed, not the wave celerity.

A number of existing datasets do include speed measurements under long waves (e.g. Baldock et al., 2009 [3]). For these cases, a reasonable data-model comparison with the wave elevation will generally imply a similarly reasonable, albeit with larger error (e.g. Borrero et al., 2015 [4]), comparison with the speed. The more challenging long wave speed tests are those where the currents are de-coupled from the wave. Here, this de-coupling implies cases that examine turbulent eddies and wakes in shallow flow (e.g. Lloyd and Stansby, 1997a,b [18, 19]; Park et al., 2014 [24]; Kalligeris et al., 2016 [13]); in such cases, the eddies are of course forced by the long waves, but once generated are no longer locked to the wave motion. The significance of eddies for hazard mitigation, including the types of impacts they have caused in recent events, is discussed in Lynett et al (2012) [21]. To properly predict these phenomena, a model must be able to capture the generation and evolution of the turbulent structures (the wakes and eddies), including their interaction with the "background" tsunami motion. In this paper, we examine some challenges in modeling currents in turbulent tsunami flows, and make some general recommendations on how to address these challenges.

2. Review of Existing Approaches

In the realm of physics-based numerical simulation of tsunami impacts, the modeled equations solve some, often reduced, form of the Navier-Stokes equations. The most common set of equations found in application are the non-dispersive Nonlinear Shallow Water Wave Equations (NSW). These are solved via a wide range of numerical schemes (e.g. Shuto et al., 1990 [27]; Titov and Synolakis, 1995 [31]; George, 2008 [10]). Numerical models based on the Boussinesq-type equations are also in widespread use for tsunami simulation (e.g. Wei et al., 1995 [34]; Son et al., 2011 [28]; Shi et al., 2012 [26]), and provide a weakly dispersive correction to the traditional NSW model. For these two types of shallow-water approaches (NSW and Boussinesq-type), dissipation is handled through a combination of physical submodels and numerical dissipation. The effects of bottom shear stress are approximated through bottom friction models, which typically employ either a quadratic friction law, the Chezy equation, or the Mannings equation. As the vertical structure in these shallow-water models is analytical, bottom stress cannot alter the vertical distribution of momentum, and thus the bottom friction models are intended to approximate the relevant vertical mixing in a depth-averaged sense. This aspect will be of particular importance when we discuss the modeling of tsunami-induced eddies and turbulent structures. Wave breaking, with few exceptions (e.g. Kennedy et al., 2000 [15]), is handled through numerical dissipation, wherein the numerical truncation error is tuned, either intentionally or fortuitously, to capture the transformation of a breaking wave front (e.g. Kazolea et al., 2014 [14]).

Models that do not presume an analytical structure of vertical kinematics comprise another class of tools used for tsunami simulation. These models are capable of capturing 3D flow, with varying application restrictions due to, for example, physical assumptions (e.g. hydrostatic, single-valued free surface) and the employed turbulence closure model (e.g. constant eddy viscosity vs large eddy simulation). Large-scale application with this class of model is slowly becoming feasible, at least with relatively coarse vertical resolution (e.g. Zhang et al., 2016 [39]). In this paper, we will not discuss in detail this class of models, due to their limited relevance to the application space of focus.

For the rest of this section, a selection of recent efforts to capture tsunami-induced currents will be discussed. In February of 2015, the National Tsunami Hazard Mitigation Program (NTHMP) organized a workshop to investigate simulation of tsunami-induced currents. A summary of the workshop and the primary results can be found in Lynett et al. (2016) [20], but some of the relevant aspects of this study will be presented here. For this workshop, 12 different numerical modelers attempted five different benchmarking datasets. The 12 models covered a range of governing equations and numerical schemes, and were primarily composed of models currently in use for tsunami hazard mapping in the USA. The benchmarking datasets were selected based on characteristics such as: 1) geometric complexity; 2) currents that are shear/separation driven (and thus are de-coupled from the incident wave forcing); 3) tidal coupling; and 4) interaction with the built environment. While tsunami simulation models have generally been well validated against wave height and runup (e.g. Synolakis et al., 2008 [30]), comparisons with speed data are much less common. As model results are increasingly being used to estimate or indicate damage to coastal infrastructure (e.g. Chock et al., 2016 [7]), understanding the accuracy and precision of speed predictions becomes increasingly important. It was thus a major goal of this workshop to better understand our ability to properly model tsunami-induced currents.

Figure 1 provides an important observation from the workshop. The output shown in this figure is from Benchmark Problem #2, where the modelers were tasked at predicting the water surface elevation and currents in Hilo Harbor, Hawaii, during the 2011 tsunami (Cheung et al., 2013 [5]). Initial and boundary conditions were both simplified and idealized in order to reduce any model variability due to differences in model setup. For this Benchmark Problem, a water surface elevation time series just offshore of the harbor was provided to all the modelers, and the modelers were asked to provide maximum elevation and speed maps as well as time series at a number of specified locations. From the 12 different model results, the intermodal-mean of all the maximum speed maps can be calculated, and this is shown as **Fig. 1a**. As can be seen from this figure, the strongest currents are found in the vicinity of the end of the harbor breakwater, and in the shallow areas closer to the shoreline. The strong currents at the end of the breakwater are due to flow convergence as the tsunami energy wraps around the structure.

While the intermodal-mean map provides the ensemble prediction of the maximum speed, one can also calculate the standard deviation across all the 12 model predictions of maximum speed. This standard deviation is given in **Fig. 1b**. While there is clearly a spatial correlation between the greatest maximum speeds (**Fig. 1a**) and the greatest inter-model standard deviations in maximum speeds (**Fig. 1b**), this correlation is not terribly strong. Clearly, the greatest standard deviations are found at and near the tip of breakwater; these standard deviations are driven by turbulent eddies. Upon inspection of the numerical results, it is noticed that boundary and bottom friction shear lead to strong flow separations at the end of the breakwater. With the oscillatory nature of the tsunami, these separations shed off the breakwater, forming eddies. As the formation and evolution of an eddy is very sensitive to small perturbations in the flow, different models, even if they predict the creation of an eddy at the same time and location, are not likely to predict the same path of the eddy. Therefore, we see that, in areas where eddies exist, we should expect that local speed predictions have low confidence.

This local speed variability due to eddies can be seen in a different manner by examining **Figs. 1c)** and **2d)**. These images show snapshots of vertical vorticity from the same numerical model at the same time, but using two different spatial resolutions: 10-m in **Fig. 1c** and 5-m in **Fig. 1d**. While the vorticity patterns in the two simulations are qualitatively similar, the precise location of the largest coherent eddies is different between the two simulations. This is again expected, as the flow patterns in the two different resolution simulations will be different, and the finer resolution simulation will be able to better resolve shear gradients, leading to different vorticity distributions. The logical conclusion from this demonstration is that numerically convergent prediction of tsunami-currents, in a local and deterministic sense, is likely infeasible in areas affected by flow separations and eddies.

As deterministic predictions of nearshore tsunami currents may yield a limited perspective of the potential currents, it is sensible to examine the probability distribution of currents. **Fig. 2** provides such a distribution. This figure provides two sets of probability distribution functions (pdf's) created from simulation data at Pillar Point Harbor, located along the central coast of California, as discussed in Ayca and Lynett (2016) [1]. Looking first to **Fig. 2b**, we see three different pdf's of maximum water surface elevation. Each of the three pdf's is from a different tsunami source, with each source tuned to produce a one meter amplitude tsunami signal just offshore of the Harbor. The pdf is generated by taking the maximum pre-

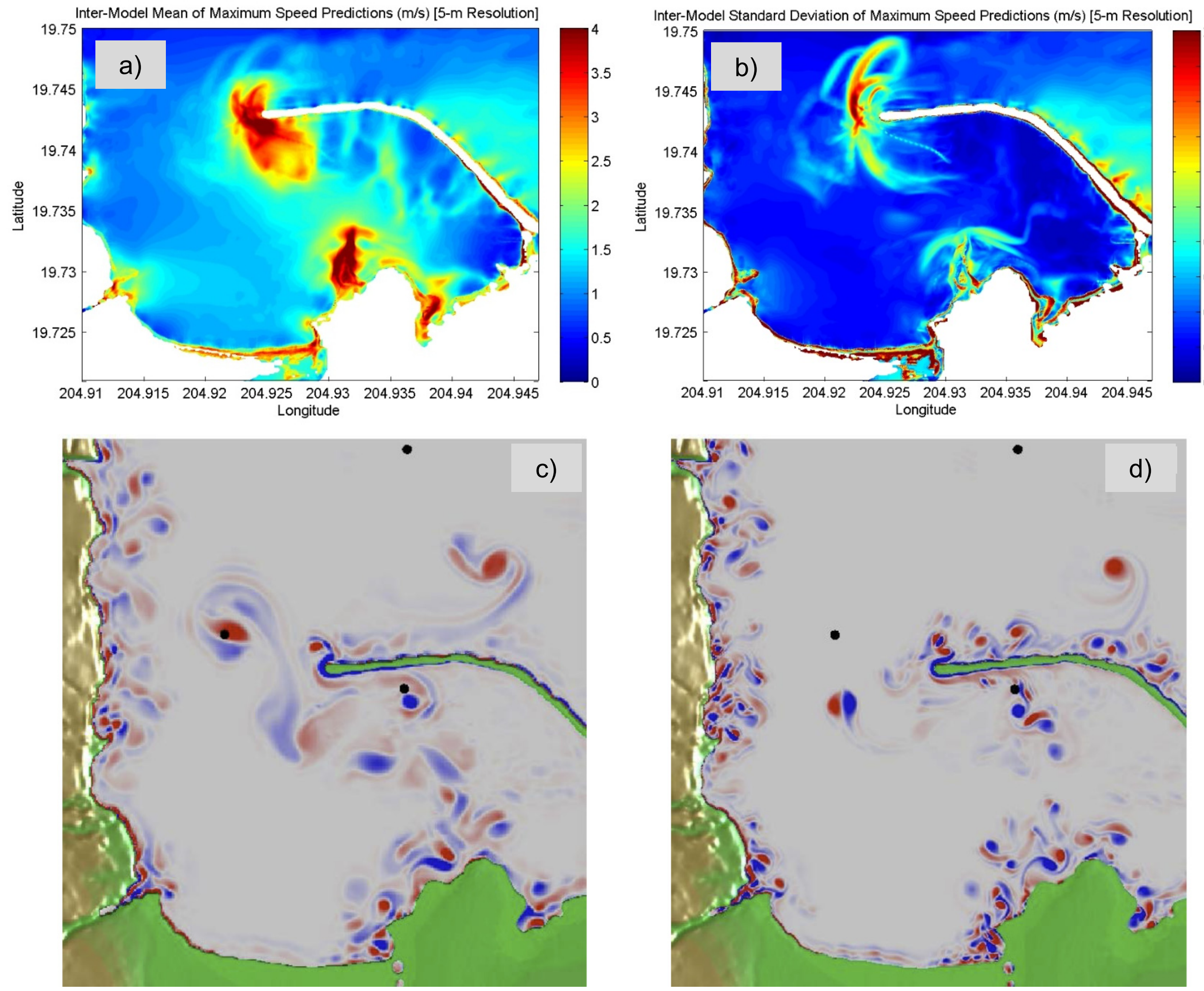

Fig. 1. In the top row, a summary of inter-model spatial statistics for a tsunami simulation is Hilo harbor. Top left a): Inter-model mean of predicted maximum speed as taken from the 5-m resolution runs. Top right b): Inter-model standard deviation of predicted maximum speed as taken from the 5-m resolution runs. In the lower row are shown snapshots of vertical vorticity at the same simulation time for the same numerical model, with 10-m resolution (c) and 5-m resolution (d). Figure adapted from Lynett et al. (2016) [20].

dicted elevation at every grid point inside of the Harbor, generating an exceedance distribution, and then taking the derivative of that exceedance distribution. What is evident from the pdf's of elevation is that, for all three sources, the maximum water surface elevations are very tightly bunched between 0.5 and 1.0 meters. In these elevation distributions, standard deviations are near 30% of the peak-probability values. Looking now to the velocity distributions, shown in **Fig. 2a**, the functions are much more spread. For the maximum current distributions, standard deviations are 300% of the peak-probability values. As with the previous example, this great spread in potential maximum speed is driven by small-scale flow convergence due to bathymetry, coastal structures, and eddies. Thus, relative precision in elevation might not equate to a similar precision in speeds, particularly when looking at local predictions.

The previous two examples focused on estimation of tsunami currents in ports and harbors, i.e. in coastal areas that are initially submerged before the tsunami. Here, we examine similar processes for overland flow, first looking at model results typical of large-scale runup simulations, using spatial resolution on the order of 10–30 m. Such simulations approximate sub-grid topography features, such as vegetation and structures, through bottom friction (e.g. Wang and Liu, 2007 [33]). For this example, we examine two different numerical models:

- MOST: The MOST code was originally developed by Titov and Synolakis (1995) [31] at the University of Southern California and was shortly after, adopted by the NOAA Center for Tsunami Research (NCTR) to develop operational, real-time modeling capabilities for NOAA's Tsunami Warning Centers. The MOST model provides solutions to the NSW equations, including generation, propagation and inundation onto dry land (e.g. Wei et al., 2008 [35]; Gica et al., 2008 [11]. The model uses an explicit scheme

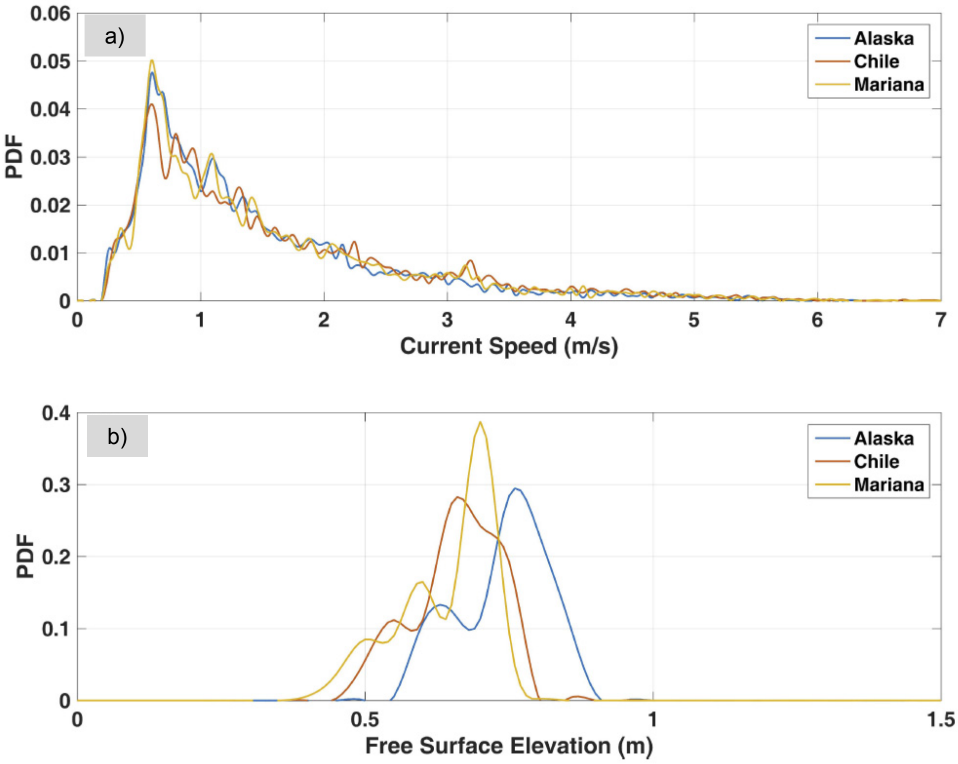

Fig. 2. Probability distribution functions (PDF's) of maximum tsunami-induced current speed (a) and maximum water surface elevation (b) at Pillar Point Harbor for three different tsunami sources. Figure adapted from Ayca and Lynett, (2016) [1].

to discretize the NSW equations, using an algorithm based on the method of fractional steps (Yanenko, 1971 [36]; Durran, 1999 [8]).

- GEOCLAW: The open source GeoClaw software has been actively developed at the University of Washington and by collaborators elsewhere for over 10 years, starting with the work of George (2008) [10] and George & LeVeque (2006) [9]. GeoClaw solves the nonlinear NSW equations using a high-resolution shock-capturing finite volume method based on solving Riemann problems at cell interfaces and applying second-order correction terms with limiters to avoid non-physical oscillations near discontinuities. These general methods are described in detail in LeVeque (2002) [17].

Both models were configured with identical bathymetry/topography grids, bottom friction, spatial grid sizes, and initial and boundary conditions. Thus, the differences in the model results will be due to physical and numerical differences in the models only; the comparison will provide some guidance on inter-model variability only.

Figure 3 gives summary information from a comparison of numerical models for overland flow, adapted from Montoya et al. (2016) [23]. The top row of this figure, subplots a) and b), show the maximum water surface elevation recorded for a simulation of the 2011 tsunami over the Sendai Pain from MOST and GeoCLAW, respectively. While no statistical comparison is provided here, the two models in general are in good agreement throughout the domain, and yield similar predictions of the inundation limit. This inter-model agreement is an indication that the models exhibit precision; comparison with field data, which is not discussed here, would be a requirement for a statement concerning accuracy. Next, the maximum water speeds predicted by the two models are shown in **Figs. 3c** and **3d**. Here, for maximum speeds, the inter-model variability in spatial patterns of flow speed are relatively great, with large areas of substantial (i.e. greater than 6 m/s) differences between models. This is a very similar conclusion of that found in the previous examples looking at coastal currents. With such an inferred lack of precision in our ability to model maximum speeds during overland flow, it would be expected that establishment of accuracy may be a challenge, due to the previously noted paucity of available speed data from the field. **Fig. 3e** shows the comparison between simulated maximum flow speeds and field data, with the field data taken from Hayashi and Koshimura (2012) [12]. Clearly, the numerical predictions vary greatly depending on the model and the choice of bottom friction coefficient used. Both the inter-model variation in speed prediction and the error between model results and field data vary between 2–4 m/s for the four locations shown; as a relative error this can be expressed as a 50%–100% error, and the models both under- and over-predict maximum speeds in this error range. These large errors do not lend confidence that the numerical models tested can provide a (deterministic, local) velocity prediction that is useful for applications requiring anything more

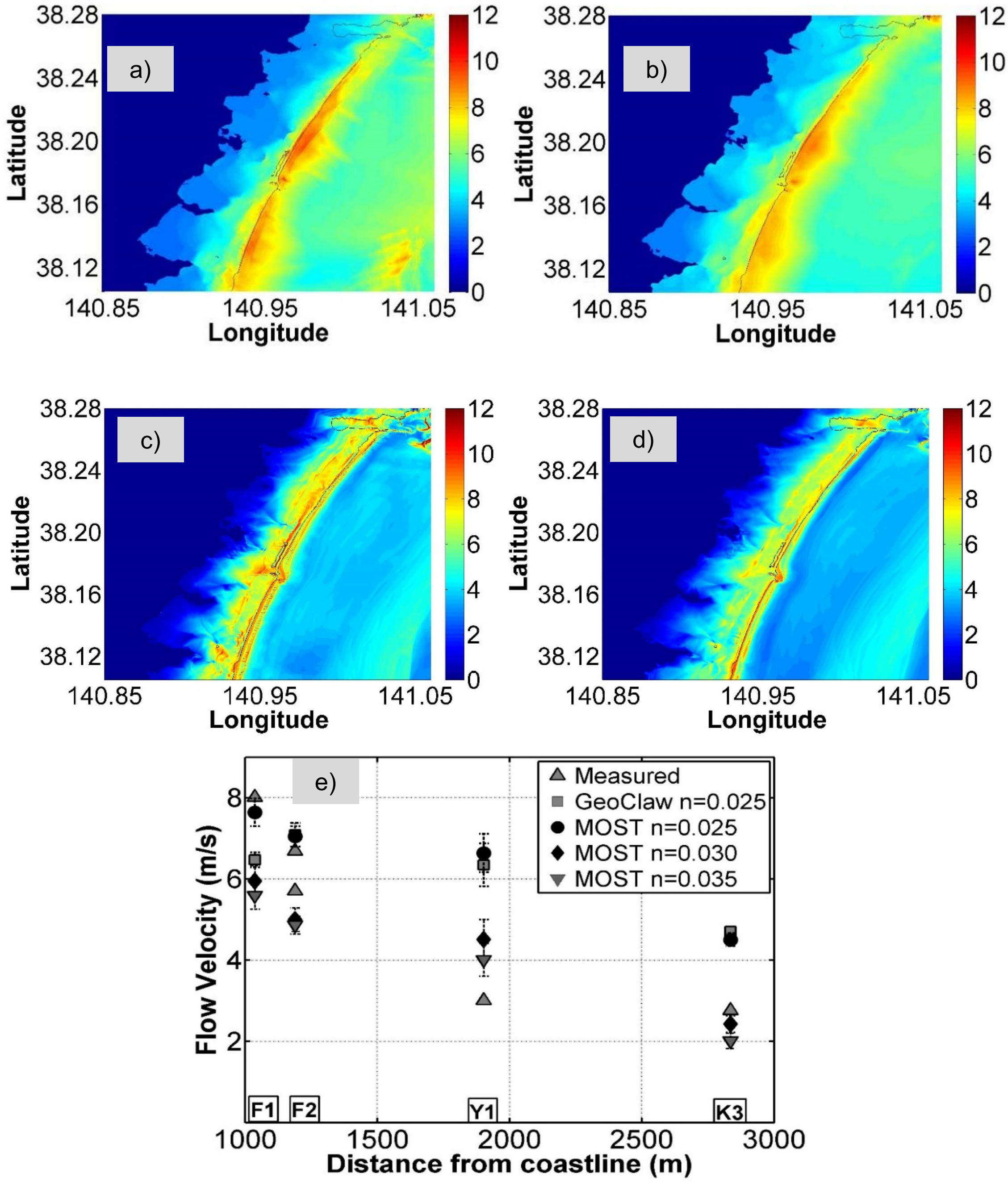

Fig. 3. Summary of inter-model comparison for inundation of the Sendai Plain from the 2011 tsunami: a) shows the maximum water surface elevation (m) from the MOST model; b) shows the maximum water surface elevation (m) from the GeoClaw model; c) shows the maximum water speed (m/s) from the MOST model; d) shows the maximum water speed (m/s) from the GeoClaw model; and e) shows the comparison of maximum flow velocities at the Sendai plain between Koshimura and Hayashi (2012) [12] measurements (gray triangle), GeoClaw predictions (gray square), MOST predictions using $n = 0.025$ (black circle), MOST predictions using $n = 0.030$ (black diamond) and MOST predictions using $n = 0.035$ (gray upside down triangle), where the vertical bars on the model data provide the standard deviation of the predictions in the measurement window. Note that the initial shoreline is shown by the black line in a)–d). Figure adapted from Montoya et al., (2016) [23].

than a rough estimate of speeds.

The accuracy errors discussed above are difficult to interpret, as we don't have knowledge about what the potential distribution of the currents may be, i.e. how sensitive is the maximum current to the precise location of measurement and the specification of dissipation parameters (bottom roughness), which change in time and space?

To provide an example of the possible natural variability of overland flow properties through the built environment, we examine a simulation of a large tsunami traveling through a city-like grid of rigid buildings. Specifically, this simulation is a recreation of the experiments presented in Park et al. (2013) [24], which are themselves a scale model of the town of Seaside, Oregon. The numer-

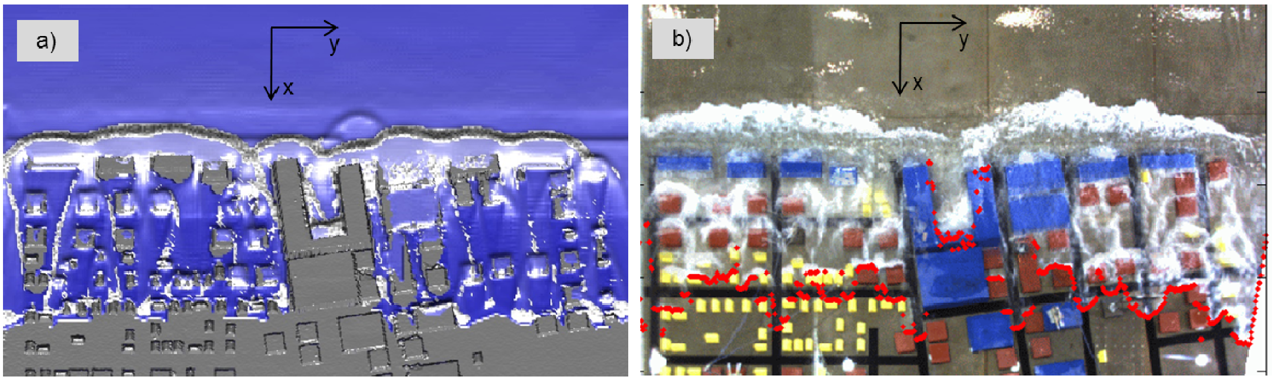

Fig. 4. Overhead view of inundation from a) numerical simulation and b) physical modeling. In the numerical simulation, areas of high eddy viscosity are colored in white; in the experiment, breaking is indicated by the white (aerated) water and the bore front is given by the red dots. Note the coordinate system, where x is in the cross-shore direction positive pointing inland and y is in the alongshore direction.

ical model used for this example is pCOULWAVE, which solves the fully nonlinear Boussinesq-type equations with a high-order finite volume scheme (Kim et al., 2009 [16]). An example of the simulation output and experimental results are given in **Fig. 4**; both the simulation configuration and the experimental layout are described in Park et al. (2013) [24]. As opposed to the previously discussed examples in this paper, here, the structures are resolved in the simulation, which is not a common approach in tsunami inundation simulations (although becoming more frequent, e.g. Baba et al., 2014 [2]).

A summary of the numerical results is given in **Fig. 5**. For this comparison, we are focusing on maximum "specific momentum flux," which is the maximum of the product of flow depth (H) times speed (V) squared. This metric is used as it is expected to be the most relevant parameter for structural design, where tsunami loads are often governed by fluid drag loads (Yeh, 2007 [37]). **Fig. 5b** shows the spatial map of maximum momentum flux. The interaction between the flow and the structures is obviously very strong, with clear focusing of flow energy between buildings. Each individual structure generates its own wake, and these wakes interact leading to a complex and highly-variable distribution of momentum flux. In these situations, maximum momentum flux can vary by an order of magnitude over real-world distances of 10 meters. However, the locations of these sharp gradients are likely to be functions of the incoming wave properties, building type, and building layout, which are pieces of information that are not precisely known for any future event.

To better understand the effect of the structures, we also run a "bare-earth" simulation using the same wave parameters, but with the buildings removed from the numerical domain; results from this comparison are given in **Fig. 5c**. In this subplot, we see that along the beach, before the structures begin ($x <\sim 32.5$ m), the maximum momentum flux predictions from the bare-earth and the with-structures model agree, as expected. In the presence of structures, this changes. Close to the initial shoreline, the alongshore-mean of the maximum momentum flux is greater than the bare-earth simulation, indicating that the effects of focusing and funneling of the flow overcomes the effects of offshore reflection by the buildings and increased energy dissipation due to the higher "effective" roughness of the urban layout. This relationship changes with increasing distance onshore. Perhaps the most interesting aspect of this comparison is the plot of the alongshore-maximum of the maximum momentum flux. While not a terribly useful value from the statistical perspective, comparing this alongshore-maximum to the alongshore-mean does provide an estimate of the potential range in values. We see here that, along the first few rows of structures, the alongshore-maximum is 6-30 times greater than the alongshore-mean and between 8-80 times greater than the bare-earth value. The design implication of this observation is that, for example, if one used the bare-earth simulation to estimate the force on a structure, that estimate for force could possibly be under-estimating the true force by a factor of 80.

3. Challenges in Prediction

From the above discussion, a few primary observations can be given:

- In areas affected by eddies and strong flow convergence, ensemble-model variance of current magnitude is likely to be very high, on the order of the ensemble-model mean current magnitude
- For overland flow, widespread areas of high ensemble-model variance of current should be expected
- For a given coastal area, the distribution of current magnitude is likely to be much wider than the distribution of ocean elevation, with distributions scaled by the most-likely values
- Maximum currents are highly sensitive to numerical

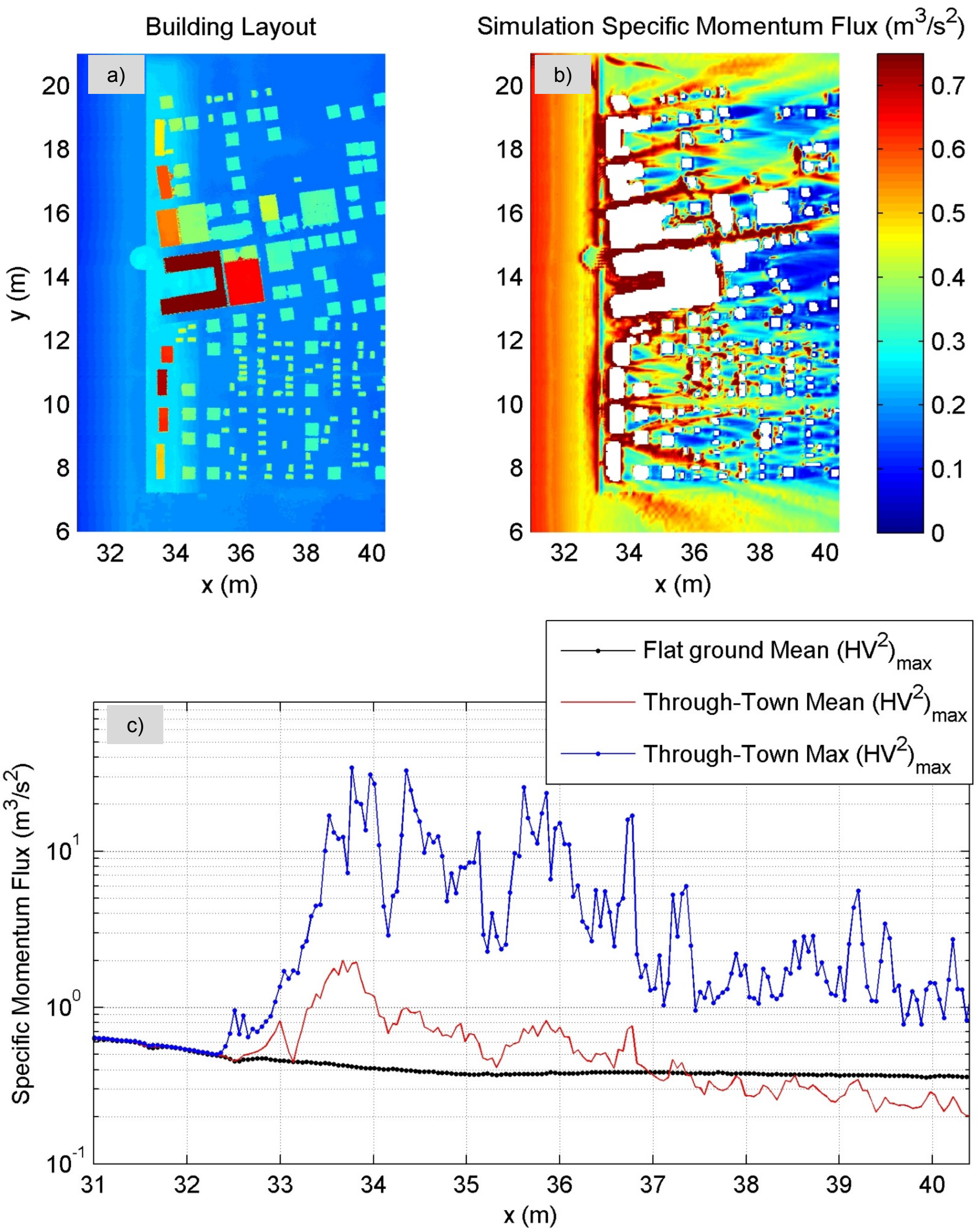

Fig. 5. Summary of the maximum specific momentum flux, $(HV^2)_{\max}$, predicted by the simulation; a) the building layout over the initially dry land, b) the surface of $(HV^2)_{\max}$ (note that values on building roof tops are removed from the plot to better visualize flow patterns), and c) the mean and maximum $(HV^2)_{\max}$, including the mean value for a flat ground (bare earth) simulation.

parameters that control the dissipation, most significantly bottom friction, and this sensitivity appears greatest for overland flow. Furthermore, certainty and precision in the specification of these dissipation parameters is low

- Urban environments modify the flow patterns in drastic and highly localized ways, which cannot be captured or inferred from bare-earth models

That areas affected by eddies show high variance should not be a surprise. Eddies are, at least in the geophysical context of a tsunami, turbulent structures; a precise deterministic prediction should not be expected. This realization alone should be enough to push the discipline towards stochastic or ensemble simulation of such features, if it is decided that capturing these eddies is relevant to hazard mitigation (e.g. Lynett et al., 2014 [22]). However, the physical generation process of these tsunami eddies requires a bit more discussion. In the context of tsunamis, an eddy that spins in the horizontal plane (characterized by strong vertical vorticity) is generated through the tilting of rotation in the vertical plane (horizontal vorticity). This horizontal vorticity is generated through bottom shear, and the tilting is forced by spatial variations in the mean flow, usually driven by spatial variations in bathymetry or topography. Thus, physically, it should not be possible to generate a tsunami eddy spinning in the horizontal plane without a proper description of the generation and transformation of horizontal vorticity. For our depth-averaged or depth-integrated class of models, such a proper description is not possible; a fully 3D model is required. Therefore, the depth-averaged class of model, in order to accurately predict the generation of tsunami eddies, must rely on the "black-box" of a bottom friction model to reasonably predict the horizontal shear in the mean velocity field generated, physically, through gradients of horizontal vorticity. The point of this discussion is that depth-averaged models, fundamentally, are not well-posed to ***generate*** vertical vorticity, and thus this generation is dependent on empirical or semi-empirical dissipation sub-models, which have not been calibrated for this generation process. That some models in the depth-averaged class appear to accurately capture this generation (e.g. Kim et al., 2009 [16]) is likely a testament to the robustness of the NSW basis for tsunami problems. However, great care should be taken when said models are used to describe said process, particularly since areas of high velocity shear are the most likely areas to be affected by numerical dissipation (e.g. Lynett et al., 2012 [21]).

For the remainder of the discussion in this section, let us assume that we have numerical models at our disposal that have been calibrated and benchmarked for accurate speed predictions for tsunami flow over complex bathymetry and topography; we have confidence that these models are accurate for tsunami-induced speed predictions, at least as we can prove them to be. Furthermore, any two models may provide different predictions for local currents, and this difference may be relatively large, but both models are considered "equally" accurate. Also, it has been demonstrated in previous discussion that small changes in topography and bottom friction can lead to large changes in speed predictions, and topography and bottom friction can change significantly during a tsunami event (Richmond et al., 2012 [25]). So, we have both an artificial variability, due to different interpretations of the physics among different models, and a natural variability; we stay away from attempted definitions of epistemic and aleatory uncertainty in this discussion. From the discussions in the previous section, it is reasonable to expect that deviations from either source be in the range of 50-100% of some mean value. Again we can say that a single deterministic simulation may not hold much meaning for the prediction of tsunami-induced currents.

To summarize, during a strong tsunami, it is expected that eddies, wakes, and fluid jets are formed as the water flows around irregular topography. Many aspects of these processes are expected to be fundamentally stochastic, in that their behavior is influenced by small perturbations in initial and boundary conditions that are irresolvable or unknown, at least with current state-of-the-art modeling approaches. The strongest currents in an area, whether it be in coastal or overland flow, are likely to be characterized by eddies, wakes, and fluid jets. Thus, the strongest currents are best suited to stochastic prediction.

4. Conclusions

In this paper, we have reviewed the challenges in simulation of tsunami-induced currents. The discussion is largely aiming to show that precise, local prediction of currents with a deterministic approach should not be possible in many cases. The natural conclusions of the arguments presented are that the community should look to some type of stochastic approach for current hazard modeling, whether that be a community-wide ensemble approach or a stochastic re-formation of our hydrodynamic theories. Until such tools are available, existing deterministic simulations of tsunami-induced currents require a high level of expert judgement in the analysis, presentation, and usage of model output.

Acknowledgements

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Selected Publications:

- P. Lynett, J. Borrero, S. Son, R. Wilson, and K. Miller, "Assessment of the Tsunami-Induced Current Hazard," Geophysical Research Letters, doi: 10.1002/2013GL058680, 2014.
- P. Lynett, J. Borrero, R. Weiss, S. Son, D. Greer, and W. Renteria, "Observations and Modeling of Tsunami-Induced Currents in Ports and Harbors," Earth and Planetary Science Letters, Vol.327/328, pp. 68-74, doi: 10.1016/j.epsl.2012.02.002, 2012.
- P. Liu, P. Lynett, J. Fernando, B. Jaffe, H. Fritz, B. Higman, C. Synolakis, R. Morton, and J. Goff, "Observations of the International Tsunami Survey Team in Sri Lanka," Science, Vol.308, No.5728, pp. 1595, June 10, 2005.

Academic Societies & Scientific Organizations:

- Coastal Engineering Research Council (CERC)
- American Society of Civil Engineers (ASCE)
- American Geophysical Union (AGU)