Tsunamis rank among the most devastating and unpredictable natural hazards to affect coastal areas. Just 3 years ago, in December 2004, the Indian Ocean tsunami caused more than 225,000 deaths. Like many extreme events, however, destructive tsunamis strike rarely enough that written records span too little time to quantify tsunami hazards. To assess tsunami risk, tsunami deposits in the geologic record have been used to extend the record of tsunami occurrence but not the magnitude of past events. To quantify tsunami hazard further, we asked the following question: Can ancient deposits also provide guidance on the expectable water depths and speeds of tsunami wave propagation?

It has been well documented in the past 20 years that tsunami deposits, both ancient and recent, act as natural recorders of tsunami waves [Tappin, 2007]. With reliable dating, such deposits enable us to quan-

The State of the Science

Moreover, tsunami deposits provide the first line of evidence to enhance this collaboration. Promising preliminary work, based on a tsunami sedimentology workshop held in spring 2007 in Friday Harbor, Wash., suggests that benchmarks are now ready to link an improved understanding of tsunami physical processes and to advances in our ability to quantify paleotsunami magnitudes by interpreting the geologic record.

Developing quantitative tools to estimate flow depth and speed from tsunami deposits involves intense interdisciplinary collaboration among the coastal geomorphology, sedimentary geology, sediment transport, hydrodynamics, remote-sensing, and seismology communities. This article presents a strategy for using “sedimentology benchmarks” to enhance this collaboration. Promising preliminary work, based on a tsunami sedimentology workshop held in spring 2007 in Friday Harbor, Wash., suggests that benchmarks are now ready to link an improved understanding of tsunami physical processes and to advances in our ability to quantify paleotsunami magnitudes by interpreting the geologic record.

The State of the Science

Tsunamis deliver highly energetic, sustained flows that can erode everything from large blocks to fine sediment and transform them up to thousands of meters across coastal plains. The long-period waves of a tsunami approach the shore at speeds of tens of kilometers per hour, causing near-shore water surface fluctuations with amplitudes of several to tens of meters. The leading wave—commonly related to the pattern of seafloor displacement in the source region—can erode or advance a beach. The incoming waves commonly break offshore, where they form a bore or series of bores—relatively short breaking waveforms riding on the tsunami longer wave. For example, in many videos of the 2004 Indian Ocean tsunami, the first tsunami waves reach onto dry land much like a suffocating flood. Several additional large waves, with typical periods of tens of minutes, continue to erode and advance flooding typically lasts for hours. The tsunami sedimentation models have been around for years and have been shown to be fairly accurate at predicting basin-scale travel times and deep-water wave amplitudes, models of tsunami inundation—where waves approach shore and flood the land—are less common and have not been adequately tested against field data. Recent inundation models consider wave evolution by simulating both linear and highly nonlinear processes of various length scales and timescales. For example, post-tsunami deposits are particularly sensitive to effects of local bathymetry and coastal topography that cause tsunami runup to vary significantly, even in neighboring areas. Inverse models of tsunami deposits [see Tappin, 2007] and forward models of deposits from flow [Gelfenbaum and Jaffe, 2007] are relatively new and still under development. These models exploit the dependence of sediment transport on the relationship between grain size (grain settling velocity) and flow shear stress. Deposition occurs either when sediment converges or when deceleration permits sediment to fall out of suspension. Empirical relationships to infer deposit characteristics from flow velocities and, conversely, flow velocities from deposits have been developed from steady channel-flow experiments. This suggests that it should be possible to combine tsunami hydrodynamics and knowledge of the sediment available for transport to predict the structure and texture of tsunami deposits—or to reconstruct tsunami flow histories from deposit characteristics. However, fundamental questions remain regarding tsunami turbulent flow structure and the applicability of existing sediment transport models to tsunami’s timescale and initial dry-bed conditions.

Benchmarking for Tsunami Sedimentology

Benchmarking tsunami sedimentology models entails developing test cases that can be treated using different approaches, allowing the model results to be compared and problems to be tackled in an efficient, coherent manner. Given the limitations of existing tsunami inundation and sediment transport models, two key challenges are well suited for such an approach: (1) closing the knowledge gap in linking modern events to their deposits with an improved understanding of tsunami sediment transport, and (2) adapting that relationship to interpret the geologic record.

Traditionally, benchmarks rely on analytical solutions or controlled experiments of known initial conditions with which to test and compare models or laboratory equipment. Our working definition of a benchmark is somewhat different for several reasons. First, there is no adequate analytic solution available for “tsunami sediment” transport and deposition. Second, while initial conditions of laboratory experiments can be specified in detail, comparing these small-scale experiments to nature is limited by scaling difficulties. Most important, while conventional benchmarks are used to rank models in well-established fields of study, tsunami sedimentology is at such an early stage that benchmarking serves instead to enhance collaboration in exploring physical processes and to improve models and predict the behavior of which collaboration has already resulted from benchmark exercises that have investigated the hydrodynamics on which tsunami runup models are based [Yeh et al., 1996].

Benchmarking for tsunami sedimentology requires agreed-upon goals that promote interdisciplinary collaboration and development of appropriate data sets. For example, the community must identify key parameters to be estimated (e.g., wave height and speed) and set sensitivity study targets (e.g., effect of grain size on deposit thickness). These actions will ensure that the focus and scope of modeling studies are comparable. Identifying these parameters also helps to determine the minimum amount of information a benchmark data set must contain.

Proof of Concept

As a test of this approach, we performed pilot benchmark exercises on two data sets of tsunami deposits, one modern (2004 Papua New Guinea) and the other ancient (twelfth, thirteenth centuries, Kaminoko, Russia). Detailed treatment of the modern case (Figure 1) was aimed at linking modern events to their deposits and improving the understanding of tsunami sediment transport. The application of the models to the ancient case allowed us to evaluate how well the models were performing.

Figure 1. Flow depth and speed estimates for the 1998 Papua New Guinea tsunami. (a) Location and sample sites [Gelfenbaum and Jaffe, 2003]. (b–e) Data collected from tsunami deposit (red symbols), field-based estimates of tsunami flow elevation (sum of flow depth and land elevation, white circles) and speed (white triangle) predictions using hydrodynamic model of Lynett [2007] with incorporated transport model following Rakha et al. [1997] (bold blue lines), and inverse model predictions of Jaffe and Gelfenbaum [2007] (black symbols).

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Sandy Signs of Tsunami Onshore Depth and Speed

By K. Benedict, J. Bourgeois, E. Gelfenbaum, P. Linton, B. Jaffe, H. Yeh, and R. Weiss

VOLUME 88    NUMBER 52    25 DECEMBER 2007

Eos, Transactions, American Geophysical Union

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Models were used to estimate tsunami characteristics such as flow depth, flow speed, number of waves, and where possible, tsunami source for each benchmark. The data sets included grain-size distributions, deposit thickness, topographic profiles, and bathymetry. In the case of the modern deposit, additional information (from field estimates and eyewitness accounts) on the tsunami was available [Gelfenbaum and Jaffe, 2003]. Paleotsunami modeling efforts were complicated by incomplete deposit preservation, lack of flow depth or inundation limit indicators, and poorly constrained pre-tsunami topography at Muiravsky Bay.

Forward modeling of tsunami inundation was based on high-resolution bathymetry and topography collected along the nam-
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 ple tracer for each benchmark. For the Papuan New Guinea (PNG) case (Figure 1), further model constraints were provided by the simulation of inundation limits and flow depth indicators identified in the field and by the number of waves reported by eye-witnesses. Model-inferred depths and flow thicknesses were comparable (Figure 1c). The observed wave height and flow depth snapshot (Figure 1e) shows flow accelerations and decelerations as the wave cascades over a topographically high, illustrating the complexity of flow-topography interaction.

 Estimates of maximum flow speed from inverse modeling were based on assumptions of steady and uniform flow and on observed grain-size distributions and deposit thicknesses. The inverse model used in the PNG benchmark (Figure 1c) is consistent with independent field estimates of flow speed (calculated using Beresfordian morpho- logical processes in the ice sheet component likely lead to an underestimation of sea level rise forced by a warming climate. The result is a lower sea level projection, and thus for climate policy, have been widely discussed since the publication of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007). The assessments and models studied above do not include “the full effects of changes in ice sheet dynamics and Earth’s ice sheet literature is lacking.” The report also notes that the understanding of rapid dynamical changes in ice flow “is too limited to assess their likelihood or provide a best estimate or an upper bound for sea level rise.”

 Credible predictions of ice sheet evolution and sea level change will require a new generation of ice sheet models that can simulate atmosphere-ocean general circulation models (AOGCMs). Although the development of these new models is underway (e.g., physically justifiable model assumptions) demands institutional, cross-disciplinary, and cross-institutional coordination of researchers working on numerical algo-

 Toward A New Generation of Ice Sheet Models

 Large ice sheets, such as those presently covering Antarctica and Greenland, are important in driving changes of global climate. Changes in ice sheet mass balance, as developed to predict climate change and ice sheet-driven sea level fluctuations have substantial implications for the societal processes in the ice sheet component likely lead to an underestimation of sea level rise forced by a warming climate. The result is a lower sea level projection, and thus for climate policy, have been widely discussed since the publication of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007). The assessments and models studied above do not include “the full effects of changes in ice sheet dynamics and Earth’s ice sheet literature is lacking.” The report also notes that the understanding of rapid dynamical changes in ice flow “is too limited to assess their likelihood or provide a best estimate or an upper bound for sea level rise.”

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 refinement development, software engineering and computer architecture. Perhaps more important, developing these models will require a significant collaboration with glaciologists, climate modellers, and end users to implement physically sound ice dynamics while working within the constraints of AOGCMs. A concerted effort to develop a new generation of ISMs coupled to AOGCMs can significantly improve observational efforts and glaciological process studies, yet progress is hampered by a lack of cross-disciplinary and cross-institutional cooperation (and resources) focused on this goal.

 Current Status

 The comprehensive continental-scale ice sheet models used to predict global sea level change have been substantially modified in the past decade. The models are based primarily on the assumption that gravitational driving stresses are balanced locally by basal traction, resulting in flow dominated by horizontal shear (i.e., the horizontal transport of stress is unimportant) (e.g., Huybrechts et al., 2004). This assumption is appropriate where creep is the dominant ice flow process and where the effects of subglacial meltwater can be neglected. These BMs have been partially checked against direct observations (understanding the need for more direct observational data), leading to the development of all-ice sheet models in the United States and around the world, which are more consistent with the current state of the science (IPCC, 2007, Third and Fourth Assessments).

 Why Scientists and Policy Makers Are Interested

 In the past decade, our knowledge of ice sheet dynamics has improved dramatically, due to the application of satellite tech-

 niques such as radar altimetry and interferometry, together with airborne and surface observations (reviewed by Shepherd and Wingham, 2007). New, unexpected observations include the thinning and acceleration of Greenland outlet glaciers, West Antarctica, and the acceleration of many upstream glaciers leading to the collapse of Larsen A on the Antarctic Peninsula. In addition to this new observational evidence, studies of the flow regime in polar regions suggest that sea level rise during glaciations may have occurred, at least episodically, at rates not attainable by current ice sheet models. However, ice sheet simulations assessed by the IPCC can only predict a small subset of the potential behavior of these ice sheets because of a lack of observations that enable the production of ice sheet models that can simulate atmosphere-ocean general circulation models (AOGCMs). Although the development of these new models is underway (e.g., physically justifiable model assumptions) demands institutional, cross-disciplinary, and cross-institutional coordination of researchers working on numerical algo-

 rithms in isolation, and then simulating the results of these base models in a time-dependent boundary condition. Incorporating this capability will necessitate a reconsideration of the ice sheet model components, whose lateral and vertical resolution of the ice sheet is necessary to allow for the detailed analysis of processes such as melt water production and flow, ice shelf buttressing, and the assessment of the spatial and temporal extent of these potentially important feedbacks.

 Underlying Problems

 Continental-scale ice sheet models have the least skill where the influences of meltwater production and flow, ice shelf buttressing, and subglacial sediment deformation are important. These processes can interact in complex ways to accelerate sea level rise. Current computer-based projections of ice sheet contributions to sea level rise are therefore not adequate to diagnose sea level rise, and thus are only diagnostic tools, which are only of limited use to practitioners and policy makers. These models can be developed in isolation, and then coupled to AOGCMs. A comprehensive understanding of how ice sheets respond to boundary conditions and to changes in climate will require a new generation of ice sheet models that can simulate atmosphere-ocean general circulation models (AOGCMs). Although the development of these new models is underway (e.g., physically justifiable model assumptions) demands institutional, cross-disciplinary, and cross-institutional coordination of researchers working on numerical algo-

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