turn the float to Rhode Island. After several telephone calls during the Thanksgiving holiday period, it was not clear how to send Mr. Kamara a box for the float and pay for the shipping charges. Dr. Hebert convinced Mr. Kamara to deliver the float to the U.S. Embassy in Conakry. A box for the float could be shipped to the Embassy. Although wary of trying to deliver such a strange item to an embassy in Africa, Mr. Kamara did just that. With the assistance of Special Agent Daniel Wilhelm and the Embassy staff in Conakry, the float was return to Rhode Island at the end of January, a little more than two years since it left the state. The float was in excellent condition. Drs. Hebert and Rossby appreciate the assistance of Mr. Kamara and the Embassy in returning this instrument.

This float was one of those equipped with the novel oxygen sensor from Aanderaa. The return of the instrument allowed them and us to assess how well the sensor fared from prolonged exposure in the ocean and to see how much biological fouling occurred. Visual inspection of the float and the sensor suggests only modest fouling took place during its half-year drift on the surface in near-equatorial waters.

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Satellite Altimeters Measure Tsunami

EARLY MODEL ESTIMATES CONFIRMED

by Walter H.F. Smith, Remko Scharroo, Vasily V. Titov, Diego Arcas, and Brian K. Arbic

Radar altimeters on-board the *Jason-1*, *TOPEX*, *Envisat*, and *GFO* satellites obtained profiles of sea surface height on transects across the Indian Ocean between two and nine hours after the December 26 Sumatra earthquake. The data are received hours to days after "real time," too late to be used in detection and warning of tsunamis. We compared the sea level anomaly profiles of December 26 measured along the satellite tracks (Figure 1D-G) with the measurements on previous passes of the same satellites 10 days, 35 days, and 17 days earlier. This allowed us to remove the majority of permanent and slowly varying features of sea level, revealing transient signals. The altimeters also provide wind speed and wave height data, and these allowed us to interpret a sea-level anomaly at 16°S in the Jason-1 profile (Figure 1D) as being due to a severe storm. The remaining sea-level anomaly signal appears to be associated with the tsunami. The signal of the leading edge two hours after the earthquake is particularly prominent, with an amplitude of 60 cm and two narrow peaks where the NOAA tsunami model forecast shows two overlapping peaks coalescing into one broad (250 km) crest. Increased sea-surface roughness at spatial scales from 150 to 15 km wavelengths also appears inside the portion of the ocean excited by the tsunami.

The first model simulation results of the Indian Ocean tsunami (Figure 1A-C) were obtained from the "MOST" (Method of Splitting Tsunamis) model (Titov and Synolakis, 1998) and were posted by V.V. Titov on the Internet Tsunami Bulletin Board less than 12 hours after the earthquake. MOST is part of the tsunami forecasting and warning system under development for the Pacific Ocean (Titov et al., 2005) that will provide fast real-time estimates of tsunami amplitudes using preset models, real-time seismic data, and, most importantly, deep-ocean tsunami amplitude data from a network of deep-ocean pressure sensors. Other researchers also ran models and posted results. Results of MOST and other model runs have been widely used worldwide by the media for early planning of relief efforts and for post-tsunami field surveys. Unlike the Pacific, the Indian Ocean does not yet have a network of deep-ocean pressure sensors, and so coastal tide gauges provide the only direct measurement of Indian Ocean tsunami amplitudes. The satellite altimeter data we present here are the only measurements of the amplitude of the December 26 tsunami in the deep, open ocean.

At the time of the first MOST model simulation, earthquake source mechanism models described a rupture confined to only the southernmost portion of the broad region mapped out by the aftershock pattern. However, it seemed clear that the tsunami should have been generated by displacements distributed along the entire aftershock zone. The initial conditions for the MOST model were set assuming this more spatially distributed source, with initial amplitude guesses based on preliminary estimates of the earthquake magnitude and one coastal tide-gauge measurement from Cocos Island. Because of the lack of *in situ* deep-ocean data, the tsunami simu-

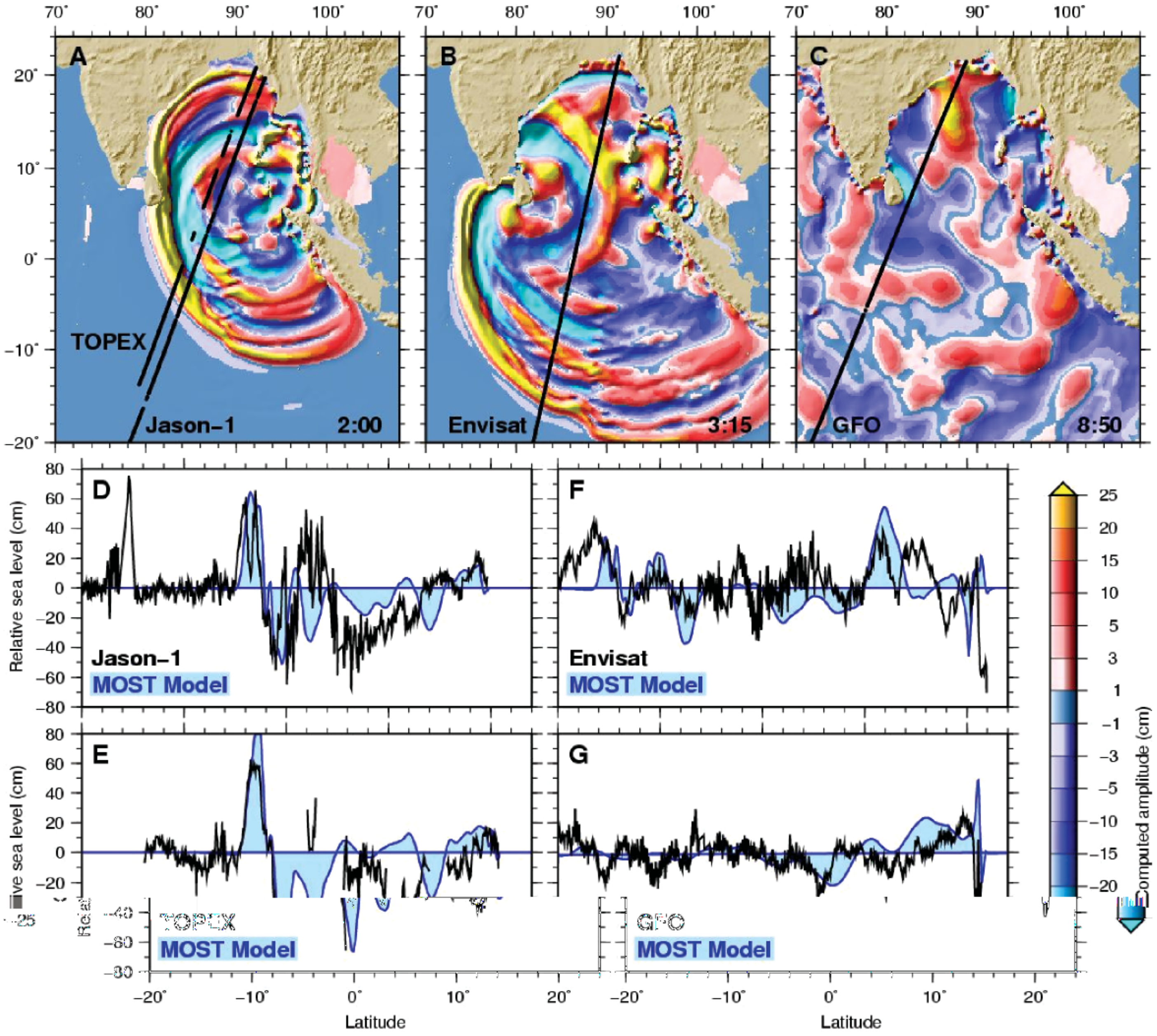

Figure 1. (A to C) Tsunami wave heights generated by the December 26, 2004 Sumatra earthquake, computed by the MOST model at (A) 2:00 hours, (B) 3:15 hours, and (C) 8:50 hours after the earthquake. These times coincide with overflights of the satellites Jason-1 and TOPEX, Envisat, and GFO, respectively. (D to G) Comparison between the sea height deviations as measured by the satellite altimeters and the modeled wave heights.

lation accuracy was uncertain until the satellite altimeter data arrived.

The first value of the altimeter data is in basic confirmation of the general pattern of the deep-water features of the model. However, detailed inspection shows that there are some discrepancies between altimeter observations and model predictions. These might be explained either by a more complex excitation mechanism and/or by a more complex ocean response. To assess the likelihood of the latter, we employed a global tide model that includes the effects of baroclinicity, self-attraction, loading, and topographically induced dissipation (Arbic et al., 2004). We adapted this model to the simulation of tsunamis and compared the results with the MOST model. At present, it seems that none of these factors alter the model solution to first order. Instead, a more complex source mechanism is probably needed to explain the features of the tsunami seen in altimetry.

At this writing, the seismology community is still discussing the nature of the December 26 rupture. The duration, intensity variations, and spatial movement of the locus of radiation of energy of high-frequency elastic P-waves (Peter Shearer, Scripps Institution of Oceanography, personal communication, February 2005) and acoustic T-waves (Catherine deGroot-Hedlin, Institute of Physics and Planetary Geophysics, personal communication, February 2005) both suggest that the rupture process did propagate from south to north over several minutes, sweeping across the whole zone outlined by the aftershocks, with perhaps two bursts of intensity. The more northerly rupture details still elude seismologists and are the basis of an ongoing debate about the magnitude of the event. We hope that further modeling of the altimeter data shown here will shed light on the rupture mechanism.

As this article was going to press, the Sumatra area was struck by another great earthquake. In this event, tide gauge data show that the tsunami was much smaller (only 10 cm at Cocos Island), and the space-time sampling of the satellite ground tracks was not as fortuitously distributed as on December 26. Preliminary analysis suggests that this more recent event will be difficult to measure by satellite altimetry. This inability to detect small events, as much as the lack of real-time reporting with complete spatial and temporal coverage, demonstrates that satellite altimetry probably should not be the first choice of technology for an early detection and warning system.

Acknowledgements

Our analysis of altimeter data is facilitated by "RADS," the Radar Altimeter Database System (for more information about RADS see M. Naeije et al. [2002]). This study was supported and monitored by the Office of Research and Applications of the National Oceanic and Atmospheric Administration (NOAA) under Grant Number 263100-B-4572. The views, opinions, and findings contained in this article are those of the authors and should not be construed as an official National Oceanic and Atmospheric Administration or U.S. Government position, policy, or decision. B.K. Arbic was supported by NSF grant OCE-0327189. This publication is [partially] funded by the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) under NOAA Cooperative Agreement No. NA17RJ1232, Contribution #1133.

References

Arbic, B.K., S.T. Garner, R.W. Hallberg, and H.L. Simmons. 2004. The accuracy of surface elevations in forward global barotropic and baroclinic tide models. *Deep-Sea Research II* 51:3069-3101.

Naeije, M. E. Doornbos, L. Mathers, R. Scharroo, E. Schrama, and P. Visser. 2002. Radar Altimeter Database System: Exploitation and Extension (RADSxx), Final Report. NUSP-2 report 02-06, NUSP-2 project 6.3/IS-66. Space Research Organisation Netherlands (SRON), Utrecht, The Netherlands.

Titov, V.V. and C.E. Synolakis. 1998. Numerical modeling of tidal wave runup. *Journal of Waterways, Ports, Coastal and Ocean Engineering* 124(4):157-171.

Titov, V.V., F.I. González, E.N. Bernard, M.C. Eble, H.O. Mofjeld, J.C. Newman, and A.J. Venturato. 2005. Real-time tsunami forecasting: Challenges and solutions. *Natural Hazards* 35(1):41-58.

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