

Oceanographic Instrument Returns After Two Years

By David Hebert and Tom Rossby

IN EARLY JANUARY 2003, 92 subsurface isopycnal RAFOS floats were loaded on a truck for the start of a long voyage. The floats were delivered to Fort Pierce, Florida and loaded on the R/V *Seward Johnson II* at the Harbor Branch Oceanographic Institution. In March, Drs. Hebert and Rossby started on a month-long expedition from the Canary Islands to deploy these floats south of the Cape Verde Islands. The goal of this project, the Lagrangian Isopycnal Disper-

sion Experiment (LIDEX), funded by the National Science Foundation, is to determine the processes that mix the waters in the ocean horizontally (along constant density surfaces) and at what rate. When these scientists departed from the Canary Islands to deploy the floats, little did they know that one of their floats would eventually be returned by a fisherman.

Mixing in the ocean is separated into two components: diapycnal and isopycnal (i.e., across and along density

surfaces, respectively). In the last few years, significant effort has been made to determine the processes responsible for diapycnal mixing in the ocean's interior, and now these processes are known. However, the stirring and mixing of water along isopycnals is poorly understood, and even the use of the terms "stirring" and "mixing" depends on the horizontal scales that are being resolved. The effective isopycnal eddy diffusivity is generally believed to be scale-dependent (i.e., process-dependent). Models currently used for climate studies cannot resolve the mesoscale eddies and submesoscale mixing processes because the grid size they use in their models is larger than the size of a mesoscale eddy (tens to hundreds of kilometers across). Thus, the fluxes by these eddies must be represented in terms of quantities resolved by the models (i.e., parameterized). To date,

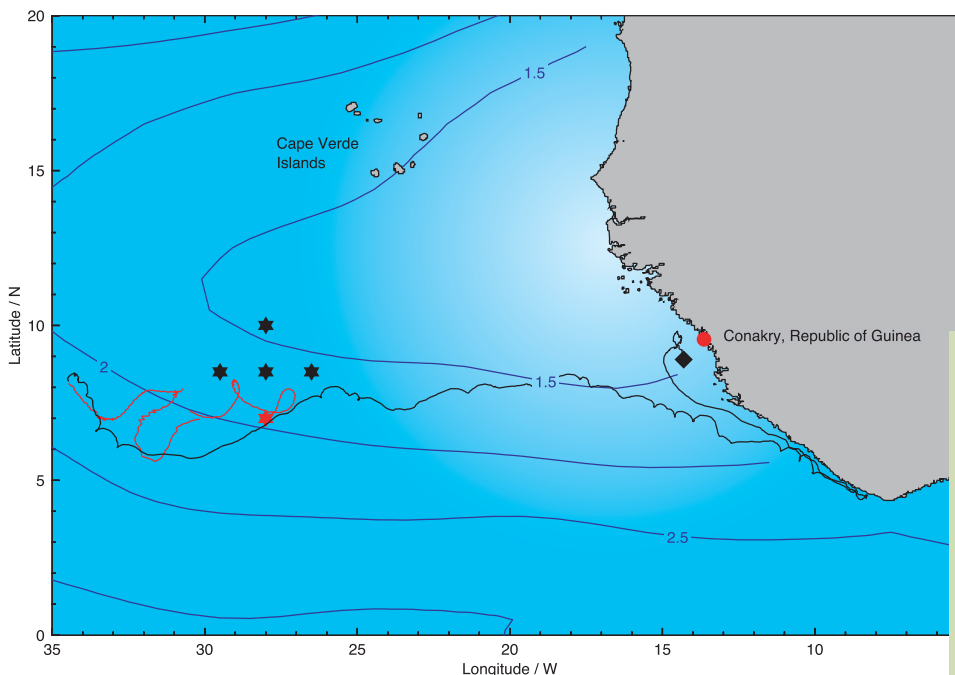


Figure 1. Clusters of isopycnal RAFOS floats were deployed at five locations (stars) and at two depths in March and April 2003. The trajectory of one isopycnal RAFOS float (#329) is shown while underwater (red line) and on the surface (black line), and at deployment location off of northwestern Africa (red star). The blue contours show the mean dissolved oxygen concentration at 500 m depth. This float was recovered (black diamond) by a local fisherman, taken the U.S. Embassy in Guinea (red circle), and returned to the University of Rhode Island.

there is a lack of good field observations to test any eddy flux parameterizations. In LIDEX, the processes and dynamics of dispersion on isopycnal surfaces on scales from several kilometers to hundreds of kilometers will be examined. These data will significantly improve ocean models.

Clusters of isopycnal RAFOS floats were deployed at five locations and on two density surfaces in the low-oxygen tongue off of northwest Africa (Figure 1). The nominal depths of the density surfaces were 500 m and 800 m. The floats were to remain underwater for nearly two years. All of the floats measure pressure and temperature every six hours. The 50 floats on the shallower density surface measured dissolved oxygen using the new Aanderaa Optode sensor. The location of each float is determined every six hours by triangulation using sound sources. The data are sent back to the laboratory through the Argos satellite system (for more information go to <http://noaasis.noaa.gov/ARGOS/> and <http://www.argosinc.com/>) after the float surfaces at the end of its mission. Thus, estimates of the isopycnal fluxes of temperature and oxygen can be made after all the data are received.

The study area off of northwestern Africa (Figure 1) was chosen for two reasons. First, the mean currents in the region are weak. Thus, the floats should



Figure 2. Picture of the RAFOS float in Guinea and the fisherman, Mr. Kamara (center), who found it. The float was in excellent condition.

remain in the region for their two-year mission. Second, the mean dissolved oxygen concentration isopleths (blue contours in Figure 1) are not parallel to the mean isotherms, which are mainly zonal. The low-oxygen tongue off northwestern Africa is due to both isolation of the water from the surface and enhanced productivity and organic regeneration in the coastal upwelling zone off North Africa. It is believed that the low-oxygen water is advected westward from the coastal upwelling sites. With this assumption, and the fact that the dissolved oxygen concentration is increasing to the west, only isopycnal and diapycnal mixing of higher-oxygenated waters can be responsible for the observed dissolved oxygen concentration horizontal structure. This description assumes a mean westward zonal current, which has not been conclusively proven. The direction of the weak circulation in this region is

not known. The mean movement of the floats can answer this question.

One of the floats that was deployed at 7°N, 28°W on April 6, 2003 (red star in Figure 1) surfaced prematurely. This float remained underwater for 420 days before surfacing. While underwater, its position was determined from acoustic beacons (red track) every six hours. The float moved slowly westward while making large looping motions due to eddies that stir the ocean. While at the surface, the location of the float was determined from the Argos satellites (black line in Figure 1). During the 185 days on the ocean surface, surface currents carried the float eastward to Africa, down along the coast, and then back northwards along the coast off of the Republic of Guinea (black diamond). At that location, a local fisherman, Mr. Osman Kamara, found the float (Figure 2). He brought it to Conakry, Guinea (red circle



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Figure 3. Picture of the RAFOS float after its return to University of Rhode Island to Professors Hebert and Rossby.

in Figure 1), the country's capital.

Although the actual recovery of the floats is not critical or expected, it is often useful to see how well the floats survive after being underwater for long periods. Thus, contact information is included within each float. Mr. Kamara contacted Dr. Hebert in order to return 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 (Figure 3). 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

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

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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 simulation 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

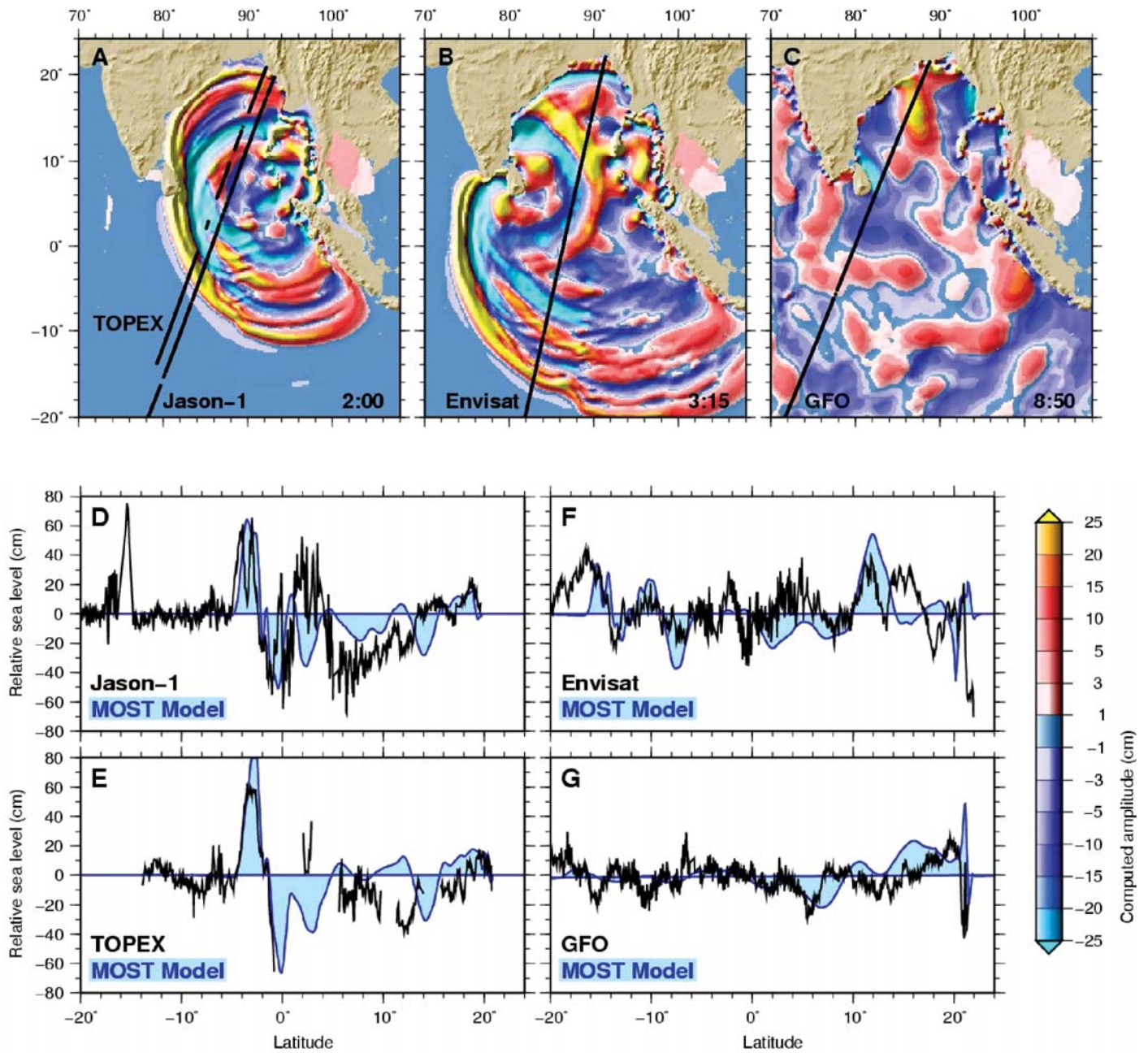



Figure 1. (A to C) Tsunami wave heights generated by the December 26, 2004 Sumatra earthquake, computed by the MOST model at (A) 2:00 hours, (B) 3:15 hours, and (C) 8:50 hours after the earthquake. These times coincide with overflights of the satellites Jason-1 and TOPEX, Envisat, and GFO, respectively.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

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.

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