

Response to Comment on "The Great Sumatra-Andaman Earthquake of 26 December 2004"

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We support the revised estimate of tsunami source length (~800 km) obtained by Neetu *et al.* Sea-level monitoring with a high sampling rate, good azimuthal coverage, and real-time access, along with detailed bathymetry data around the stations, would improve source region estimation from tsunami arrival times.

Neetu *et al.* (1) estimate that the northern end of the tsunami source area of the 2004 Sumatra-Andaman earthquake extended to around 11°N, rather than our estimate of 9°N to 10°N (2). Neetu *et al.* found that the tide-gauge record at Port Blair, which had constrained the northern end of the source area in (2), had a clock error of about 46 min and a data gap, and they excluded that station from their reanalysis. They instead used a tsunami arrival time from Paradip, India, to make the

new estimate. This appears to be an improved result.

It is not surprising that the new set of data provides a different result, although Neetu *et al.* used basically the same method and bathymetry data as we did for the back-projection of the tsunami arrival times. At the time of writing, we were not aware of the large clock error at Port Blair; we relied on the arrival time as reported by the Department of Ocean Development of India (3). The Port Blair tide-gauge record may contain additional complexity in that it may have recorded slow slip prior to the tsunami arrival (4). The back-projection method for tsunami source area estimation works best for stations outside the source area; hence, we fully support Neetu *et al.*'s selection of data set, i.e., the exclusion of Port Blair and the addition of Paradip.

We note that it is important to allow for finite slip duration and rupture extent for an earthquake as large as the 2004 event. Thus, the rupture likely extended somewhat north of 11°N. The seismic rupture models in Ammon *et al.* (5) indicate diminishing slip north of 10°N, so there is compatibility between the seismic and tsunami observations. There remain inconsistencies in the amount of slip inferred from seismology and geodesy in the north, with geodetic indications favoring more slip than in the seismic models. This may have been released over a longer time scale than the 10-min duration of the main seismic rupture. Modeling of satellite altimetry

observations favors additional slip 37 to 50 min after the main shock began (2, 6), but this has not yet been resolved in seismic recordings.

We would also like to point out that tsunami travel times are affected considerably by shallow bathymetry near tide-gauge stations. For a water depth of 10 m, the tsunami speed is about 10 m/s. If such a shallow region extends for 3 km, for example, it would take a tsunami 5 min to travel across that region. Both Lay *et al.* and Neetu *et al.* used ETOPO2, gridded bathymetry data (at a 2' or about 3.7-km interval) derived from satellite altimetry observations combined with shipboard echo-sounding measurements (7). These data are accurate for deep-ocean regions with little sediment, but shallow bathymetry is not always accurate enough to be used for robust tsunami computations. More detailed nearshore bathymetry data will improve the accuracy of back-projection of tsunami travel times.

Sea-level monitoring, both on coasts and offshore, with high sampling rate, good azimuthal coverage, and real-time access are needed for better estimation of tsunami source extent. Many coastal tide-gauge data, including those in India, are in analog form with slow paper speed. For tsunami recording, the sampling interval should be 1 min or less, both for accurate measurement of arrival times and for waveform modeling. Global Sea Level Observation System (8) data and some Australian tide-gauge data are recorded in digital form and are available in real time through Web sites. Such open sharing of data has advanced seismology considerably in the past several decades and would also benefit tsunami research.

References and Notes

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