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Author Information

G. Robert Brakenridge, Dartmouth Flood Observatory, Departments of Geography and Earth Sciences, Dartmouth College, Hanover, N.H.; Son V. Nghiem, Jet Propulsion Laboratory, California Institute of Technology, Pasadena; Elaine Anderson, Dartmouth Flood Observatory, Departments of Geography and Earth Sciences, Dartmouth College, Hanover, N.H.; and Steven Chien, Jet Propulsion Laboratory, California Institute of Technology, Pasadena

For additional information, contact G. R. Brakenridge, E-mail: Robert.Brakenridge@Dartmouth.edu.

A Strategy to Rapidly Determine the Magnitude of Great Earthquakes

PAGES 185, 189

In the initial hours following the origin of the Sumatra-Andaman Islands earthquake at 0058:53 GMT on 26 December 2004, the event was widely reported as having a magnitude of about 8. Thus, its potential for generating a damaging teletsunami (ocean-crossing tsunami) was considered minimal.

The event's size later was shown to be approximately 10 times larger, but only after more than four and a half hours had passed, when a moment estimate based on 2.5 hours of data became available from Harvard University's Centroid-Moment Tensor (CMT) Project (M. Nettles and G. Ekstrom, Quick CMT of the 2004 Sumatra-Andaman Islands earthquake, Seismoware FID: BR345, e-mailed announcement, 26 December 2004). This estimate placed its magnitude at $M_w \approx 9.0$, in the range capable of generating a damaging teletsunami. Actually, the earthquake had caused a teletsunami, one that by that time had already killed more than a hundred thousand people. The magnitude estimate has been subsequently revised to at least 9.3 (Stein and Okal, http://www.earth.northwestern.edu/people/~seth/research/sumatra.html), with the exact magnitude of the event likely to be a subject of further research in the coming years.

Kerr's [2005] account of difficulties that seismologists encountered in those first hours is gripping—and damning! Seismologists couldn't get right the magnitude of the most important earthquake to occur in over 40 years. This is serious criticism, and seismologists everywhere should be outraged. But more important, seismologists should start thinking about how to get it right the next time.

As shown here, a reliable magnitude estimate—one that identifies the Sumatra–Andaman Islands earthquake as capable of causing a damaging teletsunami—can be achieved using only data collected within one half hour of its origin, and using only a magnitude-based (as contrasted to a moment-based) approach. Had such a determination been made in the first hour after the event's origin, it could have been used to issue a timely preliminary alert.

The size of an earthquake can be objectively quantified by its seismic moment, m_0, (the product of fault area, average slip, and the rigidity of the surrounding rock), or, equivalently, the moment magnitude, M_w, a quantity directly computed from moment using the standard formula $M_w = 2 \log 10(m_0)/3-10.73$.

Moment estimation is based on laborious, wiggle-for-wiggle matching of observed and predicted seismograms. Routine magnitude determination techniques use only the peak amplitude of the observed seismograms, and produce quicker results. They are widely used, even though they have a tendency to underestimate the size of the very largest earthquakes (a fact well known amongst seismologists since the 1970s) [*Aki,* 1972; *Geller,* 1976]. This magnitude underestimation problem arises from the fact that the slip that occurs on a long fault is not instantaneous. Slip on a thousand-kilometer-long fault, such as that of the Sumatra-Andaman Islands earthquake, occurs over about 500 s, because the rupture front propagates at a speed of about 2 km/s from one end of the fault to the other. Consequently, the seismic waves that radiate from the fault are systematically deficient in energy at periods shorter than this characteristic timescale.

Routine techniques typically are optimized for estimating magnitudes of small earthquakes. That is because earthquakes with magnitude 6 or 7 occur many times each year, and everyone wants to know their magnitude. These routine methods use seismic waves with periods in the 1–20 s range—much less than 500 s—because the signal-to-noise ratio is highest in that band.

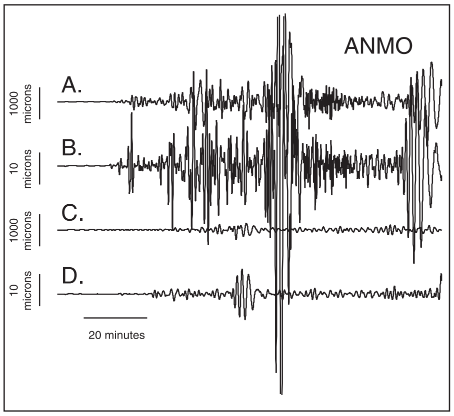

Fig. 1. Vertical displacement seismograms, band-pass filtered between periods of 50 and 200 s, for (a) the moment magnitude $M_w = 9.0$ great Sumatra–Andaman Islands earthquake, (b) a nearby $M_w = 7.2$ event occurring on 11 November 2002, (c) the $M_w = 8.1$ 2004 Macquarie Island earthquake, and (d) a nearby $M_w = 6.7$ event occurring on 20 March 1998. All moment magnitudes are from the Harvard University Centroid Moment Tensor catalogue.

Consequently, routine magnitude estimation procedures have a systematic downward bias when applied to the rare magnitude 9 or larger event. The upper magnitude limit of these techniques can be extended by attempting to correct for the bias [*Sipkin,* 2003]. For very large earthquakes, longer periods must be used in the magnitude estimation procedure. However, the longer the period, the more data that must be collected before a magnitude estimate can be made, leading to a delay in issuing a public announcement of a very large earthquake's magnitude.

That the Sumatra–Andaman Islands earthquake had a magnitude much greater than 8.0 is apparent even at the 50–200 s period band. As an example, the vertical ground displacement of this earthquake is compared with the smaller, magnitude $M_w = 8.1$ Macquarie Island earthquake of 23 December 2004. Both earthquakes were observed at station ANMO (Albuquerque, New Mexico) (Figure 1).

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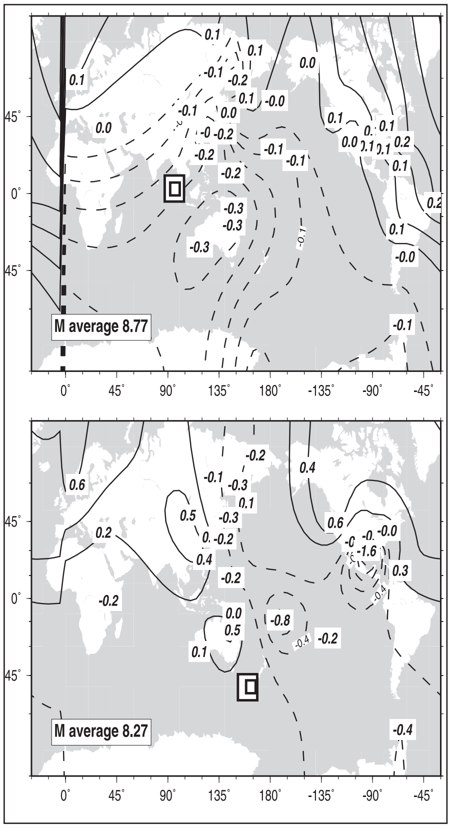

Fig. 2. Map of global distribution of magnitude residuals for the (top) Sumatra–Andaman Islands and (bottom) Macquarie Island earthquakes. Numbers indicate the deviation of the individual station magnitudes from the overall mean. The location of the candidate event and reference event are indicated by large and small squares, respectively. Station magnitudes for the Macquarie Island event show the greater scatter, possibly due to its strike-slip mechanism, which caused a greater geographic variability of displacement amplitude.

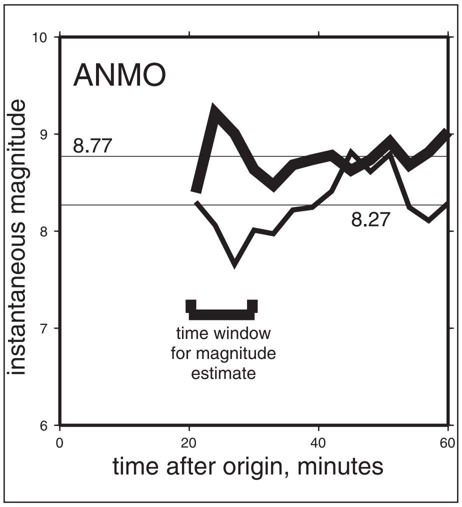

Fig. 3. Instantaneous magnitude for the Sumatra (bold curve) and Macquarie Island (thin curve) earthquakes observed at the station ANMO located in Albuquerque, New Mexico. Estimated are based on the logarithm of the ratio of root-mean-square amplitudes of the candidate and reference events, calculated in 3-min time windows. The values scatter around the overall averages of 8.77 for Sumatra and 8.27 for Macquarie Island, respectively (horizontal lines).

The displacement of the Sumatra-Andaman Islands earthquake is about 10 times larger than that of the Macquarie Island earthquake, even though two events are roughly the same distance from ANMO. Because magnitude is proportional to the $\log_{10}$ of displacement, the factor of 10 difference in displacement implies that the Sumatra earthquake is about 1 magnitude unit larger than the Macquarie Island (thus M_w is on the order of 9.1).

Furthermore, the Sumatra-Andaman Islands earthquake has a displacement at ANMO that is roughly 50 times larger than that of the 2 November 2002 magnitude $M_w = 7.2$ earthquake that occurred in roughly the same region. Given the logarithmic relationship between displacement and magnitude, the magnitude difference between these events would be expected to be $\log_{10}(50) = 1.7$, and thus the magnitude of the Sumatra-Andaman Islands earthquake would be expected to be about $M_w \approx 8.9$. These two rough estimates, $M_w = 9.1$ and $M_w = 8.9$ are both lower than Stein and Okal's value of $M_w = 9.3$. But they clearly show that the Sumatra-Andaman Island earthquake is much larger than a magnitude 8, and that a magnitude estimate of about 9 can be easily and rapidly made.

The above examples suggest an approach to rapidly determine the magnitude of great earthquakes: First, determine the location of a candidate earthquake *C* using standard means (e.g., Geiger's method) and then systematically compare the long-period (e.g., 50–200 s) displacement with that of a reference event *R* (located in the same general geographic region as *C*, and observed on the same seismometer). A station magnitude, M^s, is then estimated as $M^s_C = M_R + \log_{10}(r^s)$, where r^s is some measure of the ratio of displacement amplitudes at stations. An overall magnitude is then estimated from an average of all available station magnitudes. The choice here of the 50–200 s period band is somewhat arbitrary, but trades off data collection time with the tendency to underestimate the magnitude of the very largest events (downward bias starts at about magnitude 8.6 in this case).

Thus, this method is designed primarily to evaluate if the magnitude of the candidate earthquake is at least 8.6, which is large enough to cause a damaging teletsunami. That is, after all, the question that needed to be answered on the morning of 26 December 2004.

In the cases examined here, an actual, previously-occuring earthquake is used as the calibration event, selected as the nearest magnitude ~7 event for which data are available from the Incorporated Research Institutions for Seismology (IRIS) Data Management System. An alternative approach that has not been explored here would be to use synthetic seismograms, either drawn from a database of previously computed examples or calculated on the fly. Of course, computation of synthetic seismograms on the fly, once pursued to its extreme, just reinvents the moment-estimation method.

Ideally, the candidate and reference events should be co-located. However, events separated by up to a few hundred kilometers will suffice, given the long periods that are used. Events should also have similar focal mechanisms. In practice, the range of plausible focal mechanisms for a great earthquake in a particular tectonic setting is limited (e.g., most great subduction-zone events are low-angle thrusts), so similarity of focal mechanisms requirement is not much of a problem, either.

The purpose of the reference event is twofold: First, it provides a way to normalize the amplitudes of the many distinct seismic phases (e.g., *PKP*, *P*, *SS*, *R*, *G*, etc.) that contribute to the seismogram, and to correct for the decrease in amplitude with distance. Second, it provides a readily understandable standard by which a decision maker can judge the reliability of the magnitude estimate. The most compelling check on the validity of the output of an automated magnitude determination system should be the examination of the actual ground displacements and the verification that they are in the size range expected for an earthquake of that magnitude.

This method is applied to estimating the magnitude of both the 2004 Sumatra-Andaman Island and 2004 Macquarie Island earthquakes (magnitudes 9.0 and 8.1, respectively). High-quality, broadband seismic data from a representative selection of 25 globally distributed IRIS Global Seismic Network stations are used. Only data starting at the onset of the first arriving wave (*P* or *PKP*) and ending 30 min after the origin are used. Station magnitudes (Figure 2), computed from amplitude ratios (Figure 3), have means of 8.77±0.02 (1σ) and 8.27±0.09 (1σ) for Sumatra and Macquarie Island, respectively.

Thus, the method correctly singles out the Sumatra-Andaman Island earthquake as having the potential to generate a damaging teletsunami. The choice of a 30-min window is arbitrary, but trades off the interest in using sufficient data (that is, including at least three or four oscillations of 200-s period at every station) with being able to complete the estimate in a timely fashion, so as to allow the possibility of issuing an early alert.

Since the Sumatra-Andaman Island earthquake, and especially since U.S. President George W. Bush's 10 January 2005 announcement of the United States' intent to participate in an expanded global tsunami warning system, attention has been focused on the technical and human resources needed to make such a system reliable. Seismic methods have a critical place within such a system. They must, however, be optimized toward answering the right questions in the shortest amount of time. They must be explicitly designed to work well for the largest earthquakes, and must be easily verifiable by decision makers responsible for issuing alerts.

Acknowledgments

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Author Information

William Menke, Lamont-Doherty Earth Observatory of Columbia University, Palisades, N.Y.; and Vadim Levin, Rutgers–The State University of New Jersey, New Brunswick

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NEWS

NASA Earth Science Budget and Plans Criticized

PAGE 186

A new report by the U.S. National Research Council of the National Academy of Sciences sharply criticizes NASA's budget and commitment to the Earth sciences, and states that "today the nation's Earth observation program is at risk."

The report, issued on 27 April, states that "recent changes in federal support for Earth observation programs are alarming. At NASA, the vitality of Earth science and application programs has been placed at substantial risk by a rapidly shrinking budget that no longer supports already-approved missions and programs of high scientific and societal relevance."

The report continues, "Opportunities to discover new knowledge about Earth are diminished as mission after mission is canceled, descoped, or delayed because of budget cutbacks, which appear to be largely the result of new obligations to support flight programs that are part of the Administration's vision for space exploration."

U.S. President George W. Bush's 14 January 2004 announcement of a Vision for Space Exploration has prompted an organizational restructuring within NASA. The Bush Administration's fiscal year 2006 budget request for NASA calls for $1.37 billion for Earth science funding. This represents an 8% decrease from the 2005 budget of $1.49 billion, and a 14% decrease from the 2004 budget's forecast of $1.6 billion for 2006 funding. The 2006 budget request includes NASA Earth science programs within an "Earth-Sun System" theme in the agency's Science Mission Directorate.

"Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation," issued by a committee of the National Research Council's (NRC) Space Studies Board, is an interim report of a survey to identify high-priority Earth science and applications from space over the next decade. NRC anticipates completing the decadal survey in 2006. The interim report was requested by study sponsors and congressional staff to provide an indication of urgent issues that require attention.

According to the report, six NASA missions recently have been delayed, descoped, or cancelled. The committee called for two missions to proceed immediately: the delayed Global Precipitation Measurement (GPM) mission, and the cancelled Atmospheric Soundings from Geostationary Orbit mission that includes the Geostationary Imaging Fourier Transform Spectrometer (GIFTS) to measure atmospheric temperature and water vapor.

The committee recommended "urgent" reconsideration of three other missions—Ocean Vector Winds, Landsat Data Continuity, and Glory—and called for evaluating the plans to transfer mission capabilities to the U.S. National Oceanic and Atmospheric Administration's (NOAA) and the Defense Department's National Polar-orbiting Operational Environmental Satellite System (NPOESS). The committee also called for developing a technology base for exploratory Earth Observation Systems, and for continued support for NASA's Earth System Science Pathfinders (ESSP) research program of small, experimental satellites.

The report noted that the change in the agency's priorities "jeopardizes NASA's ability to fulfill its obligations in other important presidential initiatives, such as the Climate Change Research Initiative and the subsequent Climate Change Science Program. It also calls into question future U.S. leadership in the Global Earth Observing System of Systems."

Hearing Airs Issues

Alphonso Diaz, NASA Associate Administrator for the Science Mission Directorate, appeared before a 28 April hearing by the U.S. House of Representatives' Science Committee in part to respond to the NRC report.

He said NASA's fiscal year 2006 budget "supports a highly effective program of research and development of Earth sciences, and plans are now being formulated to continue this significant effort into the future." Diaz added that the agency's budget "should be interpreted as a sign of the administration's interest in accelerating the evolution of Earth science to a national program, not as a retreat from our NASA commitment to Earth science."

He noted that 16 Earth science missions presently are in orbit and there are plans to

Fig. 1. (left to right) AGU President-Elect Timothy Killeen, AGU Past President Sean Solomon, and AGU Past President Marcia McNutt presented testimony at the U.S. House of Representatives' Science Committee hearing. Photo by Jonathan Lifland/AGU.