Great Earthquakes and Global Seismic Networks

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INTRODUCTION

Seismologists often jest that “the best way to stop earthquakes is to deploy seismic stations.” The laborious effort to install seismometers to record signals from earthquakes or to pursue targeted investigations of Earth’s structure is sometimes confounded by the vagaries of earthquake occurrence, which is decidedly nonuniform in space and time. Of course, this often proves to be more of an anxiety than a reality, and most efforts, especially those employing multiyear installations, succeed in gathering valuable seismic data. One of the most gratifying examples of success is provided by the deployment of the Incorporated Research Institutions for Seismology–National Science Foundation–U.S. Geological Survey (IRIS-NSF-USGS) Global Seismographic Network (GSN) in parallel with numerous international deployments of broadband seismometers in the Federation of Digital Seismic Networks (FDSN). Between about 1982 and 2004, global installations of high-quality broadband digital seismometers proliferated, replacing the obsolete analog systems of the World-Wide Standardized Seismograph Network and upgrading sparse institutional observatories and first-generation digital networks. While deployments of important additional stations continue, by 2004 the GSN had achieved its basic design goals: openly available continuous broadband data from roughly 130 stations providing real-time global coverage and large dynamic range (Butler *et al.* 2004). Then the 26 December 2004 great Sumatra-Andaman earthquake (M_w 9.2) occurred—the first event to exceed magnitude 9 since the 1964 Alaska earthquake. The GSN and FDSN provided unprecedented global seismic recordings for this event and enabled more detailed seismological investigation than was possible for any prior event of such size (*e.g.*, Lay *et al.* 2005; Bilek *et al.* 2007). Those same globally distributed seismic stations have gathered data from a substantial number of great earthquakes; from 2001 to 2010, there have been 18 events with $M_S \geq 8$ and 13 events with $M_w \geq 8$, whereas over the previous century an average of only six or seven events with $M \geq 8$ occurred per decade (for simplicity,

we use “ M ” to represent a mixture of M_S and M_W values). In the time interval of construction of the GSN (1986–2004), the number of global events/decade with $M_w \geq 7.5$ has more than doubled and has increased by a factor of 6.5 for $M_w \geq 8.0$. So, perhaps the new seismic adage should be “if you build it, they will come.” Long-term maintenance and operation of the high-quality global digital seismic networks will certainly provide invaluable scientific data far into the future.

GLOBAL SEISMIC INSTRUMENTATION

Global seismograph observatories with fairly standardized seismometer designs began to be deployed early in the 20th century. Over several decades modest “global” networks of 20–30 stations were deployed in the Milne networks supported by the British Association for the Advancement of Science (Adams 1989) and at Jesuit observatories (Udias and Stauder 1996), along with a handful of additional national efforts, primarily at universities and other research center observatories (Figure 1). Prompted by the initiation of underground nuclear testing in 1957, a significant expansion of the global seismic station coverage occurred when the World-Wide Standardized Seismograph Network (WWSSN) was constructed from 1960 to 1966 (Oliver and Murphy 1971). In addition to establishing standardized observatory sensors and recording equipment, the WWSSN pioneered a system for global data exchange by transferring all seismograms to microfilm. Full or partial collections of the WWSSN archive were established at the USGS, Lamont, Caltech, and other research centers. While primitive by modern data center standards, the relatively easy access to data from the analog WWSSN network provided critical observations that contributed to the plate tectonics revolution of the 1960s (*e.g.*, Isacks *et al.* 1968) and the advent of quantitative ground motion modeling that commenced in earnest in the 1970s.

As technology advanced, digital seismic recording and broadband sensors became the standard for global seismograph installations. The French GEOSCOPE program of the Institut de Physique du Globe de Paris began its deployment of broadband digital seismic stations in 1982 (Roult *et al.* 2010), and from 1986 onward the IRIS-NSF-USGS Global Seismic Network (GSN) built upon earlier digital seismic networks such as the Seismic Research Observatories (SRO), Auxiliary Seismic Research Observatories (ASRO), digital WWSSN conversions, and International Deployment of Accelerometers (IDA)

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▲ **Figure 1.** Global seismic networks with relatively standardized instrumentation deployed from 1900 to 2010, which have provided seismic recordings for research on earthquakes and Earth structure (Simpson 2002).

networks (Hutt *et al.* 2002). In concert, many parallel efforts deploying permanent broadband digital seismographs for global earthquake observations joined together in 1986 to form the Federation of Digital Seismic Networks (FDSN; <http://www.fdsn.org/historical/>). Especially in areas of high earthquake hazard, there has also been a rapidly expanding incorporation of modern digital broadband systems in regional earthquake monitoring networks. The substantial increase in global seismographic observatories is interesting to juxtapose against the corresponding 110 years of global great earthquake activity.

GREAT AND DEADLY EARTHQUAKE HISTORY

Most practicing seismologists today were not active in the field back in 1964 (many were not even born), and from about 1970 to 2000 there were not very many great earthquakes for seismologists to investigate (Figure 2). However, during the past decade, as the GSN approached its design goal, the situation changed. Numerous great earthquakes have occurred and have produced ground motions that truly exercised the bandwidth and dynamic range of modern recording systems. Figure 2 indicates the large fluctuations in great earthquake

activity throughout the age of seismic instrumentation, but those seismologists attentive to the occurrence of great earthquakes cannot help but have noticed the increased rate over the past decade relative to the prior few decades. The relative paucity of great earthquakes between the 1964 Alaska and the 2004 Sumatra-Andaman earthquakes corresponds to the time interval between completion of the WWSSN and build-up of the GSN (Figure 3). Activity was relatively low while the WWSSN declined and the number of new GSN and FDSN stations was low. When the 2004 Sumatra-Andaman event struck, hundreds of broadband digital stations were operating, and for the recent February 27, 2010 great Chile earthquake ($M_w = 8.8$), data from more than 1,200 global broadband stations were readily retrievable within a few hours after the event through the IRIS Data Management Center (<http://www.iris.edu/data/>) and other network data-center portals. The near real-time sharing of so much data is a major step forward from the film chip exchange pioneered by the WWSSN and a significant asset for global earthquake monitoring and international science. Figure 4 illustrates the quality of data recorded for some of the great earthquakes of the past few years; corresponding motions on WWSSN analog recordings would

▲ **Figure 2.** Time line of great (seismic magnitude ≥ 8.0) earthquakes from 1900 to 2010 from the PAGER-CAT of Allen *et al.* (2009) updated using the Harvard and Global Centroid Moment Tensor catalogs through the 2010 Chile (M_w 8.8) event. Note the relative dearth of great events from 1970 to 2000.

▲ **Figure 3.** Time line of deployment of recent major global seismic networks relative to the largest global earthquakes from 1900 to 2010. The Milne/Jesuit global networks information is approximate. Note the relative surge of great earthquakes during the last decade apparent here for magnitudes ≥ 8.0 .

have been several meters in amplitude with all details off-scale. In addition, the WWSSN response was severely limited in bandwidth, especially in the ultra-long-period range that is so important for full characterization of great earthquakes. This is a tremendous advance from the data availability of the preceding century of seismic observations of great earthquakes.

The increase in global high-magnitude seismic activity over the past few decades is intriguing. In response to the inevitable questions about increasing earthquake frequency following any clustering of newsworthy events, seismologists have traditionally insisted that global averages of seismic activity remain stable when considered over sufficient space and time intervals. Any consideration of long-term seismicity behavior is complicated by non-uniformity of catalogs, magnitude measures, and numbers of stations operating over time. Nonetheless, it is interesting that a total of 18 shallow earthquakes with $M_S \geq 8.0$ occurred globally during 2001–2010, about triple the average number (6 ± 3) per decade over the prior century, as tabulated in the catalog of Pacheco and Sykes (1992). Although

it is preferable to use seismic moment magnitude (M_w) when possible, for events prior to 1970 there are very few direct determinations of seismic moment by procedures comparable to those for recent events. Several researchers have attempted to approximate seismic moments for early events based on various estimates of event size (*e.g.*, Pacheco and Sykes 1992; Engdahl and Villaseñor 2002), allowing comparisons with the trend found using M_S to be performed.

The PAGER-CAT catalog of Allen *et al.* (2009) presents a composite list of events with “Preferred Magnitudes” taken from scaled M_w estimates based on M_S or M_B or information about historical rupture dimensions for earlier events (largely drawn from the catalogs of Pacheco and Sykes 1992 and Engdahl and Villaseñor 2002), and direct M_w measurements from Harvard and Global centroid-moment-tensor (CMT) inversions for recent events. Figure 5 indicates that for PAGER-CAT Preferred Magnitudes (M), the occurrence of great earthquakes over the past century has indeed been variable on the decadal timescale. The trend is not as pronounced

as for M_S , but the number of $M \geq 8.0$ events in the past decade (13) is about a factor of two higher than the average number per decade during the preceding 10 decades (6.8 ± 2.3).

Figure 6 shows M versus time for events with $M \geq 7.5$ from 1900 to 2010, along with running estimates of the number of events per 10-year interval for $M \geq 7.5$, 7.7, and 8.0. The most recent decade of activity includes a higher total number of events per decade for each magnitude threshold than experienced in any 10-year interval throughout the prior century. The recent increase is more prominent as the magnitude threshold is increased from 7.5 to 8.0, but vanishes if one uses a lower threshold such as $M \geq 7.0$.

While the recent activity levels relative to pre-1970 are subject to ambiguities associated with the catalog magnitudes, the increase in global seismicity that occurred during the deployment of the GSN (1986–2004) is robust, as it involves only rigorous M_w determinations and a complete global catalog. The large number of great events during the past six years has produced a steeper overall slope of cumulative seismic moment versus time relative to any comparable time interval during the preceding century that does not include a giant event (Figure 7).

We leave it for other investigations to explore any statistical significance of the recent vigorous great earthquake activity (*e.g.*, Brodsky 2009) and attendant analysis of effects of magnitude threshold and clustering of events. The point in this article is that the establishment of extensive global digital seismographic networks, many of which have open data access, came about in time to capture substantial numbers of seismic recordings of the recent surge of great events (and, of course, thousands upon thousands of smaller events as well).

▲ **Figure 4.** Broadband vertical ground displacement records from the STS-2 instruments at stations POHA and ABPO for the four largest earthquakes of the past decade. The upper three traces are for events along Sumatra in 2004, 2005, and 2007, while the lower trace is for the 2010 Chile earthquake. The M_w of each event is indicated after the date. Amplitudes were adjusted to equalize for effects of source depth and 360-s period Rayleigh wave radiation pattern. All the signals were recorded about 100° distance from the sources. These signals would have all been far off-scale for almost all earlier generations of analog recording systems.

▲ **Figure 5.** Number of events with $M \geq 8.0$ per decade interval from 1901 to 2010 in the PAGER-CAT (Allen *et al.* 2002) updated with CMT M_w values to 2010. The most recent decade had 13 $M_w \geq 8.0$ events, whereas the average number per decade in the preceding 10 decades was 6.8 ± 2.3 . Figure 6 shows running mean number of events per decade for various size thresholds and annual sampling, for which this is just a single realization.

▲ **Figure 6.** Top panel: Timeline of $M \geq 7.5$ events from 1900 to 2010 based on the USGS PAGER-CAT (Allen *et al.* 2002) updated to include events through early 2010. Lower three panels: Running average number of events per 10-year interval, centered on each point, for PAGER catalog preferred magnitudes (M) ≥ 7.5 (upper), 7.7 (middle), and 8.0 (lower). The recent decade has experienced numbers of large and great earthquakes exceeding those of early times in the seismological record. Note the dramatic increase in activity from a dramatic lull in the mid-1980s to a substantially active present.

SCIENTIFIC OPPORTUNITY AND LONG-TERM COMMITMENT

With more great earthquakes in the last decade than in the previous two decades and an increase in the number of high dynamic range broadband seismographic stations to more than 1,000 that contribute openly accessible seismograms, seismologists have been provided with a substantial collection of ground motions for investigations of large earthquake rupture processes as well as Earth structure. The global seismological networks constitute a multi-application tool for monitoring Earth processes that is central to addressing major scientific challenges in Earth sciences (Forsyth *et al.* 2009).

The situation would be different had the international seismological communities not undertaken the global broadband digital seismic network deployments and not established procedures to facilitate the open distribution of data. The importance of the observations collected by these networks to basic research on earthquake processes is self-evident. The societal importance of recording and archiving signals from future destructive earthquakes is reinforced by considering Figure 8, which summarizes the loss of life from earthquakes since 1900 tabulated in the PAGER-CAT (Allen *et al.* 2009). The perceptible increase in occurrence of deadly earthquakes that is accompanying growth of human population in earthquake-prone regions is clear (Hough and Bilham 2006). Global seis-

▲ **Figure 7.** Plot of cumulative seismic moment of global seismicity constructed using PAGER-CAT events with $M \geq 7$, which dominate this type of plot. Slopes of robust line fits for the intervals shown are listed in the table in the upper left and the linear fits are shown with dotted lines (slightly extended to make them easier to see). The cumulative-moment growth rate was similar before and after the cluster of events from 1952 to 1965. Moment accumulation since 2004 has been nearly double the rate of earlier roughly uniform-rate time intervals.

mic observations, openly available in real time, can facilitate important improvements in tsunami warning systems (*e.g.*, Morrissey 2007; Leith 2008) in post-earthquake assessments of faulting and population exposure to shaking (*e.g.*, Earle and Wald 2007; Allen *et al.* 2009).

Intermittently, a question asked of seismologists is, “Why keep operating global seismic networks, don’t you just see similar signals again and again?” To which the best answer may be, “Isn’t it unthinkable to have future great earthquakes that we cannot quantify and understand as well as the events that are occurring now?” Federal and international programs need to sustain their commitment to operation and maintenance of these critical Earth monitoring facilities, and seismologists must commit to understanding all that we can from the signals they record. Seismic networks play a central role in earthquake and volcano monitoring efforts, make critical contributions to detecting underground nuclear explosions, and have provided valuable information on glacier and ice sheet dynamics. Many interesting aspects of lithospheric interaction (*e.g.*, subduction) and the corresponding earthquake processes require long-term collection of seismological (and geodetic) observations (*e.g.*, Christensen and Ruff 1988; Ekström 2007; Blewitt 2007; Ammon *et al.* 2008; Furlong *et al.* 2009; Ogata *et al.* 2010;

Lay *et al.* 2010). One of our responsibilities to future geoscientists and to society is to do our best to provide the highest quality observations that we can so that those in the future can see deeper into the processes than we are able to today because of the limitations of our current short time interval of observations. ☒

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▲ **Figure 8.** Estimated loss of life from individual deadly earthquakes from 1900 to 2010. Sources are the PAGER-CAT (Allen *et al.* 2002) and the many references therein. There are many more events that have claimed fewer than 1,000 lives.

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