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The surge of great earthquakes from 2004 to 2014

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ABSTRACT

During the decade from mid-2004 to mid-2014 18 great ($M_w \geq 8.0$) earthquakes occurred globally (∼1.8 per year), compared to 71 from 1900 to mid-2004 (∼0.68 per year), yielding a short-term rate increase of 265%. Six events had $M_w \geq 8.5$, larger than any prior event since the 1965 Rat Islands earthquake. The December 26, 2004 M_w 9.2 Sumatra earthquake had the longest recorded rupture length of 1300+ km and a rupture duration exceeding 450 s. The largest recorded strike-slip earthquake (M_w 8.7) occurred in the Indo–Australian plate on April 11, 2012. The largest recorded deep focus earthquake (M_w 8.3) occurred under the Sea of Okhotsk on May 24, 2013. While this overall surge of activity has not been demonstrated to be causally linked, regional spatio-temporal clustering is clearly evident for great events along the Sumatra, Kuril and Tonga subduction zones, and longer-range interactions have been established for global seismicity and seismic tremor at lower magnitudes following some of the events. This recent decade of intense great earthquake activity coincided with vastly expanded global networks of seismometers, GPS stations, tsunami gauges, and new satellite imaging capabilities such as InSAR and LandSAT interferometry and gravity measurements by GRACE and GOCE, enabling unprecedented analyses of precursory, co-seismic and post-seismic processes around the subduction zone environments where most of the events occurred. Individual events such as the March 11, 2011, Tohoku, Japan M_w 9.0 earthquake produced more ground motion and tsunami recordings than available for all great earthquakes of the last century collectively. Joint inversion and modeling of the diverse data sets exploit complementary sensitivity of the signals to different aspects of the earthquake processes. Major advances have been achieved in quantifying frictional locking and strain accumulation prior to some great events and in relating it to co-seismic slip heterogeneity. Many surprising aspects of these well-quantified great earthquakes have been manifested, associated with their rupture dimensions, tectonic location, compound faulting, triggering interactions, slow slip and foreshock migration precursors, aftershock complexity, and depth-varying seismic radiation characteristics. Regions with potential for near-future great ruptures include mature seismic gaps along the Mentawai Islands and northern Chile, as well as western North America and the Himalayan front, so more great earthquake activity can certainly be anticipated.

1. Introduction

Plate tectonics causes earthquakes of all sizes, but usually the most significant events in terms of both hazards and tectonic motions are "great" earthquakes, classically defined as those with seismic magnitudes ≥8.0. For the seismic energy-based moment magnitude M_w (Kanamori, 1977) this corresponds to events with seismic moments $M_0 \geq 1.26 \times 10^{21}$ Nm. There is nothing particularly significant about this value in the continuum of earthquake size, but for this study the focus will primarily be on great earthquakes as a convenient threshold for discussion.

Over the time interval of seismological recording and reliable measurement of earthquake size from seismic waves dating from about 1900 to present, there have been about 89 great earthquakes around the world. This number is taken from the U.S. Geological Survey National Earthquake Information Center bulletin (USGS-NEIC: http://earthquake.usgs.gov/earthquakes/map/), which draws upon the PAGER-CAT compilation for events prior to 1973 (Allen et al., 2009). Magnitudes of events early in the 20th century are uncertain due to sparseness of observations, uncertain instrument responses, and variable measurement procedures, whereas the modern events that are discussed here have relatively robustly determined seismic moments and M_w.

Fig. 1 shows locations of great earthquakes around the Pacific and Indian Ocean subduction zones from 1900 to present,

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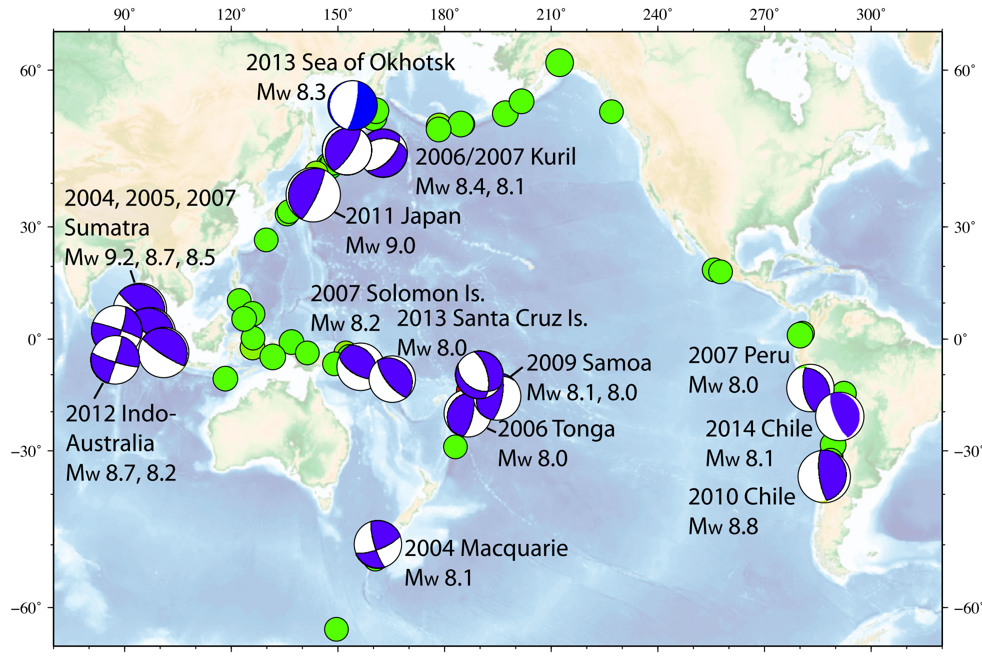

Fig. 1. Locations of 89 great ($M_w \geq 8.0$) earthquakes from 1900–2014 (green circles), with the 18 labeled events from 2004 to 2014 being depicted with lower hemisphere focal mechanisms for the best double-couple geometry of the corresponding global centroid-moment tensor (GCMT) solutions for all except the triggered M_w 8.0 thrust event of the 2009 Samoa Islands doublet (Lay et al., 2010c).

with focal mechanisms included for all recent events from December 2004 to April 2014. The latter are the best-double couple solutions for the corresponding global centroid-moment tensor (GCMT) inversions (http://www.globalcmt.org/CMTsearch.html) for these events with one exception being for a triggered thrust event in Tonga that overlapped the 2009 Samoa normal-faulting earthquake (Lay et al., 2010c). The recent great events have been widespread, occurring in close proximity to subduction zones that have hosted the majority of earlier great events (Fig. 1). 11 of the 18 recent events have been located on interplate megathrust faults, two are normal-faulting events that ruptured near the outer rise in subducting Pacific plate, three are strike-slip events located seaward of a plate boundary, one (May 3, 2006, Tonga) is a 65 km deep intraslab event, and one (May 24, 2013, Sea of Okhotsk) is 610 km deep in the subducted Pacific slab. The megathrust faulting events along Chile, Peru, Kuril Islands, Japan, Sumatra, Solomon Islands and Santa Cruz Islands all struck regions that were recognized as seismic gaps or zones of uncertain earthquake potential to varying degree (e.g., Nishenko, 1991); the other events have far less clear tectonic frameworks for having anticipated the size and style of faulting involved.

The time sequence for global earthquakes with magnitudes greater than 7.5 from 1900 to 2014 is shown in Fig. 2a. The magnitude used here is the PAGER-CAT preferred magnitude (M) for events prior to 1976 and GCMT M_w for subsequent events other than for several preferred results from finite-fault modeling solutions. Ammon et al. (2010) show that the running decadal average of events with magnitudes ≥7.5 (or 8.0, but not for 7.0) is greater for the most recent decade than for any prior decade in the seismological interval from 1900 to present. The interval from 1950 to 1965 experienced 13 great earthquakes, including the 1960 Chile ($M_w \sim 9.5$) and 1964 Alaska ($M_w \sim 9.2$) events, which are the two largest seismologically-recorded events.

This short seismological record appears inadequate for reliably evaluating statistical significance of clustering or interaction of great events, although efforts to do so generally indicate that the data cannot rule out a random Poissonian distribution

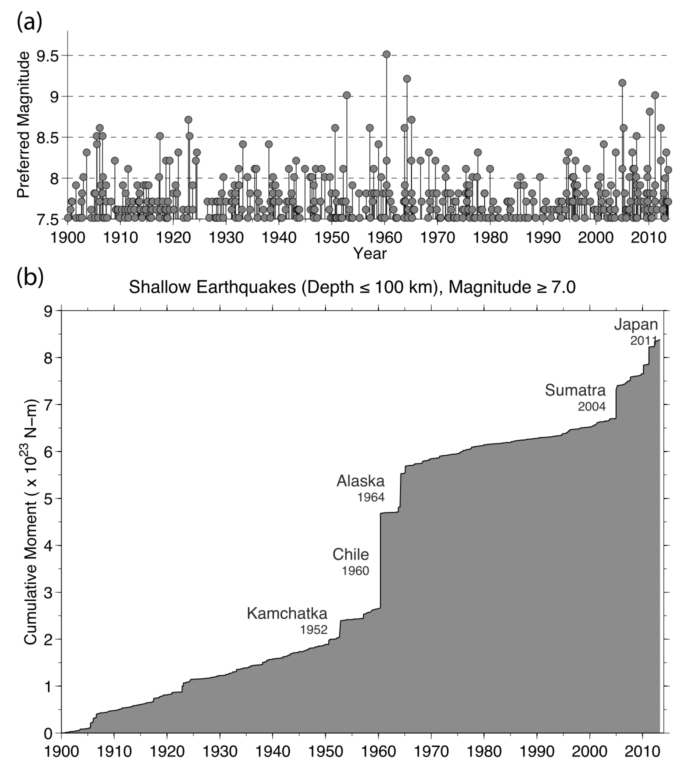

Fig. 2. (a) Time sequence of global large earthquakes with preferred magnitudes, $M \geq 7.5$ from the NEIC-PAGER catalog, for the seismological record from 1900 to 2014. (b) Cumulative seismic moment for earthquakes with hypocentral depths less than 100 km with $M \geq 7.0$ from 1900 to 2014 using moment estimates listed in the USGS NEIC-PAGER catalog. Large increases due to events with $M_w \geq 9.0$ are labeled. Modified from Ammon et al. (2010), courtesy of Charles J. Ammon.

of events, after conventionally defined aftershocks are removed (e.g., Michael, 2011; Daub et al., 2012; Parsons and Geist, 2012; Shearer and Stark, 2012; Ben-Naim et al., 2013), although there