How many great earthquakes should we expect?

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Great earthquakes of magnitude 8.5 or larger occur infrequently. For a nearly 40-y period after the February of 1965 M 8.7 Rat Islands, Alaska earthquake, the world did not experience a single great earthquake; however, in the 7 y since late December of 2004, there have been a barrage of five great earthquakes. These earthquakes include the 2004 M 9.1 Sumatra, Indonesia earthquake; the 2005 M 8.7 Nias, Indonesia earthquake; the 2007 M 8.5 Bengkulu, Indonesia earthquake; the 2010 M 8.8 Maule, Chile earthquake; and the 2011 M 9.0 Tohoku-oki, Japan earthquake. This cluster of great earthquakes seems to signal an anomalous increase in their frequency, but does it really? In their paper, "The global risk of big earthquakes has not recently increased," Shearer and Stark (1) present a quantitative assessment of that perception. Their analysis tests three different attributes of the earthquake catalog against the null hypothesis: That the observed seismicity is a plausible realization of a Poisson process (1). None of the three tests allows the Poisson assumption to be rejected with high confidence, which leads them to the conclusion that the recent spate of large earthquakes is not anomalous (1).

Seismologists know that earthquakes cluster in space and time to some degree. Omori's Law (2) states that the frequency of aftershocks after a large earthquake decays inversely with time, and this law is more than 1 century old. The law by Omori (2) has been used in epidemic-type aftershock sequence models to quantify earthquake clustering locally (3). Earthquakes are thought to interact by static stress triggering (4), in which earthquakes induce a stress change on nearby faults and thereby trigger or suppress other earthquakes, but static stress decays rapidly with distance. Dynamic stress, affected through the transient seismic waves of an earthquake, is known to be capable of triggering small earthquakes at much larger distances (5). For large earthquakes, however, such triggering does not seem particularly strong. A recent study found no short-term change in earthquake probabilities for earthquakes of magnitude 5.0 or larger beyond a distance of several earthquake source dimensions (6).

We have a little more than 1 century of earthquake monitoring for which magnitudes can be instrumentally determined; however, early in the instrumental period, the reliability of magnitudes is suspect because instrumentation in the early 20th

Fig. 1. $M > 7.0$ earthquakes from the Prompt Assessment of Global Earthquakes for Response - Catalog (PAGER-CAT) catalog (12). *Upper* shows seismicity with a cutoff magnitude of 8.5. *Lower* shows the same but with a cutoff magnitude of 7.0. The apparent temporal clustering in *Upper* is less obvious in *Lower*.

century had limited bandwidth and seismographs were sparsely deployed. Considerable uncertainty surrounds the size of some older events (7), and there are behaviors in earthquake catalogs (8) early in the 20th century that suggest biases in magnitudes. Even if the data were perfect, 100 y is a very short time to try to establish an expected rate given the rarity of the largest earthquakes (9). We are left with only a very fuzzy idea of how frequently great earthquakes should be expected, which makes it more difficult to detect an anomalous cluster.

A more subtle effect is cherry picking, which amounts to defining retrospectively the behavior that is considered anomalous. In the first sentence of this article, I cherry picked by defining 8.5 as the threshold magnitude for what should be considered a great earthquake (Fig. 1). The definition is arbitrary. A different definition would have led either to a shorter quiet interval in the case of a lower threshold or a less impressive recent cluster in the case of a higher threshold. In an interesting twist, the work by Shearer and Stark (1) attempts to assess how common unlikely anomalies are found to be present in individual realizations of a Poisson process if they are defined posthoc. They find, for example, that, when anomalous clusters are defined retrospectively, 30% of realizations of a Poissonian earthquake catalog will contain clusters that should occur less than 1% of the time (1). This cautionary exercise has

relevance far beyond earthquake occurrence. The work by Michael (10) independently made the same point and reached the same conclusion: that the recent sequence of earthquakes is consistent with the Poisson assumption. So where does the perception of an anomaly arise?

A contributing factor to the perception of an increase in earthquake rates has to be the coverage and broadcasting of earthquake effects. For instance, 10 y ago, tsunami footage was exceedingly rare. Classic footage of the 1964 Alaska earthquake tsunami in Valdez harbor used to be shown as an example, but the film is so grainy that it is difficult to discern what is happening. That is not the case with the exceptionally clear and harrowing tsunami footage from Japan. Another factor contributing to the perception is that the exposure to earthquakes, and hence, their consequences, is increasing (11). The exposure has at least two aspects. The most obvious aspect is that earthquakes occurring in the wrong place can have catastrophic consequences because of the unfortunate overlay of fragile construction with urbanization in earthquake-prone regions. The 2010 Haiti earthquake killed over 200,000 people, which makes it by far the deadliest natural disaster in the history of the Western hemisphere, but the magnitude of the earthquake, 7.0, was not exceptional. There have been over 1,700 earthquakes that size or larger since 1900 or about one every 4 wk. The other aspect is that globalization has increased the reach of earthquakes. Interruption of technology and automobile manufacturing supply chains after the March of 2011 Tohoku-oki earthquake is one example of the impact. Decisions to turn away from nuclear power, not just in Japan but in such far-flung corners of the world as Germany and Mexico, in the aftermath of the multiple meltdowns at Fukushima Daiichi are another impact.

Where do we go from here? Clearly we need to develop a better understanding of what the Earth is capable of and how frequently large earthquakes occur. Sound application of earthquake statistics is a part of this issue, and a deeper understanding of the earthquake process is another. The March 11 earthquake occurred offshore

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one of the mostly intensely studied subduction zones in the world, but its great size was surprising; the results of underestimating the maximum size of potential earthquakes in the Japan Trench proved lethal. Earthquake scientists everywhere are reappraising their models of earthquake occurrence as a result. A systematic search for traces of past earthquakes and tsunamis worldwide is an obvious and im-

portant endeavor. Another important endeavor is additional development and widespread application of seafloor geodesy to measure crustal strain energy accumulation, which provides the fuel for earthquakes. Such efforts will be time-consuming and expensive, but the scientific and societal payoff should be tremendous.

Because we cannot predict earthquakes in the short term, earthquake science is

something of a waiting game. The work by Shearer and Stark (1) offers some guidance for what it would take to render the recent spate of large earthquake activity significantly anomalous. Three $M \geq 8.5$ earthquakes in the next year would be sufficient, but it is a daunting prospect. In that sense, let us hope that Poissonian statistics prevail.

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