February 2012

The M9.0 Tohoku, Japan Earthquake: Short-Term Changes in Seismic Risk

RMS Special Report

EXECUTIVE SUMMARY

On Friday, March 11, 2011 at 2:46 p.m. local time, a M9.0 earthquake occurred off the coast of Northern Japan, rupturing an area approximately 450 km long and 150 km wide and triggering a massive tsunami that inundated over 52,600 hectares (525 km^2) of land along the coastline. The 2011 Tohoku Earthquake and Tsunami was an unprecedented event, from which many lessons can be learned for catastrophe modeling and disaster research. The event produced both the largest number of ground motion recordings for a “great” earthquake (i.e., M≥8.0) and the highest measured tsunami waves in a well-prepared region (with run-up heights over 35 m above sea level). As of late January 2012, close to 15,900 people were confirmed dead and another 3,400 people are still missing[1]. The devastating economic and social impacts to Japan—which include the worst nuclear crisis since Chernobyl—will have a lasting impact on the culture of risk management within the country and worldwide.

Since the event’s occurrence, the seismic hazard research community has been concerned with understanding whether other related damaging earthquakes can now be expected around Japan and how this great event may have affected the timing (advance or delay) of other earthquakes in the region. This work has involved exploring microseismicity[2] patterns and stress changes across the seismic sources in the area from northern Tohoku to the Tokyo region. As part of the research that Risk Management Solutions is undertaking to re-characterize post-event seismic risk, this paper explores the range of alternative models for the coseismic slip distribution of the 2011 Tohoku event, their uncertainties, and their potential implications for estimating static stress changes on Japan’s seismic sources. Furthermore, elevated seismicity patterns since March 11, 2011 are analyzed to determine their influence on overall short-term[3] seismic risk.

These seismicity rate changes and modeled “Coulomb” static stress changes have been incorporated into the RMS® Japan Earthquake Model framework (via rate changes in the stochastic event set) in order to explore short-term changes in probabilistic earthquake risk for concentrations of exposure across Japan. The paper concludes with a discussion of the management of Japan earthquake risk in the post-Tohoku environment. The study’s highlights include the following:

- Significant variability exists among the proposed finite fault slip solutions for the 2011 Tohoku Earthquake, which creates a wide range of static stress changes and consequently, varied occurrence rate changes for the seismic sources across the impacted region.
- Subduction sources—and some crustal sources—near the edge of the Tohoku event’s rupture area show stress increases, while all sources within the rupture area itself exhibit stress decreases. However, calculated static stress changes show large variability in areas where the slip models are most dissimilar (i.e., at the north and south ends of the rupture zone).
- Occurrence rate changes cannot be resolved exclusively by analyzing static stress changes on known seismic sources. The presence of many unknown seismic sources makes this a limiting approach to understanding short-term changes in hazard—and risk.
- Across the Northeast Honshu region, sensitivity testing of occurrence rate changes due a combination of static stress and microseismicity rate changes is recommended to explore the range of changes in short-term risk estimates.
- Estimated occurrence rate changes, based only on the calculated static stress changes, indicate that short-term earthquake risk to the Tokyo region, where approximately 10% of Japan’s population resides, has remained

[1] The latest information on casualties by prefecture is available at http://www.npa.go.jp/archive/keibi/biki/higaijokyo_e.pdf.
[2] Microseismicity includes events of M≤6.0.
[3] In this research, short-term is defined as within 2 years of the event’s occurrence, as this analysis is not valid for extended time periods, such as a 30-year risk perspective.

relatively unchanged following the 2011 Tohoku event. Considering increased patterns of post-event seismic activity, however, average annual loss estimates (AALs) can potentially increase up to 70%.

- Occurrence rate changes due to both static stress and post-event seismicity changes result in a range of risk impacts across the prefectures of Northeast Honshu. These sensitivity analyses highlight the challenges in estimating short-term earthquake risk in Japan following the 2011 Tohoku Earthquake.

Sensitivity testing of risk metrics, considering potential rate changes due to static stress and post-event seismicity changes; a range of 'multipliers' on Average Annual Loss (AAL) and 100-year return period loss estimates are provided, highlighting the uncertainty in estimating short-term risk (see Table 2 on page 19)

Prefecture	Potential rate change due to static stress	Potential rate change due to elevated seismicity	Range of Multipliers for AAL	Range of Multipliers for 100-year Return Period Loss
Aomori	Large increase	Moderate increase	1.0 -1.8	1.0 -1.5
Iwate	Large decrease	Moderate increase	0.8 -1.1	0.6 -0.9
Miyagi	Large decrease	Large increase	0.5 -0.9	0.5 -0.9
Fukushima	Moderate decrease	Large increase	0.8 -1.4	0.9 -1.7
Ibaraki	Moderate decrease	Moderate increase	0.9 -1.7	0.9 -1.6
Chiba	Small decrease	Moderate increase	1.0 -1.9	1.0 -1.5
Tokyo	Little change	Moderate increase	1.0 -1.7	1.0 -1.4
Kanagawa	Little change	Moderate increase	1.0 -1.6	1.0 -1.4

TECTONIC SETTING OF JAPAN

Japan's tectonic setting is a very active one, with hazard driven primarily by convergent plate boundaries (i.e., subduction zones and the related deformation). As shown in Figure 1, the Japanese Islands span the boundary between the Eurasian Plate and the Okhotsk Plate, and are bounded to the east by the Pacific Plate, and to the south by the Philippine Sea Plate. Three major subduction-related boundaries, marked by deep oceanic trenches or troughs, define the tectonics of the region: the Sagami Trough at the interface of the Philippine Sea and Okhotsk Plates; the Nankai Trough between the Philippine Sea Plate and the Eurasian Plate; and the Japan Trench between the Okhotsk and Pacific plates. A diffuse offshore boundary exists between the Eurasia and Okhotsk plates and along the northwest coast of Honshu. The three boundary zones along the eastern coast of Japan have high earthquake activity rates and have historically produced very large, damaging earthquakes (e.g., the 1944 Tonankai and 1946 Nankai events along the Nankai Trough; the 1923 Great Kanto Earthquake along the Sagami Trough).

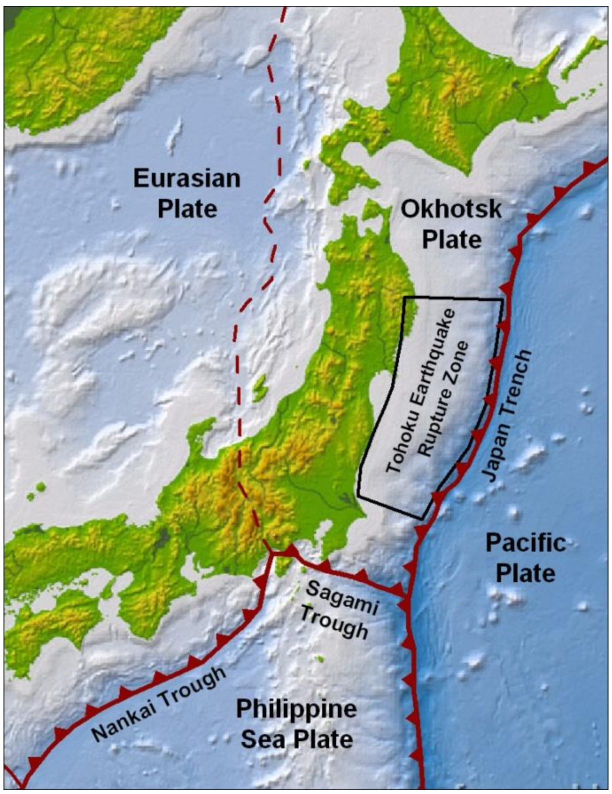

Figure 1: Japan's tectonic setting, illustrating the three subduction zones (Nankai Trough, Sagami Trough, and the Japan Trench) based on plate boundaries from Bird (2003); the rupture zone of the 2011 Tohoku event is shown along the Japan Trench

The Philippine Sea, Pacific, and Okhotsk plates converge under the Tokyo metropolitan area, resulting in a uniquely complicated tectonic environment. The convergence of the three plates creates seismic activity within and between the plates (termed "intraslab" and "interface" events, respectively), with the Okhotsk Plate overriding the Philippine Sea Plate, and the Pacific Plate dipping beneath both. There is a concentration of deeper moderate magnitude events (M<7.5 at 15-100 km depth) in the region, referred to as Chokkagata ("directly beneath") events. Understanding the hazard posed by Chokkagata-type events is difficult due to the lack of clearly defined seismic structures. Researchers have attempted to define these complex structures, based on the microseismicity and seismic velocity in the region. For the Japanese National Seismic Hazard Maps, earthquake sources beneath Tokyo were defined by the Earthquake Research Committee (ERC) Headquarters for Earthquake Research Promotion (HERP) of Japan. It should be noted, however, that there are alternative and potentially equally valid interpretations of these data, such as the work by Toda and others (2008).

2011 Tohoku Earthquake

The M9.0 Tohoku Earthquake ruptured the central section of the Japan Trench to a depth of approximately 50 km. This translates to the rupture of the sections “off Ibaraki,” “off Fukushima,” and “off Miyagi” as defined by the ERC/HERP seismic source model (Figure 2). The maximum displacement on the subduction interface is estimated to be as large as 60 m (e.g., Simons et al., 2011) and resulted in extensive deformation of the ocean floor. The March 11 mainshock was preceded by a M7.2 event on March 9, approximately 40 km from the mainshock epicenter, and was followed by a significant increase in seismicity in the immediate region of the M9.0 rupture. The two largest earthquakes following the M9.0 event, measuring M7.9 and M7.7, occurred on March 11.

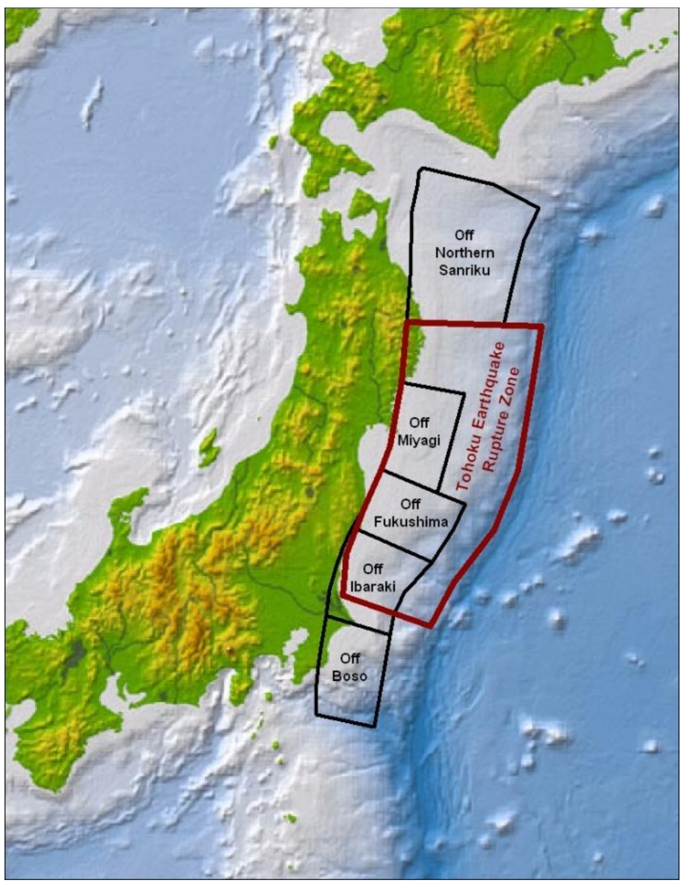

Figure 2: Japan Trench source characterization

As shown in Figure 3, over 4,700 earthquakes of M4.0 or greater occurred in the region of the mainshock rupture through December 2011. The rate of seismic activity has decayed with time since the event. These earthquake events are primarily offshore and increase in depth as they approach the coast—similar to the pattern of historical seismicity.

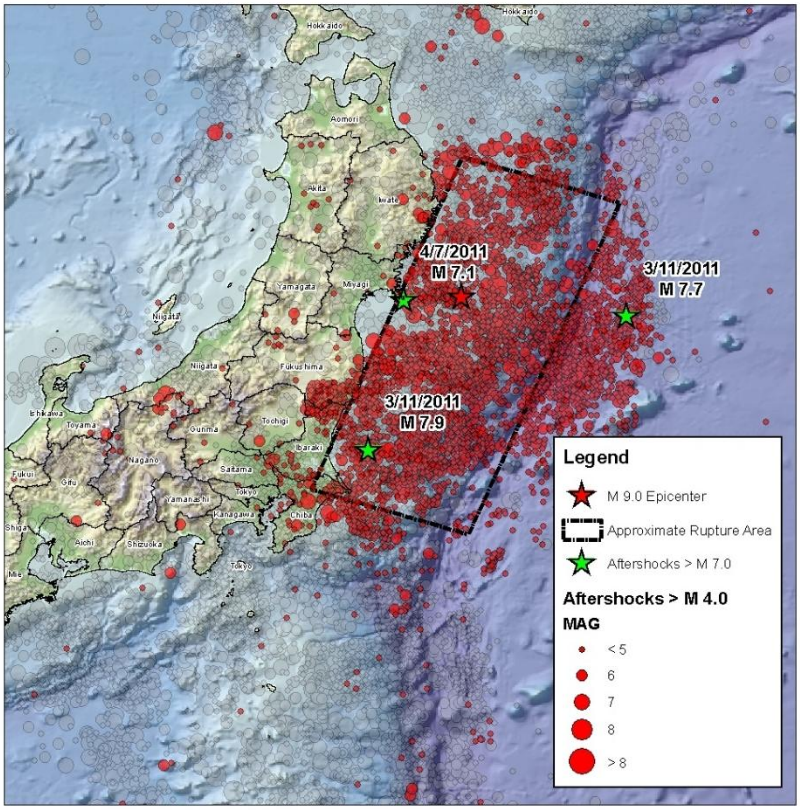

Figure 3: Seismic activity (M>4.0) following the March 11, 2011 M9.0 Tohoku Earthquake (based on USGS data available at http://earthquake.usgs.gov/earthquakes/eqarchives/epic/database.php), shown in red and sized by magnitude—with the M9.0 mainshock (red star) and three M >7 aftershocks highlighted (green stars)

Changing Landscape of Hazard

Historically, seismic hazard in Japan has been driven by megathrust events along the Japan Trench, the Sagami Trough, and the Nankai Trough. Very large and damaging earthquakes have occurred on these sources with return periods in the 40-to-400 year range. The Tokyo region's most threatening source (the Sagami Trough) generated the 1923 M7.9 Great Kanto Earthquake, and with a recurrence interval on the order of 200 to 300 years, another large event on this source is not expected soon. The same can now be said for the Tohoku region. Since the occurrence of the 2011 M9.0 Tohoku Earthquake, a large, damaging megathrust event is not expected on the central section of the Japan Trench for some time.

The reduction in the occurrence rate for large events on the Japan Trench fundamentally changes the drivers of risk for prefectures along the coast of Tohoku. For example, the risk in Miyagi Prefecture was driven by events generated on the "off Miyagi" section of the Japan Trench prior to the 2011 Tohoku Earthquake; following the event, risk in Miyagi Prefecture will be driven by shallow crustal seismicity until the stresses build up again in the "off Miyagi" source. For Tokyo Prefecture, located farther from the Japan Trench, the balance of hazard drivers is more uncertain, as the intraslab events in the Pacific and Philippine plates were contributing the most to risk before the Tohoku event. Do these intraslab events remain the key driver of hazard for Tokyo? Or is there a significant change in hazard due to the Tohoku event? To answer these questions, an analysis of the static stress changes on the surrounding seismic sources, as well as an analysis of elevated seismicity patterns, is needed.

A FRAMEWORK FOR CALCULATING HAZARD CHANGES

While the 2011 Tohoku event has significantly reduced the likelihood of another megathrust earthquake along the central section of the Japan Trench in the short term, the Tohoku region has experienced elevated rates of seismicity since the M9.0 mainshock. This elevated seismicity is due to a combination of aftershocks and triggered earthquakes. Aftershocks represent post-event seismicity occurring along the mainshock fault surface. In contrast, triggered earthquakes result from dynamic and static stress changes and generally occur off the mainshock rupture.

Dynamic stress changes occur as seismic waves from the mainshock pass through other seismic sources, triggering additional earthquakes within seconds to hours after the main event; distance ranges depend on the magnitude of the mainshock. In the case of the 2011 Tohoku Earthquake, dynamically triggered events were measured more than 1,000 km away from the main source (Miyazawa, 2011). Static stress changes reflect the redistribution of stress in the region as a result of the stress release by the mainshock fault rupture. This stress release is permanent and is offset slowly over time. Such statically triggered earthquakes may occur over a far longer period of time than dynamically triggered earthquakes.

To understand the risk in the Tohoku region today (i.e., how seismicity patterns have changed compared to the historical record, as shown in Figure 4), the risk from aftershocks, as well as earthquakes triggered by static stress changes must be considered. RMS undertook a research initiative to examine the hazard impacts following the 2011 Tohoku Earthquake, focusing first on the change in risk posed by static stress changes, then on the change in risk due to potential changing rates of seismicity. While the scope of the work included the impacted region across Northern Honshu, particular attention was given to the Tokyo region and its concentration of people and property at risk. The following sections discuss RMS' research on the change in earthquake occurrence rates in the Tohoku region due to static stress changes and post-event microseismicity patterns.

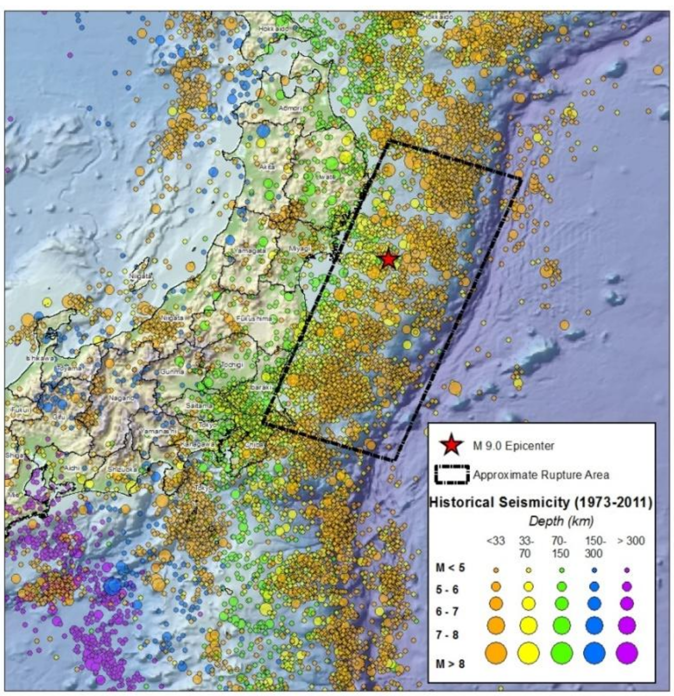

Figure 4: Historical seismicity in Japan, showing earthquakes (M >4.0) sized by magnitude and colored by depth (1973 through March 10, 2011, based on USGS data available at http://earthquake.usgs.gov/earthquakes/eqarchives/epic/database.php); the epicenter and rupture area associated with the 2011 Tohoku Earthquake is also highlighted

STATIC STRESS CHANGE ANALYSIS

The mechanisms involved with the static triggering of earthquakes are complex and require the mainshock source to be close to rupture or "primed" for an event. In order to understand which seismic sources are at risk from being statically triggered, RMS used an analytical method to calculate the impact of static stress change by the Tohoku Earthquake on the sources in the region (Figure 5). The resulting occurrence rate changes are then incorporated into the RMS® Japan Earthquake Model to estimate the changes in risk, which were captured as losses at the prefecture level.

As illustrated in Figure 5, calculating hazard changes is a three-stage process[4]:

1. Choose input models (receiver source and finite fault slip models);
2. Determine static stress changes; and
3. Calculate occurrence rate changes.

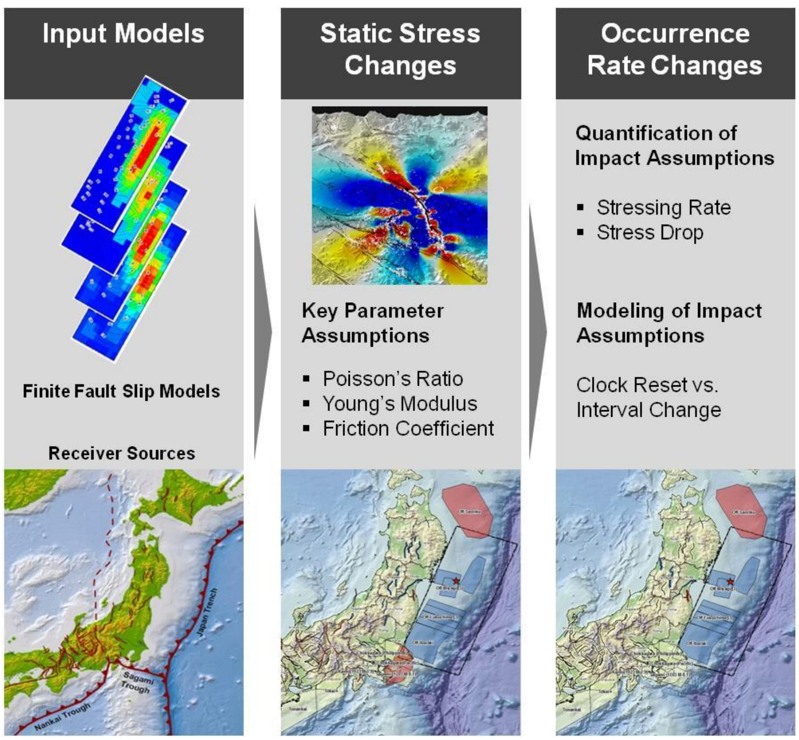

Figure 5: Framework for calculating hazard changes due to static stress changes following the 2011 Tohoku Earthquake: the input models (finite fault slip models and receiver sources) is translated first into static stress changes and then into occurrence rate changes on the sources

First, input models are gathered. These constitute a set of "receiver" sources upon which static stresses are calculated (i.e., the RMS seismic source model), and a set of finite fault slip models, which characterizes the slip on the Japan Trench due to the M9.0 event. Next, static stress changes on the receiver sources are calculated using the finite fault slip models. This calculation requires additional assumptions (Poisson's ratio and Young's modulus) to specify the characteristics of the Earth's crust, as well as the internal strength of the receiver sources (a friction coefficient). Once the stress changes on the receiver sources are determined, the rate change is calculated. This final step requires an

[4] More technical details about the three-stage process are provided in Appendices A through C (Input Models, Static Stress Changes, and Occurrence Rate Changes, respectively).

understanding of the expected recurrence on the receiver sources before the stress change (i.e., how “primed” the source is for earthquake occurrence). Stress changes are compared to both the assumed stressing rate on the source (as experienced due to its tectonic setting), as well as to the stress drop, which is the amount of stress expected to be released in a major earthquake on the source.

The stressing rate and the stress drop are utilized to calculate the new recurrence on the receiver sources—the amount of time to be added or subtracted from the estimated recurrence before the M9.0 event. For receiver sources modeled with time-dependent recurrence (e.g., using a Brownian Passage Time (BPT) model), the updated recurrence is calculated by balancing two approaches: updating the time since the last event (a “clock reset”) and updating the interval between events. For sources modeled using time-independent recurrence (e.g., using a Poisson approach), the interval between events is adjusted. The recurrence update step introduces the most uncertainty in the process, as the stressing rate and stress drop calculations are not well constrained.

Finite Fault Slip Models

A set of 13 finite fault slip models for the 2011 Tohoku earthquake was used for this analysis. The finite fault models represent realizations of discrete slip patches along the megathrust interface, and are derived from teleseismic and strong motion data, tsunami data, onshore and offshore GPS data, or some combination thereof (For more details, see Appendix A). A large set of finite fault models was used to examine the sensitivities of the analytical process to the levels of variation seen in the finite fault models. Figure 6 shows the footprints and the high slip (20-meter) contour of the 13 fault slip models. The up-dip boundaries (to the east) are generally uniform with slip terminating at the Japan Trench; however, the northern and southern extents vary by as much as 100 km across the different models. Estimates of maximum slip are more consistent, as most models agree the majority of slip was concentrated east of the epicenter.

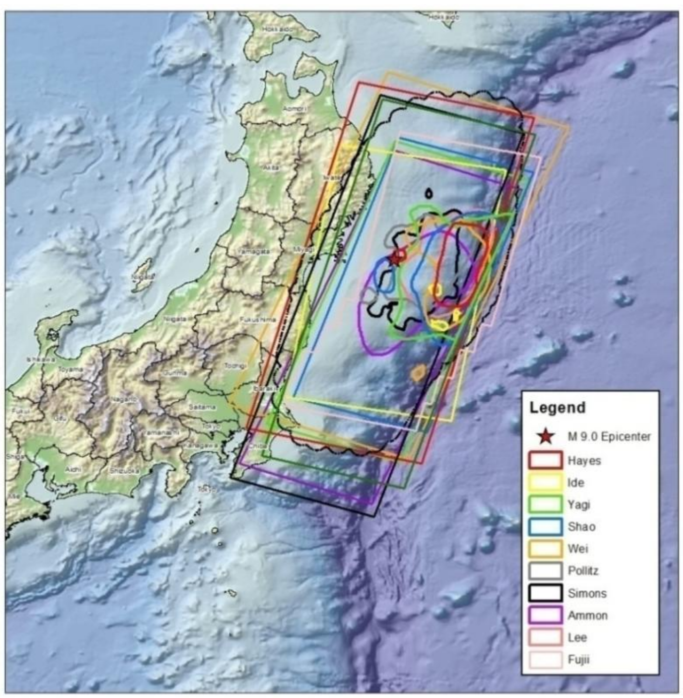

Figure 6: Footprint and associated 20-meter high-slip contour for each of the 13 finite fault slip models considered in the RMS analysis. Slip model boundaries are generally rectangular, with relatively consistent regions of high slip (>20 m), with most slip realized up-dip (east) of the March 11 Tohoku epicenter (red star)

Receiver Source Model

The receiver source model for this analysis is a subset of seismic sources within the RMS® Japan Earthquake Model comprising subduction zone sources, crustal faults, and crustal source zones. Subduction zone source events are classified either as interface (along plate boundaries) or intraslab (within subducting plates) events. Particular attention is given to the Chokkagata events under Tokyo due to the complicated plate interactions in this region. Crustal faults include close to 100 well-defined “major” faults, with many of them modeled using a time-dependent recurrence model, as well as 180 minor faults. The crustal source zones capture the seismicity associated with unknown structures (for more details, see Appendix A).

Receiver source requirements include well-defined physical characteristics: fault location, dip, down-dip extent, and the rake of the slip on the fault. Interface sources and major crustal faults were chosen as receiver sources, because the detailed information required is readily available. Subduction intraslab sources, minor crustal faults, and crustal source zones are excluded from the stress change analysis, as the detailed information is unknown for these sources.

Static Stress Change Results

Static stress changes were computed for the receiver sources in the RMS Japan Earthquake Model using Coulomb 3.3 software (Toda et al., 2011a) following the methodologies of Lin and Stein (2004) and Toda and others (2005) (for more details, see Appendix B).

The mean static stress changes on the various receiver sources, as well as the uncertainty in these changes, are illustrated in Figure 7. As noted earlier, the sources of “off Ibaraki,” “off Fukushima,” and “off Miyagi” ruptured during the 2011 Tohoku event; as a result, another event on these sources is not expected in the near future. This translates into reductions in mean static stress changes of over 1.0 bar on these sections of the Japan Trench (shown in blue on Figure 7a). In contrast, the Sanriku subduction interface at the northern end of the Tohoku rupture shows a significant stress increase that could potentially impact the risk in Aomori and northern Iwate prefectures (shown in red on Figure 7a).

For sources south of the earthquake rupture, this analysis found little or no stress change resolved on the Sagami and Nankai troughs, while the Chokkagata interface sources show a stress increase. It should be noted, however, that these sources are relatively deep and the events have relatively low recurrence rates (in comparison to Chokkagata intraslab events). Therefore, the stress changes will have minimal impact on the risk to Tokyo. This analysis does not include an “off Boso” source along the interface between the Pacific and Okhotsk plates, as consistent with the source model utilized for the Japanese National Seismic Hazard Maps. GPS observations and analysis of seismic coupling based on repeating earthquakes in this region indicate that this “off Boso” source may not be able to generate large damaging events (Loveless and Meade, 2011; Uchida and Matsuzawa, 2011).

The pattern of mean stress changes on the crustal faults follows an expected pattern, where thrust faults parallel to the subduction zone in central Honshu relaxed following the Tohoku event (i.e., decreased stress over 1.0 bar, as shown in blue in Figure 7a). The one exception is the Futaba Fault, which showed a marked increase in stress due to its proximity to the Japan Trench and preferential slip orientation (left-lateral strike-slip). The pattern of the stress changes seen in the RMS analysis for the crustal faults is very similar to other published studies on post-Tohoku stress changes (e.g., Toda et al., 2011b). Interestingly, the GPS observations following the Tohoku event show that this region is now in extension, essentially turning off the convergence responsible for the reverse fault regime in the region prior to the earthquake. Over the next several years to decades, the stress regime should slowly return to a convergent environment driven by subduction zone-related plate tectonics.

The variability in stress change across the slip models can be large, as illustrated in Figure 7b. Notably, the standard deviation of the stress change for a given fault is often larger than mean stress change estimate (i.e., coefficient of variation or CV>1.0); this is particularly true for the crustal faults in southern Honshu. In general, small CV values correspond to subduction interface sources or crustal faults closest to the rupture plane or of the same sign and magnitude of stress changes across all 13 slip models (shown in green in Figure 6b). Subduction interface sources with higher CVs (>1.0) were those sources near the edge of the slip distributions (e.g., “off Sanriku” source, Chokkagata interface sources), as the northern and southern extents of the slip model varied by as much as 100 km (as shown in Figure 6).

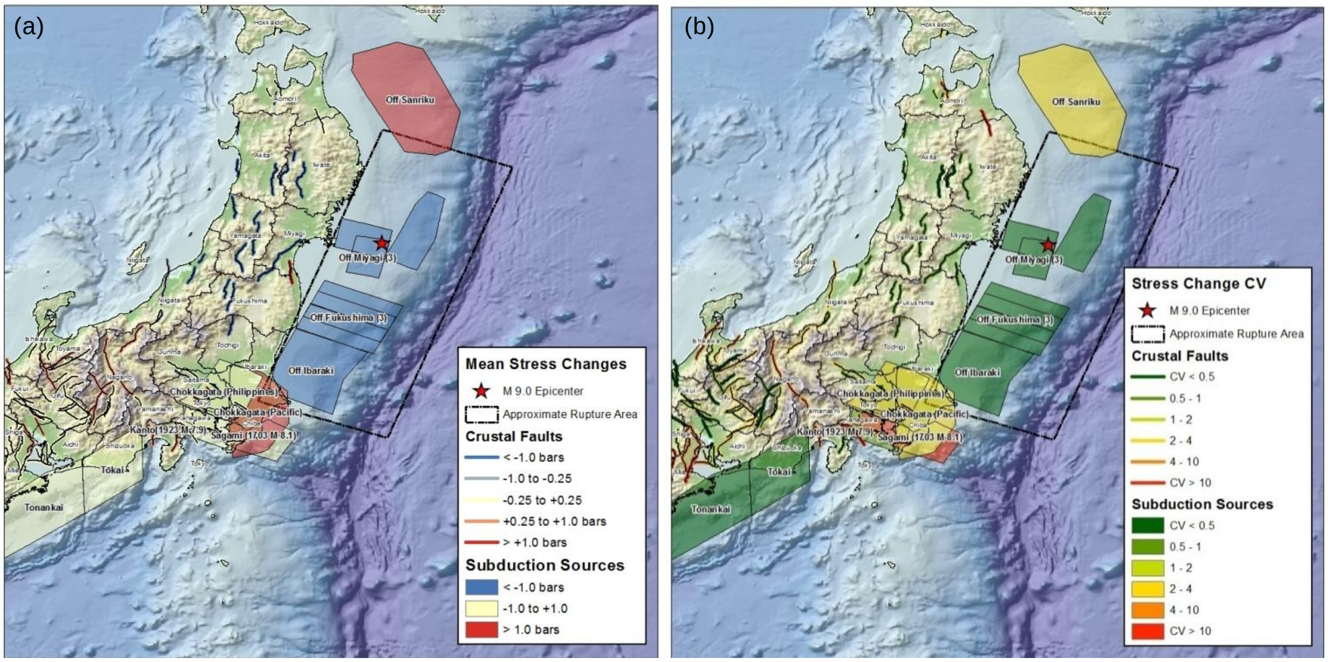

Figure 7: Static stress changes as a result of the 2011 Tohoku Earthquake, showing (a) mean stress changes across the 13 slip models with stress decreases in cooler (blue) colors and stress increases in warmer (red) colors; (b) uncertainty in stress change calculations across the 13 slip models, where the uncertainty in stress change calculations show areas of consistent slip or similar extent of the 13 slip models (lowest coefficients of variation in green) and areas of high variability across the 13 slip models (largest coefficients of variation in red)

Change in Occurrence Rates due to Static Stress Changes

With these static stress changes, occurrence rate changes for the receiver sources are calculated. As previously noted, this analysis could only be performed on receiver sources with well-defined physical characteristics: fault location, dip, down dip extent, and the rake of the slip on the fault (i.e., major crustal faults and subduction zone sources). The majority of these receiver sources are modeled within the RMS Japan Earthquake Model using a time-dependent approach, with the remaining sources modeled in a time-independent manner (for more information on time independent versus time dependent occurrence rates, see Appendix C). Using both the “clock reset” (updating the time since the last event) and the “interval change” (updating the interval between events) methods, rate changes were calculated for each of the time-dependent sources. Since neither method is favored for any particular source, the total rate change for each source was considered to be the average of the two methods. For time-independent sources, rate changes were applied by adjusting the return period (i.e., interval change method only).

The rate change is expressed as a percent change from the original rate and is calculated for each of the 13 slip models considered in this study, with the mean rate change illustrated in Figure 8. Red colors indicate areas of increased occurrence rate, with the largest rate changes occurring on the Futaba Fault and the “off Sanriku” source. Blue colors highlight rate decreases, with the largest decrease occurring on sources that ruptured during the 2011 Tohoku event ("off Ibaraki," "off Fukushima," and "off Miyagi" sources). Yellow colors highlight sources with small rate changes (±5%). While the static stress change calculations generally resulted in only minor changes in rates across the region (with few exceptions), it is important to note that these occurrence rate changes are based on ill-constrained assumptions on the sources' stressing rates, as well as the expected stress drop. (For more information on occurrence rate uncertainty, see Appendix C).

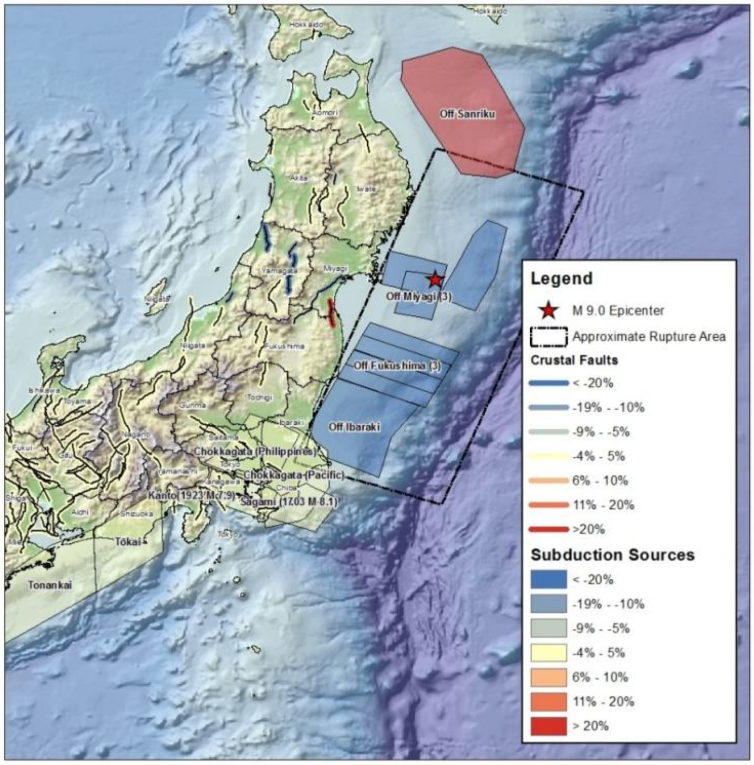

Figure 8: Occurrence rate changes as a result of the 2011 Tohoku Earthquake, showing mean occurrence rate changes based on the stress changes from all 13 finite slip models, with rate decreases in cooler (blue) colors and rate increases in warmer (red) colors

SEISMICITY RATE CHANGE ANALYSIS

Given the elevated seismicity rates following the 2011 Tohoku earthquake (Figure 3), and the presence of many unknown seismic sources in this complex tectonic region, occurrence rate changes cannot be resolved exclusively by analyzing static stress changes on known seismic sources. Therefore, RMS complemented the static stress change analysis with a detailed examination of the seismicity in the Tokyo region, as well as other prefectures along the Northern Honshu coastline, before and after the 2011 Tohoku event, to understand the impact of post-event seismicity on occurrence rates. Seismicity rate change analysis requires fewer a priori assumptions about properties of the Earth's crust and the location of seismic sources. The seismicity dataset was acquired from the Japan Meteorological Agency High Sensitivity Seismograph Network (JMA Hi-Net) and contains earthquake counts by JMA magnitude from March 11, 2010 through January 24, 2012. Comparisons between the 12 months of seismicity before the Tohoku event and the nearly 11 months after the event show a marked increase in the occurrence of earthquakes in the region across all recorded magnitude ranges ($M_{JMA}3$ through $M_{JMA}6$[5]), as shown in Figure 9 and Table 1. For example, there were 47 events of $M_{JMA}3$ or greater in the six months before the 2011 Tohoku event, but 343 events of $M_{JMA}3$ or greater in the six months after the 2011 event.

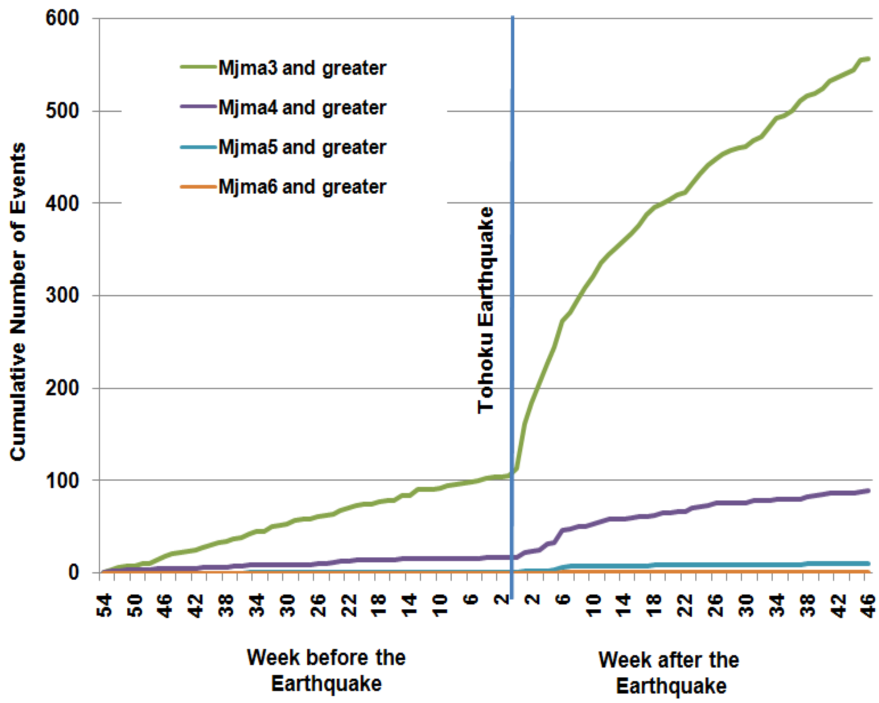

Figure 9: Seismicity rates in the Tokyo region for a full year before the 2011 Tohoku Earthquake through January 24, 2012, indicating increases across $M_{JMA}3$ to $M_{JMA}6$ following the M9.0 event

[5] The Japan Meteorological Agency magnitude (M_{JMA}) is referred to as a regional magnitude, as it is specific to Japan. It is based on measured ground motions. In contrast, the moment magnitude scale (M) is based on the seismic moment of an earthquake. For more information about magnitude scales, see Kanamori (1983).

Table 1: Number of earthquakes in the Tokyo region before and after the March 11, 2011 Tohoku Earthquake; indications of maximum magnitude within time intervals indicated in last row

Magnitude	12 to 6 months before 2011 Tohoku event	6 months before 2011 Tohoku event	6 months after 2011 Tohoku event	5 to 11 months after 2011 Tohoku event
M_{JMA}6 or greater	-	-	1	-
M_{JMA}5 or greater	1	-	8	1
M_{JMA}4 or greater	9	8	58	24
M_{JMA}3 or greater	58	47	343	156
Mmax	M_{JMA}5.0	M_{JMA}4.6	M_{JMA}6.0	M_{JMA}5.2

A more detailed analysis shows that the increased seismicity following the 2011 Tohoku event was most pronounced in the first three months following the event and has steadily decreased since this time. For example, of the 58 events of M_{JMA} 4 or greater that occurred in the 6 months after the 2011 Tohoku event, 41 occurred within the first three months. Moreover, the largest event in the dataset, an M_{JMA}6.0, occurred on April 21, 2011. In the last 6 months (5 to 11 months after the earthquake), the largest event measured M_{JMA}5.2. These results are likely linked to the temporal decay observed in aftershock sequences.

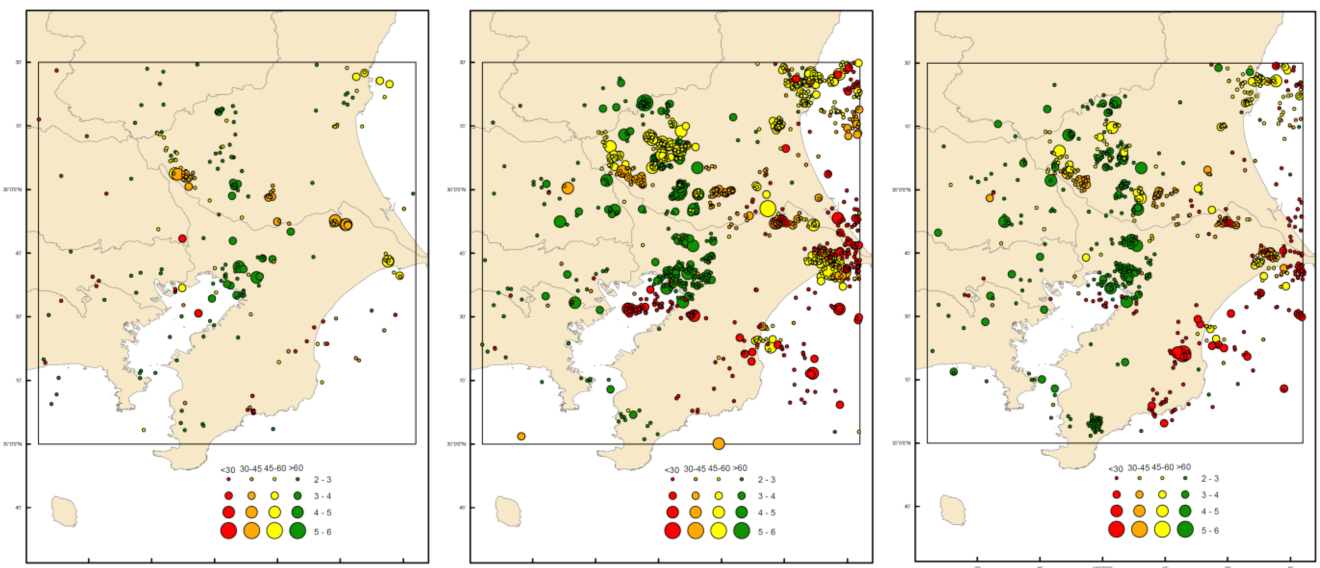

Figure 10: Temporal distribution of seismicity in the Tokyo region: seismicity 6 months prior to the 2011 Tohoku earthquake (9/11/10 – 3/10/11; left); seismicity in the 6 months after the event (3/11/11 – 9/10/11; middle); seismicity 5 to 11 months after the event (7/25/11 – 1/24/12; right)

As of January 2012, the seismicity rate in the Tokyo region is still elevated compared to pre-Tohoku seismicity rates. However, these increased seismicity rates are decaying quickly. Occurrence rates for seismic sources within the region of interest were extracted from the RMS Japan Earthquake Model and compared to the rates observed within the Tokyo region since March 2010. Earthquake magnitudes were converted from JMA magnitude (M_{JMA}) to moment magnitude (M_W or M) using a relationship consistent with the RMS Japan Earthquake Model.

Figure 11 shows the magnitude-recurrence relationship (seismicity rate) of the RMS model for M≥5 (events thought to cause loss) compared to the occurrence rates from the twelve months prior to the earthquake (pre-Tohoku seismicity rate), as well as the events in the first three months and the subsequent six months after the event (post-Tohoku seismicity rates). As shown in Figure 11, the seismicity rate in the first three months after the event was much higher than before the event, including the rate of M6.0 events estimated in the RMS model. However, the subsequent six months (June 2011–December 2011) show a much lower seismicity rate—more consistent with the RMS magnitude-recurrence relationship.

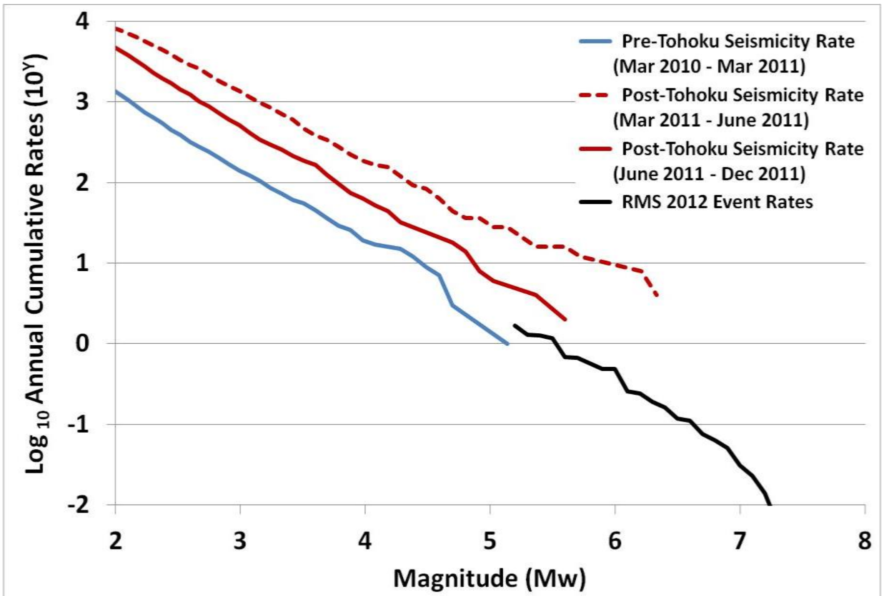

Figure 11: Magnitude-recurrence relationships based on seismicity rate for a full year prior to the 2011 Tohoku Earthquake (blue), seismicity rate in the three months following the event (red dashed), and seismicity from June to December 2011, corresponding to three to nine months following the event (red); magnitude-recurrence relationship for the region based on the 2012 event (occurrence) rates of RMS Japan Earthquake Model is shown in black

Potential for a Short-Term Damaging Earthquake

The dataset used for the RMS seismicity analysis is the same one utilized in similar analyses by the Earthquake Research Institute (ERI) at the University of Tokyo. Though the ERI research was first presented in September 2011[6], this study caught the eye of the mainstream media in mid-January 2012 (http://www.bbc.co.uk/news/16681136), as the research proposed that the probability of ~M_{JMA}7.0[7] Chokkagata ("directly beneath") earthquake within the next few years could be higher than previously indicated[8]. The ERI research estimated the recurrence for ~M_{JMA}7.0 Chokkagata event under Tokyo by applying a Gutenberg-Richter recurrence model to the observed seismicity in the months following the 2011 Tohoku Earthquake, which extends the magnitude-frequency relationship obtained for small magnitude events (as shown in Figure 11) toward larger magnitude events.

The depth profile of the post-Tohoku seismicity in the Tokyo region shows that 90% of the events are occurring at depths greater than 20 km and are potentially associated with Chokkagata sources. In order for a M7 event to occur in the Tokyo region, it must be associated with a fault structure. Due to the complex tectonic environment—particularly under Tokyo—extrapolating recurrence on higher magnitude events (on a seismic source) based on the recurrence of lower magnitude events (M≤6) is challenging. The RMS static stress analysis found only small stress changes resolved

[6]Information on this research is available at http://outreach.eri.u-tokyo.ac.jp/eqvolc/201103_tohoku/shutoseis/, with September 2011 meeting agenda available at http://www.eri.u-tokyo.ac.jp/KOHO/DANWA/MS233.html.
[7] Calculations considered M_{JMA}6.7 to M_{JMA}7.2.
[8] It is important to note that ERI indicated that this study was not an official ERI perspective on the earthquake recurrence for the region. In addition, the Earthquake Research Committee (ERC) of the Headquarters for Earthquake Research Promotion (HERP) of Japan has discussed this research with ERI and believes this perspective is not suitable for long-term recurrence estimation, as the uncertainty is too large (http://mainichi.jp/life/today/news/20120210ddm008040070000c.html).

onto the Chokkagata interface, which is inconsistent with the observed seismicity rate changes. For a comprehensive risk analysis, the possibility that there are preferentially oriented seismic sources that could produce M7.0 events in the Tokyo region should then be considered and incorporated (e.g., by increasing the occurrence rates on certain seismic sources in the region)[9].

[9] It should be emphasized, however, that this approach is only useful to estimate short-term hazard and risk.

CHANGE IN RISK RESULTS

RMS evaluated the changes in earthquake risk considering the occurrence rate changes across the impacted seismic sources, as well as the elevated seismicity patterns following the 2011 Tohoku event. Changes in risk were captured as the percent change in expected (ground up) loss to insured property, as defined in the RMS® Japan Industry Exposure Database (IED). For each city/ward, RMS has developed estimates of total insured values using a variety of sources, including sampled company premium information, census demographics and economics data, building square footage data, and representative policy terms and conditions. In essence, the personal (residential and cooperative), commercial, and industrial lines of businesses were analyzed against a new view of hazard (i.e., occurrence rate changes due to static stress and elevated seismicity).

Changes in risk due to static stress changes are first presented to illustrate the limiting nature of this analysis. Then, changes in risk due to both static stress changes and elevated seismicity are presented. RMS considers this as the more comprehensive approach to capturing the range of expected change, given the uncertainty.

Changes in Risk due to Static Stress Changes

Changes in risk due to static stress changes—resolved on seismic sources surrounding the ruptured central section of the Japan Trench—are shown in Figure 12. Overall, the largest risk decreases are observed in prefectures closest to the section that ruptured in the 2011 Tohoku event. The reduction of occurrence rates on the “off Ibaraki,” “off Fukushima,” and “off Miyagi” sources, which dropped to nearly zero immediately after the event, causes significant reductions in risk for the prefectures of Ibaraki, Fukushima, and Miyagi, as well as portions of Iwate. Conversely, areas of increased risk are observed in northern Honshu and Hokkaido, where risk is driven by the “off Sanriku” subduction source, which experienced a high stress change. Risk in the Tokyo and Chiba prefectures remains relatively unchanged; although some sources in the region exhibited static stress increases, overall occurrence rate increases were not substantial.

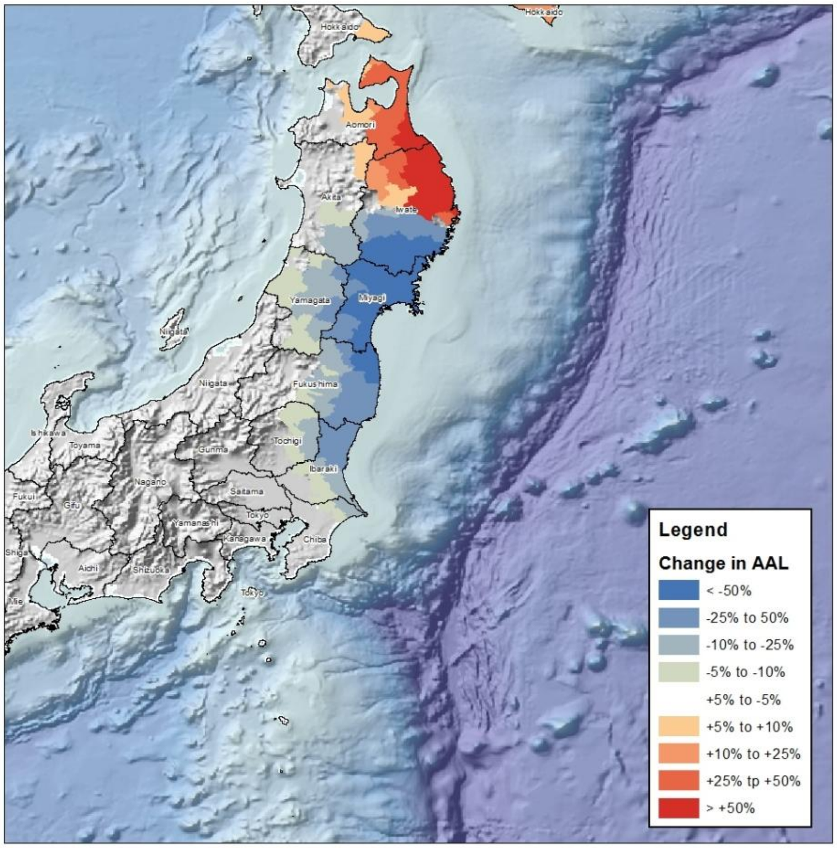

Figure 12: Change in risk (as measured by change in ground up average annual loss) in the region as a result of the 2011 Tohoku event, with warmer (red) colors indicating areas of increased risk and cooler (blue) colors indicating areas of decreased risk; changes within ±5% are not shown

Changes in Risk due to Static Stress and Seismicity Changes

Using only a static stress approach to estimate occurrence rate changes on specific sources is difficult, due to the level of uncertainty in the process and the large number of simplifying assumptions that are made for modeling static stress change. As discussed in the previous section, observed seismicity rate changes are not always consistent with a static stress modeling outcome. More research must be undertaken as the seismicity patterns in the Tohoku region change over the next several years. As the Tohoku region is subject to an ongoing aftershock sequence with short-term increased levels of seismicity, RMS conducted a series of sensitivity tests on the occurrence rates within the RMS Japan Earthquake Model to understand potential impacts on risk metrics.

Potential increases in occurrence rates for crustal source zones (seismicity associated with unknown structures) and intraslab sources are explored in order to account for short-term elevated seismicity across eight prefectures in Northeast Honshu. These rate increases are combined with occurrence rate changes (decreases or increases) due to static stress to more comprehensively estimate potential changes in risk. Table 2 presents the results of this sensitivity analysis, showing the potential short-term impacts on average annual loss (AAL) and 100-year return period loss estimates. Specifically, the ‘range of multipliers’ represents the ratio of loss using the 2012 rates within the RMS Japan Earthquake Model to the loss calculated from a range of occurrence rates, considering both static stress and elevated seismicity patterns.

Table 2: Sensitivity testing of risk metrics, considering potential rate changes due to static stress and post-event seismicity changes; a range of 'multipliers' on Average Annual Loss (AAL) and 100-year return period loss estimates are provided, highlighting the uncertainty in estimating short-term risk

Prefecture	Potential rate change due to static stress	Potential rate change due to elevated seismicity	Range of Multipliers for AAL	Range of Multipliers for 100-year Return Period Loss
Aomori	Large increase	Moderate increase	1.0 -1.8	1.0 -1.5
Iwate	Large decrease	Moderate increase	0.8 -1.1	0.6 -0.9
Miyagi	Large decrease	Large increase	0.5 -0.9	0.5 -0.9
Fukushima	Moderate decrease	Large increase	0.8 -1.4	0.9 -1.7
Ibaraki	Moderate decrease	Moderate increase	0.9 -1.7	0.9 -1.6
Chiba	Small decrease	Moderate increase	1.0 -1.9	1.0 -1.5
Tokyo	Little change	Moderate increase	1.0 -1.7	1.0 -1.4
Kanagawa	Little change	Moderate increase	1.0 -1.6	1.0 -1.4

The short-term risk perspective for Aomori Prefecture is potentially higher due to the rate increase from the "off Sanriku" source and elevated seismicity rates. In Iwate, Miyagi, Fukushima, and Ibaraki prefectures, risk is potentially lower due to the rate reduction in the Tohoku sources ("off Ibaraki," "off Fukushima," and "off Miyagi'"). This reduction but may be compensated by potentially higher seismicity in Iwate, Fukushima, and Ibaraki prefectures. Notably, in Iwate and Fukushima, seismicity is driven by shallow events, whereas in Ibaraki prefecture, seismicity increases are from both shallow and deep events. In Miyagi Prefecture, the potentially higher seismicity rates cannot completely compensate for rate reductions in the 'off Miyagi' source. Finally, in Chiba, Tokyo, and Kanagawa prefectures, there is little change in rates due to the Tohoku event; however, elevated seismicity from both shallow and deep (Chokkagata) sources could result in short-term risk increases. In particular, the sensitivity analysis for Tokyo Prefecture indicates that short-term AAL and 100-year return period loss could be negligible (0%) or increase by 70% and 40%, respectively.

The 2011 Tohoku Earthquake in Perspective

While short-term earthquake risk in the wake of the 2011 Tohoku Earthquake must be assessed, it is also important to consider the longer-term implications of this event for both earthquake risk management and modeling. Prudent catastrophe risk management should involve the re-examination of exposure accumulations across the most catastrophic loss scenarios (as in the case of the 2011 Thailand Floods) and the consideration of a range of scenarios for concentrations of risk, such as the Tokyo region or other megacities, such as Mexico City. Further, there is a need for more detailed data to be captured and utilized when transferring risk for high resolution perils, such as tsunami or flood, as well as a need for more transparency around contingent business interruption coverage.

RMS is committed to providing solutions for modeling Japan earthquake and tsunami risk and is currently exploring updates to its Japan Earthquake Model. Ongoing research includes a stochastic event set rate change, reflecting longer-term expectations for event recurrence on the Japan Trench, and tsunami scenarios (off the eastern coast of Japan) to manage concentrations of insured exposure.

CONCLUSIONS

The 2011 Tohoku Earthquake and Tsunami was an unprecedented event, from which many lessons can be learned for catastrophe modeling and disaster research. Since the event's occurrence, the seismic hazard research community has endeavored to understand whether other related damaging earthquakes can now be expected around Japan and how this great event may have affected the timing (advance or delay) of other earthquakes in the region. This work has involved exploring microseismicity patterns and static stress changes across the seismic sources in the area from northern Tohoku to the Tokyo region.

The RMS study presented in this paper reflects potential changes in short-term risk due to static stress changes in the tectonic environment in conjunction with short-term elevated seismicity as a result of the 2011 Tohoku Earthquake. Overall, the study concluded:

- Significant variability exists among the proposed finite fault slip solutions for the 2011 Tohoku Earthquake, which leads to a wide range of proposed static stress changes and consequently, varied occurrence rate changes for the seismic sources across the impacted region.
- Subduction sources—and some crustal sources—near the edge of the Tohoku event's rupture area show stress increases, while all sources within the rupture area itself exhibit stress decreases. However, calculated static stress changes show large variability in areas where the slip models are most dissimilar (i.e., at the north and south ends of the rupture zone).
- Occurrence rate changes cannot be resolved exclusively by analyzing static stress changes on known seismic sources. The presence of many unknown seismic sources makes this a limiting approach to understanding short-term changes in hazard—and risk.
- Across the Northeast Honshu region, sensitivity testing of occurrence rate changes due a combination of static stress and microseismicity rate changes is recommended to explore the range of changes in short-term risk estimates.
- Estimated occurrence rate changes, based only on the calculated static stress changes, indicate that short-term earthquake risk to the Tokyo region, where approximately 10% of Japan's population resides, has remained relatively unchanged following the 2011 Tohoku event. Considering increased patterns of post-event seismic activity, however, average annual loss estimates (AALs) can potentially increase up to 70%.

The ongoing seismicity in the wake of the 2011 Tohoku Earthquake and Tsunami suggests that there are lessons yet to be learned. In early 2012, Japan remains in the throes of the long process of rebuilding viable communities, and the final impacts of the event are still being quantified. To better understand and mitigate Japan's earthquake risk into the future, continued research on the changing seismicity patterns in the Tohoku region, as well as explorations into fully probabilistic tsunami solutions, is necessary. RMS will continue to closely monitor and examine research findings and events as they unfold.

APPENDIX A: INPUT MODELS

The key data required to evaluate the expected static stress changes following the 2011 Tohoku Earthquake are the receiver source and finite fault slip models.

Finite Fault Slip Models

The M9.0 Tohoku Earthquake ruptured along a subduction megathrust fault approximately 450 km long and 150 km wide. The slip on the underlying fault caused significant changes in the level of the seafloor, which caused the subsequent tsunami. However, the majority of the slip occurred along the megathrust, varying by location, often decreasing away from the hypocenter. Following the 2011 Tohoku event, many finite fault models were developed that estimated the size and location of the slip. These models represent realizations of discrete slip patches along the megathrust interface, and are derived from teleseismic and strong motion data, tsunami data, onshore and offshore GPS data, or some combination thereof. This data, in combination with a model of the Earth—typically elastic—is used to estimate slip along the megathrust (e.g., by determining the "best fit" of the observed data).

The finite fault slip models used in the RMS analysis of stress change are summarized in Table 3. Some slip models were produced rapidly following the earthquake and may lack the detail provided in the best solutions of other authors. These slip models are included in this analysis to illustrate how the models evolve over time and to measure any added value provided by models issued at a later date. A "simple" slip model is also included, which consists of a single patch of uniform slip with a footprint of approximately the same size as the other models. The stress changes from this model are compared with the other published models to further test the added value of the detailed slip models.

Table 3: Finite fault slip models used in RMS analysis of stress change

Author	Data Used			Moment Magnitude		Maximum Slip (in meters)	Strike (°)	Dip (°)	Rake (°)
	Seismic	GPS	Tsunami	(Nm)	(M_W)				
Ammon et al., 2011	**Yes**	**Yes**	No	3.90×10^{22}	9.0	41.0	202	12	85
Fujii et al., 2011a[1]	No	No	**Yes**	3.80×10^{22}	9.0	47.9	193	14	81
Fujii et al., 2011b[1]	No	No	**Yes**	3.80×10^{22}	9.0	37.8	193	14	81
Hayes et al., 2011 p[2]	**Yes**	No	No	4.04×10^{22}	9.0	17.9	195	15	***VAR***[4]
Hayes et al., 2011 f[2]	**Yes**	No	No	4.90×10^{22}	9.1	33.4	195	10	***VAR***[4]
Ide et al., 2011	**Yes**	No	No	4.50×10^{22}	9.0	23.8	190	10, 14	90
Lee et al., 2011	**Yes**	**Yes**	No	3.67×10^{22}	9.0	56.1	195	14	***VAR***[4]
Pollitz et al., 2011	No	**Yes**	No	3.59×10^{22}	9.0	38.0	195	***VAR***[4]	90
Shao et al., 2011	**Yes**	No	No	5.80×10^{22}	9.1	59.8	199	10	***VAR***
Simons et al., 2011	**Yes**	**Yes**	**Yes**	3.63×10^{22}	9.0	59.8	***VAR***[4]	***VAR***[4]	***VAR***[4]
Wei et al., 2011	**Yes**	**Yes**	No	4.37×10^{22}	9.0	30.0	201	14	***VAR***[4]
Yagi et al., 2011	**Yes**	No	No	5.70×10^{22}	9.1	51.2	200	12	85
Simple Model[3]	No	No	No	4.00×10^{22}	9.0	13.0	198	12	90

[1] Fujii et al., 2011 report two slip models: model "a" assumes instantaneous rupture; model "b" includes the effects of a finite rupture velocity.
[2] Hayes developed a preliminary (p) and a final (f) slip model. The preliminary model was produced within hours of the event.
[3] The simple model is not a published slip model; it is a single patch of uniform slip. See text for a detailed explanation.
[4] VAR indicates that a parameter varies by individual fault patch.

Variability Across Slip Models

A broad range of finite fault parameters is associated with the slip models. For example, estimated seismic moment varies by a factor of 2, with maximum estimated slip ranges from 18 m to 60 m, differing by more than a factor of three. Variability of the finite fault parameters reflects differences in how data have been selected and processed, the type of elasticity model chosen for the Earth, and any physical assumptions about the prevailing conditions.

Three general types of data were used for the slip inversions: seismic, GPS, and tsunami data. Seismic data are records of measured acceleration and are generally teleseismic, though some strong motion station data within mainland Japan are also included. The distribution of the seismic data is generally available in most azimuthal directions around the megathrust rupture. Finite fault slip solutions estimated exclusively with seismic data are generally found to have higher moment magnitude estimates than those estimated using GPS or tsunami data.

GPS data are displacements measured either on mainland or offshore Japan. The land-based GPS data is gathered from approximately 1,100 stations and offshore data is gathered from a small number of submarine stations. The majority of models use the onshore GPS data and few models rely on submarine stations. These GPS-based solutions tend to have lower estimates of moment release and concentrate the larger slip patches deeper and closer to land. Finally, tsunami data are records of wave heights both on land and in the open ocean. Models that exclusively use tsunami data have the largest uncertainties due to the poor resolution of input data.

Receiver Source Model

The seismic source model for the RMS® Japan Earthquake Model contains the major fault systems researched by the Earthquake Research Committee (ERC) of the Headquarters for Earthquake Research Promotion (HERP) of Japan since the 1995 Great Hanshin-Awaji (Kobe) Earthquake; minor fault systems are included as well. Thirty crustal source zones characterize the seismic activity derived from instrumental recordings. The main subduction zones are delimited, including the Kuril and Japan trenches, and the Sagami and Nankai troughs. It should be noted that the ERC model does not include an "off Boso" source along the interface between the Pacific and Okhotsk plates, as it is assumed that this source does not pose a risk to Japan.

The stochastic event set of the RMS Japan Earthquake Model contains both subduction events and crustal earthquake events. The primary events used in the receiver source model were the subduction interface events, as well as the events on the major crustal faults. As shown in Figure 13, both subduction zone sources (left) and major crustal faults (in black on right) could potentially be impacted by static stress changes. Subduction interface events occur along the surface of contact between the two plates and are generally less than M9.0 in Japan's historical record. Crustal earthquakes occur within the overriding plate and are generally less than M8.0, with the largest events associated with the major (active) faults.

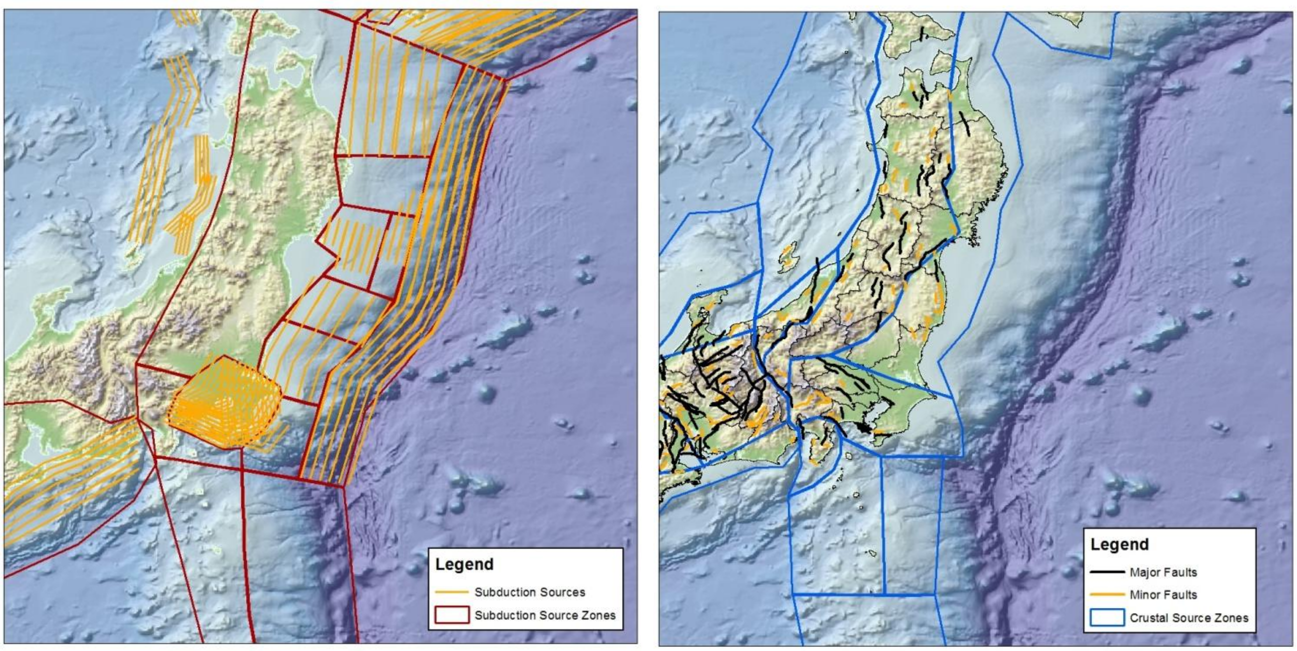

Figure 13: Seismic sources of Japan: subduction zone sources (left) and crustal sources, including major faults, minor faults, and crustal source zones (right)

APPENDIX B: STATIC STRESS CHANGES

Generally faults are thought to rupture once a threshold level of stress has been reached. Following earthquakes, the state of stress in the Earth's crust changes. Crustal stresses increase on some faults and decrease on others. These changes in stress may increase or decrease the likelihood of aftershocks or triggered earthquakes (e.g., King et al., 1994; Harris, 1998; Stein, 1999). Stress changes have implications for seismic hazard and risk estimates, but these estimated changes are not without variability.

The static stress change on a single fault, resulting from a nearby earthquake, depends on a number of factors. The most significant is the distance and location of the receiver source with respect to the causative source (Figure 14). The slip distribution of the causative earthquake, orientation of the receiver source, and material properties also influence the predicted stress changes. Figure 14a shows the predicted stress changes for normal faults following a subduction event. The stress increases in the outer rise region are evidenced for the 2011 Tohoku Earthquake by the M7.7 normal mechanism outer rise event occurring on the same day. Figure 14b shows the predicted stress changes for thrust faults following the same subduction event. The stress increases down-dip (west) of the main shock was evidenced by the M7.9 thrust event that occurred off Ibaraki on the same day.

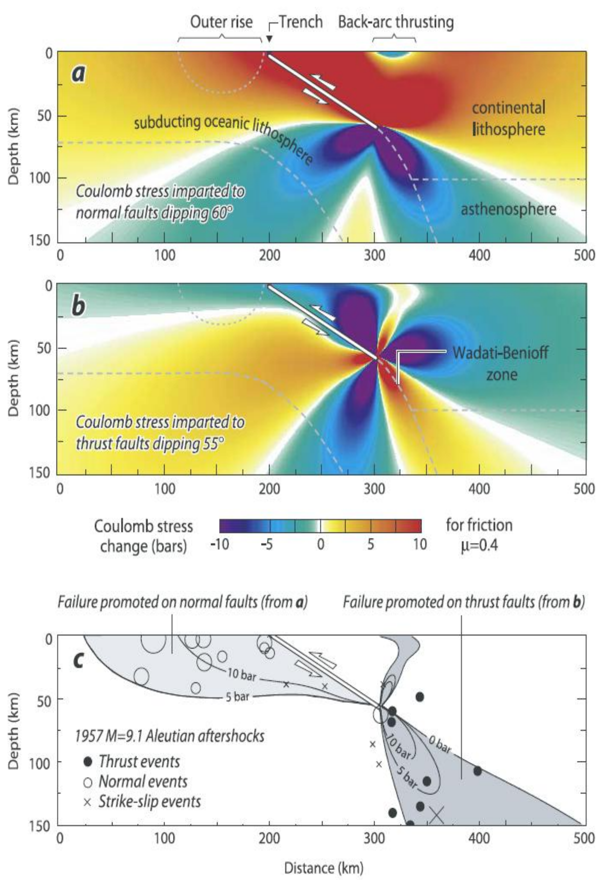

Figure 14: Static stress changes following a subduction zone megathrust rupture:(a) static stress changes for normal faults dipping at 60° (The M7.7 normal aftershock following the Tohoku earthquake occurred in the area of stress increase labeled “outer rise”); (b) static stress changes for thrust faults dipping at 55° (The M7.9 thrust aftershock occurred in the area of stress increase-Wadati-Benioff zone); and (c) down-dip stress increases for thrust faults dipping at 60° and up-dip stress increase dipping at 55° (Source: Lin and Stein, 2004)

Static stress changes were computed for the receiver sources in the RMS Japan Earthquake Model using Coulomb 3.3 software (Toda et al., 2011a) following methodologies of Lin and Stein (2004) and Toda and others (2005). Receiver sources include both subduction sources and major crustal faults, and the assigned coefficient of friction is 0.4. Other elastic parameters are kept constant in an effort to capture the variability associated with the suite of slip models (Poisson's ratio=0.25 and Young's modulus=$8x10^5$ bars).

Generally, subduction sources near the edge of the rupture area show stress increases while all sources within the rupture area exhibit stress decreases. These results are consistent with previously published studies (Toda et al., 2011b).

Uncertainty in Stress Change Calculations

Within the static stress change calculations are three main sources of uncertainty: the receiver source orientation and geometry; the mainshock slip distribution (finite fault slip model); and the assumed elastic parameters. The focus of this study is the examination of uncertainty associated with the slip distribution by considering various finite fault slip models, as it has been confirmed that most of the variability in the stress change calculations is rooted in the range of slip distributions. However, it is also useful to discuss the uncertainty associated with the receiver source orientation or elastic parameters.

The RMS Japan Earthquake Model was used to define the receiver source locations and geometry. Other source geometries can be used—and may produce different stress change estimates. For example, the RMS model includes two interface sources under Tokyo—one deeper and one shallower—maintaining (where feasible) all fault geometry complexities. Subtle changes in fault orientation, caused by simplifying fault traces, can contribute to the stress change uncertainty. For example, Toda and others (2011b) calculated stress changes on a simple Kanto fragment, which resulted in a different estimate of stress change. Because stress change estimates are dependent on receiver source location and geometry, different receiver fault configurations will always add uncertainty, particularly in areas with complex fault configurations.

Coulomb method assumptions of frictional and elastic parameters can also contribute to stress change uncertainty. However, testing showed that the range of uncertainty on these parameters is an order of magnitude smaller than the range of uncertainty from among the different slip models. Therefore, for the purposes of this study, a coefficient of friction of 0.4, a Poisson's ratio of 0.25, and a Young's modulus of $8x10^5$ bars are assumed and uncertainty related to the elastic and frictional parameters are not explicitly considered.

APPENDIX C: OCCURRENCE RATE CHANGES

The final step in determining the earthquake hazard changes due to static stress changes from the 2011 Tohoku event involves transforming the static stress changes into occurrence rate changes.

Event Occurrence

The rate of activity (inverse of the return period) is used in an earthquake occurrence model to calculate the probability of occurrence of earthquakes within a specific time window (usually one year). Common types of occurrence models include: the Poisson model and the time-dependent ("predictable") model. The Poisson model distribution assumes that seismic activity is constant through time (red line in Figure 15), independent of recent earthquake history. This model assumes time independence, meaning that events such as foreshocks and aftershocks to a mainshock earthquake event are not considered in the construction of the probability distribution. In contrast, the time-dependent model distribution considers fault slip rate and the time since the last event in estimating the probability of future events (e.g., using the Brownian Passage Time (BPT) approach). This approach can result in modeled risk at a particular point in time being significantly different from the long-term average, as stress builds up and is released over the earthquake cycle.

For catastrophe modeling, time-dependent models are used only for well-researched seismic sources in areas with high hazard and exposure. For Japan, this includes the majority of the major crustal faults and a subset of the subduction interface sources along the Kuril and Japan trenches, as well as the Sagami and Nankai troughs. To calculate the occurrence rate changes for these sources, one must consider both a "clock reset" and an "interval change," These methods are illustrated in Figure 15 (as "clock change" and "interevent-time change") using California's Hayward Fault as an example.

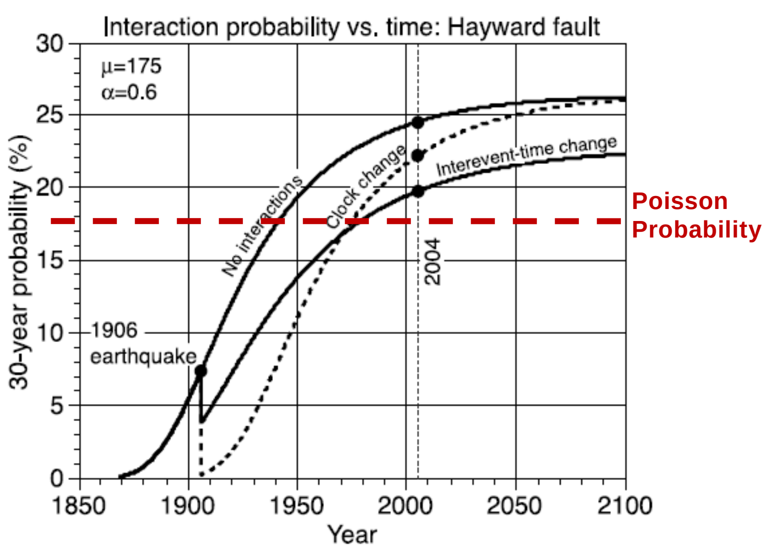

Figure 15: Thirty-year conditional probability versus time on the Hayward Fault after the stress drop associated with the 1906 M7.9 San Francisco Earthquake, illustrating two methods for time recurrence adjustment: a clock reset ("clock change") and an interval change ("interevent-time change") (Source: Parsons, 2005)

Figure 15 shows adjustments to event recurrence on the Hayward Fault as a result of the 1906 San Francisco Earthquake. Calculations were made with a clock change ("clock reset"), where the time of the last earthquake was "set forward an amount proportional to the stress change," and with an interevent-time change ("interval change"), where the time between events was "lengthened by an amount proportional to the stress change." (For more details, see Parsons, 2005.) The closer in time the rate change is to the last event (time = 0), the less impact the change has on the occurrence probability. It should be emphasized that this approach is applied only to sources modeled using time-dependent recurrence. Applying changes to sources modeled using time-independent recurrence (Poissonian) is more direct—as only an interval change between events is needed.

Uncertainty in Rate Change Calculations

The variability in the occurrence rate estimates is shown in Figure 16. As with uncertainty in stress change calculations, sources with small CVs (< 1.0) were generally those closest to the rupture plane or having the same sign and magnitude of rate changes across all 13 slip models. Within the occurrence rate change calculations are two main sources of uncertainty: the assumed stressing rates on the receiver sources and the expected stress drop on the receiver sources in characteristic events. In addition, for time-dependent sources, an assumption must be made about the earthquake cycle (i.e., time since the last event).

For example, for a source with a return period of 200 years and an assumed stress drop of 5.0 MPa (50 bars) per characteristic event, a stressing rate of 0.025 MPa (0.25 bars) per year can be assumed. If the stress change on that fault is calculated to be 1.0 MPa (10 bar), then the return period is adjusted by 40 years. However ±1.0 MPa on the stress drop assumption or ±50 years in the return period estimate results in return period adjustments ranging from 33 to 60 years or 30 to 50 years, respectively, and 25 to 62 years combined. The nature of return period estimates, stress drop estimates, and consequently stressing rates, are among the poorest constrained variables in this process.

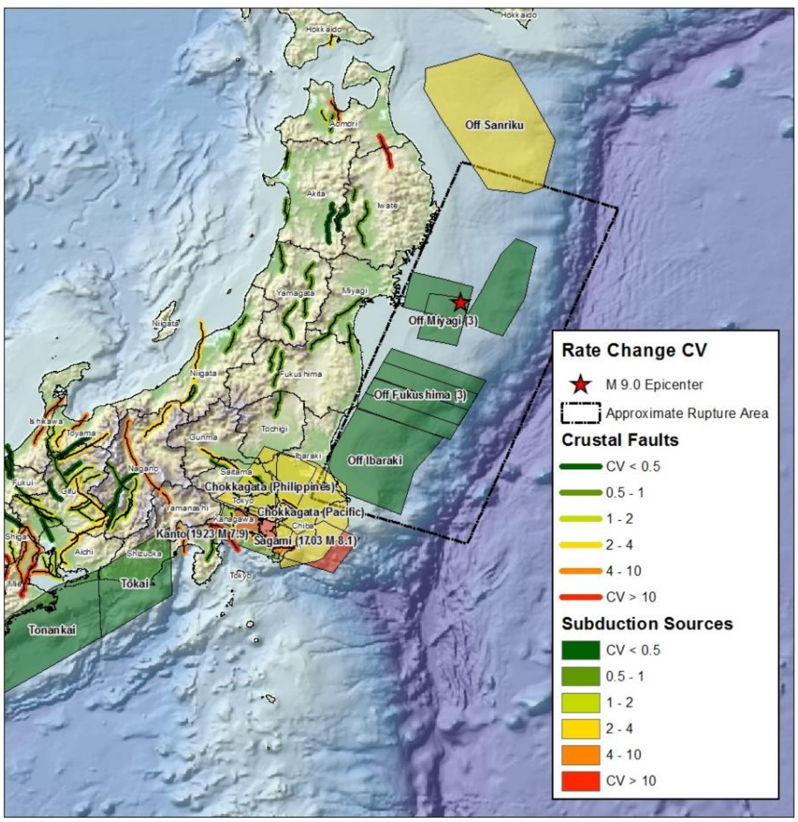

Figure 16: Uncertainty in occurrence rate change calculations across the 13 slip models; sources are colored by the rate change coefficient of variation (CV) derived from the mean rate change from the thirteen model; sources with low CVs (<1.0) correlate with areas of consistent slip or similar extent of the 13 slip models and high CVs (>1.0) correlate to areas of high variability across the 13 slip models

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