Change in seismicity beneath the Tokyo metropolitan area due to the 2011 off the Pacific coast of Tohoku Earthquake

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Static changes in the Coulomb Failure Function (ΔCFF) forecast an increase in seismicity in and around the Tokyo metropolis after the 2011 off the Pacific coast of Tohoku Earthquake (magnitude 9.0). Among the 30,694 previous events in this region with various depth and focal mechanism, almost 19,000 indicate a significant increase of the ΔCFF, while less than 6,000 indicate a significant decrease. An increase in seismicity is predicted in southwestern Ibaraki and northern Chiba prefectures where intermediate-depth earthquakes occur, and in the shallow crust of the Izu and Hakone regions. A comparison of seismicity before and after the 2011 event reveals that the seismicity in the above regions indeed increased as predicted from the ΔCFF.

Key words: 2011 off the Pacific coast of Tohoku Earthquake, static change in the Coulomb Failure Function (ΔCFF), Tokyo metropolitan area, seismicity.

1. Introduction

On March 11, 2011, a giant interplate earthquake with magnitude (M) 9.0, which was named the 2011 off the Pacific coast of Tohoku Earthquake by the Japan Meteorological Agency (JMA), struck Japan and caused a huge tsunami along the coast of the Japanese Islands. This earthquake, which we will call the Tohoku-oki earthquake for simplicity, was the largest in Japan since the start of modern instrumental observation. It was accompanied by active aftershocks in and around the source region and also by two damaging shallow crustal earthquakes more than 400 km away from the epicenter: an earthquake near the boundary between Nagano and Niigata prefectures on March 12 (M 6.7) and another in the eastern part of Shizuoka prefecture on March 15 (M 6.4). This suggests that the Tohoku-oki earthquake probably caused seismicity rate changes and may trigger large earthquakes in surrounding regions.

The metropolis of Tokyo is located 300 km away from the epicenter of the Tohoku-oki earthquake, and is situated in a high seismicity region, called the Kanto region, where earthquakes with various focal mechanisms have occurred because of its complex tectonics; the Pacific plate (PAC) is subducting from the East, and Philippine Sea plate (PHS) is subducting from the South beneath the Kanto region (Fig. 1). It is very likely that some of these earthquakes may fit the type of focal mechanism that is effectively induced by the Tohoku-oki earthquake.

Furthermore, the probability of a large ($M \sim 7$) earthquake in the Kanto region is high; the Earthquake Research Committee (2004) calculated the probability of earthquake occurrence during the next 30 years as 70%, based on five $M \sim 7$ earthquakes since 1885 (Ishibe *et al.*, 2009a, b). The Japanese government estimates up to 11,000 fatalities and economic losses of 112 trillion yen (about 1.3 trillion US$) if a large interplate earthquake (M 7.3) were to occur in northern Tokyo Bay.

This paper examines whether or not the seismicity increased in the Kanto region due to the great Tohoku-oki earthquake by calculating the static changes in the Coulomb Failure Function (ΔCFF) (e.g., Stein *et al.*, 1992; Reasenberg and Simpson, 1992; Toda *et al.*, 1998) for 30,694 previously observed receiver focal mechanisms. The ΔCFF is defined as $\Delta\text{CFF} = \Delta\tau - \mu'\Delta\sigma$, where $\Delta\tau$ is the shear stress changes resolved on a given failure plane (defined as positive in the fault slip direction), $\Delta\sigma$ is the normal stress changes (defined as positive in the compressive direction), and μ' is the effective coefficient of friction. Positive ΔCFF values promote failures; negative values suppress failures.

2. Method and Data

We calculated the ΔCFF for receiver faults estimated from focal mechanism solutions of the past events because various types of earthquakes occur in the Kanto region. Utilizing the available focal mechanisms of past earthquakes as receiver faults proved to be effective for estimating ΔCFF (e.g., Imanishi *et al.*, 2006; Toda, 2008; Ishibe *et al.*, 2011). In calculating ΔCFF, we assumed an elastic half-space, an apparent coefficient of friction of 0.4, a shear modulus of 40 GPa, and a Poisson's ratio of 0.25.

We excluded small and large absolute values of ΔCFF. For a small absolute value, the sign can easily reverse due to errors in hypocentral locations and focal mechanisms; hence we excluded absolute ΔCFF values less than 0.1 bars, the minimum threshold commonly associated with static stress triggering (e.g., Hardebeck *et al.*, 1998). Extremely high absolute ΔCFF values ($|\Delta\text{CFF}| \geq 15$ bars) obtained

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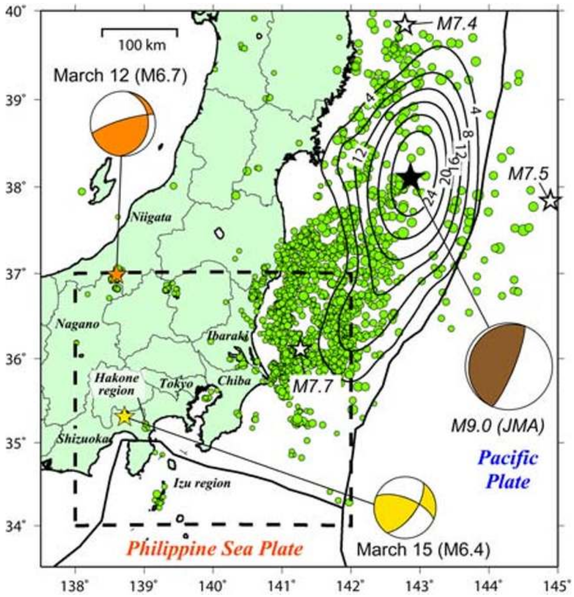

Fig. 1. Variable slip model of the Tohoku-oki Earthquake (black contour) based on continuous Global Positioning System (GPS) observation (Ozawa, personal communication). The black and white stars indicate the epicenters of the mainshock (M 9.0), and large aftershocks ($M \geq 7.0$) that occurred within 40 minutes. GPS observation data including this period was used to estimate coseismic displacement. The orange and yellow stars indicate the epicenters of the earthquake near the boundary between Nagano and Niigata prefectures of March 12 (M 6.7), and the Eastern Shizuoka earthquake of March 15 (M 6.4) from the JMA PDE catalog. The focal mechanisms are based on JMA. The green circles indicate the epicenters of earthquakes occurring within seven days after the mainshock ($M \geq 3.0$, depth ≤ 100 km). The dashed-rectangle region is the target region where the ΔCFF values were calculated. The thin line indicates the boundary between prefectures.

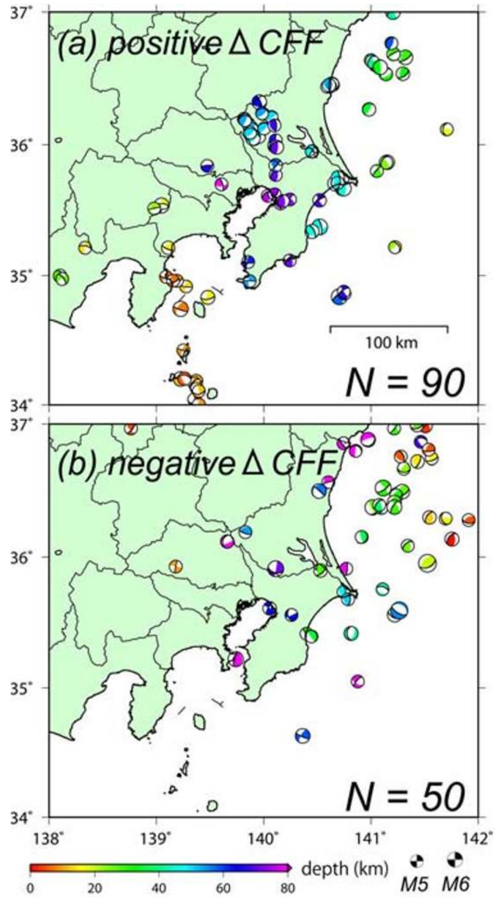

Fig. 2. (a) Focal mechanism distribution of earthquakes with positive ΔCFF ($M \geq 5.0$, depth ≤ 100 km). The black lines indicate the nodal planes on which we have resolved ΔCFF. (b) Focal mechanism distribution of earthquakes with negative ΔCFF ($M \geq 5.0$, depth ≤ 100 km).

near the source fault were also excluded because these may have large uncertainties caused by simplified source geometry and/or slip distribution.

For the source fault, a variable slip model of the Tohoku-oki earthquake (Ozawa, personal communication; Fig. 1), based on continuous Global Positioning System (GPS) observation, was used to calculate ΔCFF. As the receiver faults, we used the 30,694 focal mechanism solutions determined from the initial motion by the National Research Institute for Earth Science and Disaster Prevention (NIED) from July 1979 to July 2003 (Matsumura and Observation and Research Group of Crustal Activities in the Kanto-Tokai District, 2002). Because we do not know which of the two nodal planes an actual receiver fault is on, we repeated our analysis for the first and second nodal planes in their catalog. The Preliminary Determined Earthquake (PDE) catalog from February 1, 2011, to April 1, 2011, provided by JMA on April 2 was used to examine whether or not the forecast seismicity changes actually took place. We also used the TSEIS visualization program package (Tsuruoka, 1998) for the study of hypocenter data.

3. Result and Discussion

Among the past earthquakes we examined, those with positive ΔCFF values outnumbered those with negative values. For the entire data set, there were 18,790 (1st nodal plane)/18,828 (2nd nodal plane) earthquakes with positive ΔCFF, and 5,677 (1st nodal plane)/5,850 (2nd nodal plane) with negative ΔCFF. This suggests that seismicity in the Kanto region will increase as long as earthquakes with the same focal mechanisms continue to occur. Since the ratios of the number of earthquakes with positive ΔCFF to the number with negative ΔCFF are almost identical for both the magnitude thresholds and nodal planes (Table 1), the results for the first nodal plane will be illustrated in the figures.

The increase in seismicity does not necessarily mean that all of the regions will become active. Earthquakes at some depths with some focal mechanisms have positive ΔCFF values while others have negative values (Fig. 2). The positive events (Fig. 2(a)) are concentrated in southwestern Ibaraki prefecture and in the Izu region. For the negative events (Fig. 2(b)), no such geographical concentration can be seen. In southwestern Ibaraki prefecture, the two types of focal mechanisms are mixed: shallower earthquakes with interplate motion between Kanto and the underthrusting PHS, and deeper interslab earthquakes between PHS and PAC. The focal mechanism in the Izu region includes both strike-slip and normal faulting.

As a simple indicator for relative activation or quiescence, we calculated the percentage of positive ΔCFF val-

Table 1. Number of earthquakes with positive/negative/insignificant or high absolute ΔCFFs as a function of threshold magnitudes.

Threshold magnitude	Positive ΔCFF	Negative ΔCFF	Insignificant or high absolute ΔCFF	Total number
1st nodal plane				
2.0	18790 (61.2%)	5677 (18.5%)	6227 (20.3%)	30694
2.5	11992 (59.3%)	3935 (19.5%)	4288 (21.2%)	20215
3.0	5811 (58.6%)	2002 (20.2%)	2100 (21.2%)	9913
3.5	2527 (59.9%)	873 (20.7%)	819 (19.4%)	4219
4.0	995 (59.5%)	365 (21.8%)	312 (18.7%)	1672
4.5	354 (57.1%)	158 (25.5%)	108 (17.4%)	620
5.0	90 (53.6%)	50 (29.8%)	28 (16.7%)	168
2nd nodal plane				
2.0	18828 (61.3%)	5850 (19.1%)	6016 (19.6%)	30694
2.5	11771 (58.2%)	4211 (20.8%)	4233 (20.9%)	20215
3.0	5638 (56.9%)	2142 (21.6%)	2133 (21.5%)	9913
3.5	2395 (56.8%)	929 (22.0%)	895 (21.2%)	4219
4.0	942 (56.3%)	392 (23.4%)	338 (20.2%)	1672
4.5	336 (54.2%)	161 (26.0%)	123 (19.8%)	620
5.0	81 (48.2%)	53 (31.5%)	34 (20.2%)	168

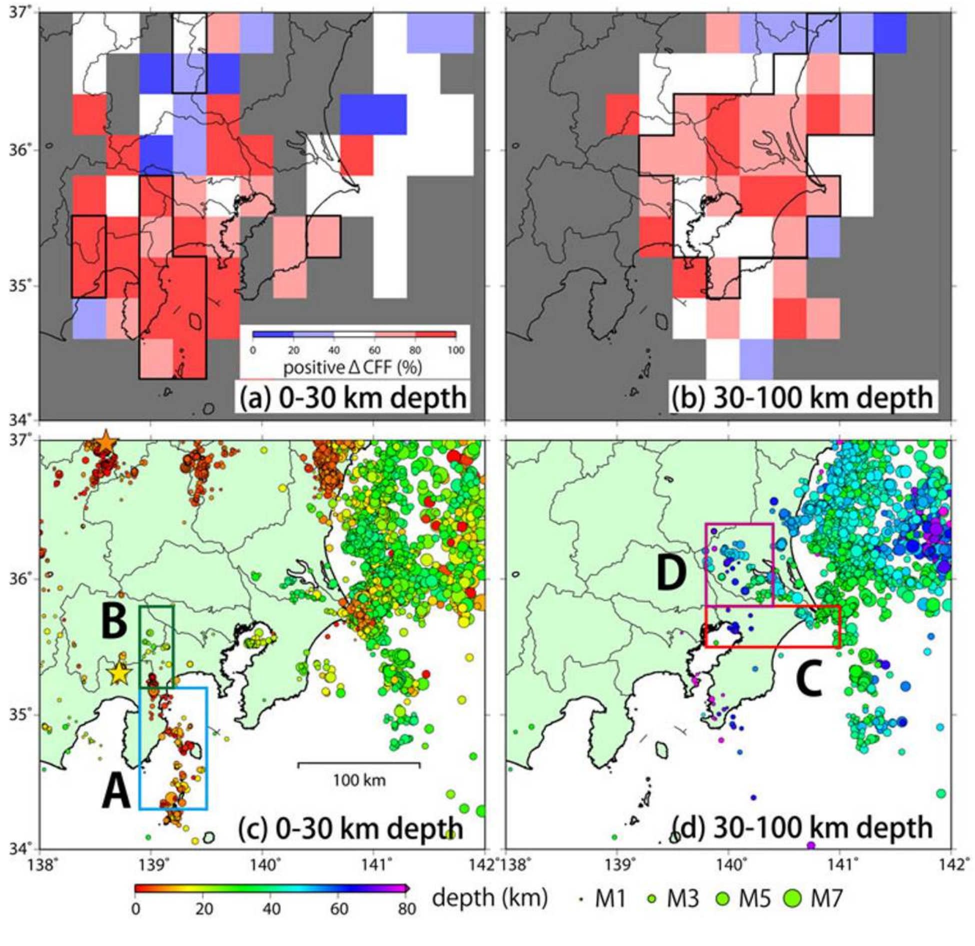

Fig. 3. (a) Percentage of earthquakes with positive ΔCFF among all of the earthquakes with significant changes in each 0.3-degree grid square for a depth of 0 to 30 km. The red (blue) regions are expected to be activated (deactivated) by the ΔCFF due to the Tohoku-oki earthquake. The grid squares surrounded by thick lines indicate that more than 100 focal mechanism solutions are available. (b) Percentage for a depth of 30 to 100 km. (c) Epicentral distribution during the three weeks after the mainshock ($M \geq 1.0$, depth ≤ 30 km). The rectangular regions (A–D) indicate regions where the earthquakes were extracted for Fig. 4. (d) Epicentral distribution during the three weeks after the mainshock ($M \geq 1.0$, 30 km $<$ depth $\leq$ 100 km).

ues among all of the earthquakes with significant changes in each grid with 0.3-degree spacing (Fig. 3). If it is 0%/100%, the ΔCFF for all of the earthquakes are negative/positive. If it is more than 50%, the number of positive ΔCFF values is greater than the number of negative ΔCFF values. When adequate focal mechanisms of past earthquakes are available, this indicates that the seismicity rate is expected to increase.

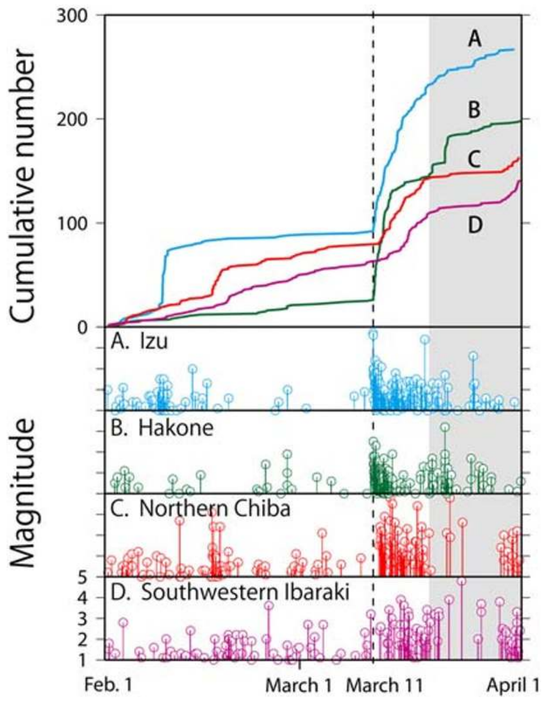

Fig. 4. Cumulative frequency curves and magnitude-time diagrams from February 1 to April 1 in the areas of (A) Izu, (B) Hakone, (C) northern Chiba prefecture, and (D) southwestern Ibaraki prefecture. The gray zone indicates possible intervals with a higher magnitude threshold.

Among the grid squares with a large number of focal mechanism solutions, we chose four areas (A, B, C, and D in Fig. 3) for verification of the predicted increase in seismicity. In all areas, the seismicity increase after the giant event is significant (Fig. 4). In the Izu region (area A), an active earthquake swarm took place in early February, while in northern Chiba prefecture (C), less active swarm-like activity occurred in the middle of the month. The increase in seismicity indicates that the seismicity rate changes in small earthquakes are fundamentally well-explained by the ΔCFF due to the Tohoku-oki earthquake. The increase in seismicity implies an increase in the occurrence probability of large earthquakes in these areas. However, forecasting large induced earthquakes is not straightforward because large earthquakes are less frequent and the background stress levels for individual events are critical.

The correlation between a decrease in seismicity and areas with negative ΔCFF, called the "stress shadow", might be a topic of discussion. However, unlike seismicity increases, it is difficult to distinguish whether a decrease in seismicity is actual or artificial because the detection capability of small events may be lowered just after a great earthquake (e.g., Ogata and Katsura, 2006). The magnitude threshold in the PDE catalog is temporally higher, presumably because the determination of the hypocenters was delayed due to occurrences of a large number of earthquakes after March 11.

Earthquakes of a previously unknown type took place in northern Ibaraki prefecture. The focal mechanisms in this cluster are dominantly normal-type, with the T-axis in the E-W direction, presumably induced by the extension of the upper plate in the gigantic thrusting. Since earthquakes with this type of mechanism are not seen in the focal mechanism catalog of past events, our method cannot forecast them. The method used in this study is entirely based on the assumption that the focal mechanisms of past and future events are similar.

There are some other possible factors that may affect seismicity rate changes and/or occurrences of large earthquakes. The first is the contribution of dynamic stress changes (e.g., Hill *et al*., 1993; Anderson *et al*., 1994). The Izu and Hakone regions are sites of geothermal and recent volcanic activities, and the resulting dynamic stress changes might be important for earthquake triggering just after the mainshock. The second factor is pore pressure change. An acceleration of slip at the deeper plate boundary might cause excess fluid dehydration, affecting the seismicity in a tiny volume of the region studied. The third factor is the contribution of post-seismic slip along the plate boundary and large aftershocks, although the slip of aftershocks that occurred just after the mainshock is included.

Our results are based on a preliminary source model and the earthquake catalog. Various fault models based on the tsunami waveform, far-field body waves, strong motion seismographs, and others are now being proposed and updated. In addition, the progress of significant afterslip is suggested, based on GPS observation. The PDE catalog that was used for post-mainshock seismicity will be revised later. Therefore, the correlation between the ΔCFF and changes in the seismicity rate should be re-examined using the final catalog and updated fault models. However, these would not affect the main results of this study.

4. Concluding Remarks

An increase in seismicity in the Kanto region after the Tohoku-oki earthquake was forecast on the basis of calculation of 30,694 static changes in the Coulomb Failure Function (ΔCFF). Almost 19,000 focal mechanisms of previous events in this region indicate a significant increase in ΔCFF compared with less than 6,000 that indicate a significant decrease. However, the areas where active seismicity is predicted are mainly in the southwestern Ibaraki and northern Chiba prefectures, where intermediate-depth earthquakes occur, and in the shallow crustal areas of the Izu and Hakone regions. A comparison of seismicity before and after the giant event shows that our method successfully predicted the activation of seismicity.

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