The Delayed Decrease of Seismicity In The Eastern Margin of The Japan Sea Due To The Megathrust Event In 2011 Along The Japan Trench

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Abstract

In the eastern margin of the Japan Sea, off the west coast of Tohoku district, the seismicity increased right after the M9 megathrust event off the east coast of the Tohoku district on March 11, 2011. Four months later, the seismicity decreased to the half level of that before the M9 event. Such quantitative study was done by the point-process model selection with AIC. The decrease lasted for eight years until an M6.7 event occurred within the area in 2019. When we compare the seismicity change between before and after the M9 event, with the post seismic change of the maximum shear stress obtained by the viscoelastic simulation for a thousand years after the M9 event, we can estimate a loading rate of the shear stress in the area before the M9 as 24 kPa/y. For the term after the M9 event, the rate is a half of it; 12 kPa/y. When we assume the whole dilatation change due to the M9 event had been canceled by the time of the M6.7, the increasing rate of the mean stress after the M9 event is 21 kPa/y at most. When we will be able to use JMA catalog for 2020 or later years, we can obtain the seismicity level after the M6.7 quantitatively, and we will be able to narrow down this estimation.
Keywords

The eastern margin of the Japan Sea, Seismicity decrease, Viscoelastic aftereffect,

Megathrust event, Point-process model selection, Strain rates before and after M9

Main Text

Introduction

The M9 mega-thrust inter-plate earthquake, which occurred off the Pacific coast of the Tohoku district on Mar. 11, 2011 (hereafter “the M9 event”), drastically changed the stress status of the northeastern Japan. The change was reflected as the dramatic activation of seismicity in many areas which had been aseismic before (e.g. Ogata, 2012). Many papers were published (e.g. Toda et al., 2011; Ishibe et al., 2015) explaining the change of seismicity in many regions for various receiver fault planes by Coulomb Failure Stress change (ΔCFS).

In the eastern margin of the Japan Sea, which is 300 to 400-km away from the center of the source area of the M9 event (Fig. 1) along the direction of the Pacific Plate
motion towards the northeastern Japan, the immediate increase of seismicity was also observed like many other regions in Japan. That increase was mainly due to the occurrence of the M6.4 a half day after the M9 event (Table 1). It is a strike-slip type earthquake in the aftershock area of the destructive thrust earthquake of M7.7 in 1983. It was the largest event around the area at that time, since Japan Meteorological Agency (JMA) started to use unified seismic data of Japan for their catalog on Oct. 1, 1997. In that region, we noticed that the significant decrease followed later (Tsumura, personal communication). The decrease sustained for more than a few years. We reported it promptly (Matsu’ura et al., 2017), and waited for the tentative hypocenter catalog of JMA would be revised for the inhomogeneous term after the M9 event. However, the M6.7 thrust event renewed the maximum M of the area on June 18, 2019. Following this event, the seismicity seems to revert to the level before the M9 event. The occurrence of the M6.7 event made us possible not only to describe the decrease of the seismicity, but also to estimate the stress status in the area for eight years after the M9 event. Since the M9 event is gigantic, in addition to the coseismic effect, which is usually
used to explain the seismicity change by ΔCFS analysis, the viscoelastic post seismic
effect for eight years must be another vital factor to affect the seismicity transition.

When we quantitatively compare the post M9-changes of seismicity with the post
seismic changes in stress field of the area, it will give us an estimation on the
background stress status of the area. Here we examined the seismicity with the latest
catalogue of JMA to be compared with the three dimensional simulation on the
viscoelastic effect of the M9 event to the area.

Data and Method for the Seismicity Analysis

In Fig.1, the location of the studied area is shown. The A-A’ line is parallel to the
convergent direction of the Pacific Plate (PAC) toward the northeastern Japan. This line
passes through the peak of the co-seismic slip in the focal region of the M9 event
obtained by Hashimoto et al. (2012). The area around this line must be the most affected
part in the eastern margin of the Japan Sea by the M9 event. In order to prevent
intentional selection of earthquakes, events within the 150km×300km rectangle, whose
shorter side is parallel to the line A-A’, and whose center is on the line A-A’, were
selected.

We used JMA hypocentral catalog obtained from its website on July 8th, 2021. For the period from Oct. 1st, 1997 to the end of 2019, hypocenters of the depth of 60km or shallower, JMA M2.0 or larger were selected. The total number of earthquakes for 8127 days are only 4224. Hereafter, those events plotted as red crosses in Fig. 1 are examined. Among them, the three largest events are listed in Table 1. Although we chose 60km as the depth limit, our target seismicity is only that in the shallow crust. We chose 60km only to avoid losing some very shallow earthquakes in the early part of the JMA catalog due to the poor depth accuracy for offshore events.

In Fig. 2, cumulative number of the whole data of 22.25 years are shown for the whole term. Even from the simple cumulative numbers, it is apparent that the seismicity increased right after the M9 event (Fig. 2(b), (c), and (d)). A half day after the M9 event, the second largest event of the area (M6.4) was induced within the aftershock area of the 1983 event, and many earthquakes followed it. However, the seismicity averaged over a long term after the M9 event is lower than that of before (Fig. 2(a)). Since the seismicity of this area is not very active, we did not use ETAS model
(Ogata, 1988) for the point process analysis in the present study. We excluded the 9% data in the tail part, which is the half-year period after the largest event of M6.7 on June 18, 2019, from the analysis to eliminate aftershocks of this largest event. A half year is too short to analyze the seismicity level after the M6.7 confidently. We examined 3844 events, which occurred in the 7930 days since Oct. 1st, 1997, and focused on the base rate comparison before and after the M9 event.

When $N(M_{th}, S, E)$ is number of earthquakes of $M \geq M_{th}$ during the period from $S$ to $E$, the averaged occurrence rate of $M \geq M_{th}$ for that term; $\lambda(M_{th}, S, E)$ is

$$\lambda_{\text{ave.}} = \lambda(M_{th}, S, E) = \frac{N(M_{th}, S, E)}{(E-S)}. \quad (1)$$

The Poisson model with the rate $\lambda(M_{th}, 0, T_{all}E)$ is the simplest point process model that there was no significant change of $\lambda$ temporarily, during the period of $\{0, T_{all}\}$.

Since the number of parameters ($n_p$) for this model is one, AIC of this model is

$$AIC_{all} = AIC(M_{th}, 0, T_{all}, n_p) = 2(n_p - \ln \text{Likelihood})$$

$$= 2 - 2 \times N(M_{th}, 0, T_{all})(\ln \lambda_{\text{ave.}} - 1). \quad (2)$$

When $\lambda$ changed at $t=T_c$, $\lambda$ for the term before $T_c$ and $\lambda$ for the term after $T_c$ are,

$$\lambda_{\text{left}} = \lambda(M_{th}, 0, T_c) = \frac{N(M_{th}, 0, T_c)}{T_c}, \quad (3)$$
\[
\lambda_{right} = \lambda(M_{th}, T_c, T_{all}) = \frac{N(M_{th}, T_c, T_{all})}{(T_{all} - T_c)}, \tag{4}
\]

and AIC of this model is

\[
AIC_{T_c} = AIC(M_{th}, 0, T_c, 1) + AIC(M_{th}, T_c, T_{all}, 1) + 2 + \text{Penalty}, \tag{5}
\]

\[
AIC_{T_c} \leq \max \ AIC_{T_c} = 18 - 2 \times N(M_{th}, 0, T_c) \times \{ \ln \lambda_{left} - 1 \} - 2 \times N(M_{th}, T_c, T_{all}) \times \{ \ln \lambda_{right} - 1 \}. \tag{6}
\]

The penalty of introducing \( T_c \) in a model is not larger than 12 (Kumazawa et al., 2010).

When \( AIC_{T_c} < AIC_{all} \), the model with the rate change is selected, and the \( T_c \) of the best model minimizes \( AIC_{T_c} \). In order to avoid the effect of inhomogeneity in the long term catalog, \( M_{th} \) of 2.5 and 3.0 are examined for model selections.

Result on the seismicity transition

In Fig. 3(a), \( \lambda_{left} \) and \( \lambda_{right} \) of \( M_{th} = 2.5 \) are shown at \( T_c \) of each day. When the M6.4 event and its aftershocks became inconspicuous, \( \lambda_{right} \) became rather stable. Models with \( T_c \) within a few-year term after the M9 event give far smaller AIC (Fig. 3(c)) than that of Eq. (2). It is confirmed that the occurrence-rate decrease delayed for a few months from the occurrence time of the M9 event (Fig. 3(d)). In order to detect the
start of that delayed decrease correctly, data within the one month after the M9 event is
excluded in the next analysis (Fig. 4). When $M_{th}=3.0$, the similar delayed decrease of
AIC is also confirmed (Fig. 5). $T_c$s with smallest three AICs of each model are listed in
Table 2 with each occurrence rate. From Figs. 3, 4, and 5, and Table 2, it is apparent that
the change point $T_c$ is not very sharp. $\lambda_{right}$ is a half of $\lambda_{left}$ for each $M_{th}$. This
delayed decrease started about four months from the M9 event. Even the immediately
induced M6.4 event and its aftershocks are included, the delayed decrease is significant
(Fig. 3). The decrease rate sustained for more than four years, which made us notice it
even from the raw distribution maps of epicenters.

Due to the COVID-19, the JMA hypocenter catalog is not yet fixed for 2020 and
2021 at present. Since available catalog after the M6.7 covers only a half year, we
cannot obtain $\lambda$ for the period after M6.7 by eliminating its aftershocks in this study
precisely. However, the most right part of Fig. 2 looks that $\lambda$ after the M6.7 at the end of
2019 is larger than $\lambda_{right}$. This must be verified in the future study with a longer
catalog. In this study, we report that the seismicity decrease to the half level prevailed
for eight years after four-month immediate activation after the M9 event.
Estimation of viscoelastic effect of the M9 event to the area

In order to estimate the deviatoric stress field of the studied area for eight years after the M9 event, not only the coseismic change, but also the post seismic viscoelastic effect of the M9 event should be included consistently. Fortunately, Hashima et al. (2014) already calculated coseismic and post seismic strain fields for a thousand years after the M9 event in the three dimensional space. In Figs. 6 and 7, vertical sections along A-A’ line of Fig. 1, of changes in dilatation and the maximum shear strain after the M9 event are shown according to their simulation. They used the coseismic slip distribution of the M9 event obtained by Hashimoto et al. (2012), because the PAC plate geometry (Hashimoto et al., 2004) of the simulation is in common with their source inversion. They simulated the elastic coseismic change and the viscoelastic after effect with the structure shown in Table 3. The area we examined the seismicity is the shallow part of the left end of their simulated region (400~550 km horizontally remoted to the WNW direction from the trench axis on the A-A’ line).

In Fig. 8, temporal changes of the mean stress and the maximum shear stress at the
point shown in Fig. 6 (10km-depth and -422km from the trench axis on A-A’) are plotted. Since that point is in the elastic layer, the dilatation and the maximum shear strain are proportional to the mean stress (the expanding direction is positive), and the maximum shear stress, respectively.

The simple approximated expression of the isotropic stress $\sigma_{iso}(t)$ of the point (-422, 10) at time t (solid line of Fig. 8) is

$$\sigma_{iso}(t) = 0.128 + 0.104 \times (1 - \exp^{-0.057t}) \quad \text{when} \ t \leq 40y \ \text{in MPa.} \quad (7)$$

The increase rate decays with an exponential function with a half-life of 12 years. About a quarter of the coseismic dilatation increased in 40 years after the M9 event due to the viscoelastic post effect. After around fifty years, $\sigma_{iso}(t)$ starts decreasing, and only 35% of the coseismic dilatation is left at $t=1000y$ (see Fig. 10 of Hashima et al., 2014) in this region.

The maximum shear stress $S_{max}(t)$ (broken line in Fig. 8) can be expressed as

$$S_{max}(t) = (0.194 + 0.014t) \quad \text{when} \ t \leq 3y, \quad (8)$$

$$S_{max}(t) = S_{max}(3) + 0.26 \times \left(1 - \exp^{-0.047(t-3)}\right) \quad \text{when} \ 3y < t \leq 40y \ \text{in MPa.} \quad (9)$$
For the first three years, $s_{max}$ increases almost linearly. Then the increase rate decays with an exponential function with a half-life of 14.75 years. In the examined area, the post seismic maximum shear stress change for 40 years is a half of the coseismic change. As Fukahata and Matsu’ura(2018) pointed out, even the viscosity is set to be $10^{19}$ Pa s, the relaxation time at this point is larger than 10 years. The relaxation time of the isotropic stress is slightly shorter than that of maximum shear stress in the studied area. After around a hundred years, the maximum shear stress starts decreasing in this region. However, only 7% of its value at $t=100y$ decreases at $t=1000y$ (see Fig. 11 of Hashima et al., 2014).

The coseismic changes of the mean stress, and of the maximum shear stress at the point are 0.13 MPa, and 0.19 MPa, respectively. After eight years ($t=8$), these increased to 0.17 MPa, and 0.29 MPa, respectively. Until the thrust-type M6.7 occurred in 2019, the post seismic dilatation was 30% of the coseismic dilatation, while the post seismic maximum shear stress increase was the half of the coseismic change.

Discussion
Among seismicity changes after a large event, activations such as aftershocks are often easy to be detected regardless of the seismicity status before that large event. The ETAS effect boosts the detectability of seismicity increase. It is no wonder that DeVries et al. (2018) selected $\Delta \tau_{\text{max}}$ that corresponds only to the activation (Matsu’ura and Terakawa, 2021) as the best indicator for predicting spatial patterns of aftershocks.

However, what we found this time is the decrease to the half level that lasted for eight years after the main shock. In our case, $\Delta \tau_{\text{max}}$ is not a good indicator at all. Since $\Delta \text{CFS}$ depends on the orientations of receiver faults, it can be used to explain the decrease of seismicity as well as the increase. However, it is impossible to determine fault orientations of all 3884 events we analyzed. $\Delta \text{CFS}$ is not very effective to what we found.

As Terakawa et al. (2013) pointed out, the occurrence of the M6.4 should be affected by the change of pore fluid pressure in the aftershock area of the 1983 event. Its fault orientation was not at all favorable to the background stress field, which is roughly compressional in the direction of the PAC subduction. Recently, Terakawa et al. (2020) expanded $\Delta \text{CFS}$ to the change of energetics-based Failure Stress ($\Delta \text{EFS}$) as the index
for predicting induced seismicity after a large event. $\Delta EFS$ does not depend on the orientations of receivers, and it does include the change of pore fluid pressure due to a large earthquake. In the four month-period between the occurrence time of the M9 event and the Tc determined in the third section, $\Delta EFS$ must be used for the analysis, since the change of pore fluid pressure in the studied area should have affected the seismicity.

However, after Tc, the seismicity of the area is so stable for eight years. We can treat the pore fluid pressure after Tc as a part of the background stress field, which should have been changing very smoothly in the area, after the drastic change of pore fluid had been settled before Tc.

Therefore, we assume that the gradually changing crustal stress after Tc was the summation of the background tectonic stress and the coseismic and post-seismic stress changes due to the M9 event. The post-seismic increase of 96 kPa in the maximum shear stress for eight years resulted in the post-seismicity of the area. To sustain the double level of seismicity for years before the M9 event, the double of the post maximum shear stress change is necessary. It give us 24 kPa/y in the studied area as the tectonic accumulation rate of shear stress before the M9 event. This rates give us a
recurrence time estimation of about two hundred years for a major event of this area

with 5 MPa stress drop. As the shear strain rate, it is equivalent to $4 \times 10^{-7}/\text{y}$. 

When we assume that the dilatation due to the M9 event, including both coseismic and post seismic changes, had been almost canceled by the time of the M6.7 in the studied area, the tectonic rate of the compressional stress in this area after the M9 event becomes 21 kPa/y. It is also equivalent to the strain rate of $4 \times 10^{-7}/\text{y}$. If we assume that the recovery was half of the pre-M9 level at the time of M6.7, the rate is 10 kPa/y. In order to determine the current mean stress status, we should examine the post M6.7 seismicity quantitatively in future study with a catalog with the extended period.

As the order estimation of the background loading rate in the eastern margin of the Japan Sea, we get 24 kPa/y of shear rate for the term before the M9 event, and 12 kPa/y of shear rate for the term after the M9 event. Since the seismicity decrease we found was stable for eight years, ignoring the effect of changes in the pore fluid pressure of the area does not affect our estimations seriously. We also ignore the effect of after slips around the source area of the M9 event, because the studied area is more than 150 km away from the regions slipping afterwards. As the background accumulation rate of
compressional mean stress after the M9 event, we get 21 kPa/y or lower. With the
analysis of the seismicity after the M6.7 event, it will be better to use ΔEFS to examine
post-M9 mean-stress status further.

The rate of horizontal strain obtained from GPS data for the eastern margin of the
Japan Sea before the M9 event (Sagiya, 2004) is a quarter of what we obtained in this
study. Fukahata et al. (2020) obtained EW-direction deformation rates from GPS data in
the Niigata region as $6 \times 10^{-8}$/y for pre-M9, and $3 \times 10^{-8}$/y for post-M9 terms. Their strain
rates are two dimensional. Plane strain is usually smaller than three-dimensional strain.

It is considered that rates we obtained are within the permissible range of the GPS
observation. The shear strain rate for the post-M9 term we obtained is a half of the pre-
M9 term. It is coincide with what Fukahata et al (2020) obtained.

**Conclusion**

We examined the delayed decrease of seismicity of the area in the eastern margin
of the Japan Sea with the point process model selection. The area remotes 300-400 km
horizontally away along the plate motion direction from the center of the mega-thrust
event in 2011. In this area, the seismicity increased right after the M9 event with the
induced M6.4 strike-slip event. After about four months, the seismicity became the half
level of that before the M9 event. The decreased rate lasted for eight years. After 8.25
years, an M6.7 thrust-type event occurred in the area. Due to the aftershocks of this
event, we cannot determine the base occurrence rate at present yet with the fixed JMA
catalogue. However, the raw cumulative number curve suggests that the seismicity is
recovering after the M6.7.

Referring the viscoelastic simulation, the coseismic and post seismic dilatation
change for eight years due to the M9 was examined. It gives the 21 kPa/y as the
maximum tectonic increase rate of mean compressional stress on this area after the M9
event, when we assume the occurrence of the M6.7 represents the full recovery of the
compressional stress field in the eastern margin of the Japan Sea. When the JMA
catalogue will allow us to analyze seismicity after the M6.7 fully, the mean stress level
at present will be clearer.

From the post seismic maximum shear strain change and the half level of the
seismicity after the M9 event, the pre-M9 seismicity in the area suggests 24 kPa/y as the
rate of tectonic shear stress increase before the M9 event. The estimated loading rates of
this region are a several times larger than those obtained from the GPS data in the plane
strain framework. However, our finding that the pre-M9 term rate is the double of the
post-M9 term well agrees with that obtained for EW-deformation rate in Niigata
(Fukahata et al., 2020). For a long-term hazard estimation of the eastern margin of the
Japan Sea area, the rates we obtained will be another proxy values.

Declarations

The authors must provide the following sections under the heading “Declarations”.

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

List of abbreviations

ΔCFS: Coulomb Failure Stress change

ΔEFS: the change of energetics-based failure stress

F-net: F-net Broadband Seismograph Network
Availability of data and materials

Mw, mechanism, and hypocentral depth of centroid moment tensor solutions for most major events in and around Japan are available at the F-net website: https://www.fnet.bosai.go.jp/top.php?LANG=en (obtained on July 8, 2021).

JMA hypocenter catalogue is available at: http://www.data.jma.go.jp/svd/eqev/data/bulletin/hypo.html. (obtained on July 8, 2021) However, JMA revises the past hypocenter catalogues irregularly. Most revisions are usually trifling matters.

Competing interests

Not applicable

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Research Promotion (HERP) of the Japanese government.

Authors' contributions

Ritsuko S. Matsu’ura analysed the seismicity. Akinori Hashima prepared the viscoelastic calculations. Takeo Ishibe examined the F-net data in the area for the discussion.

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Dr. Kenshiro Tsumura first found the seismic quiescence in the eastern margin of the Japan Sea and encouraged us to analyze it quantitatively.

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Fig. 1. The map of the examined area, and the distribution of examined shallow earthquakes. All M≥2.0 earthquakes of depth=<60km in JMA catalog from Oct. 1\textsuperscript{st}, 1997, to Dec. 31\textsuperscript{st}, 2019 in the black dotted square of the left map are shown by gray crosses in the right large map. Red crosses are analyzed earthquakes. M6.4 on 2012 Mar. 12 (JST) in the north, and M6.7 on 2019 June 18 in the southeast are the only two M≥6.0 events. Source area of the megathrust M9 event in 2011 is after Hashimoto et al. (2012). Ticks for each 100km are shown for the A-A’ line, which is parallel to the PAC-plate motion, is the same as the line in Fig. 7 of Hashima et al. (2014).

Fig. 2. Cumulative number of events shown by red crosses in Fig. 1. (a) M-T plot of events. (b) Cumulative numbers of the whole term with three thresholds of M. For the period around the occurrence time of the M9 event (shown by gray
squares on each line) are expanded in (c), (d) and (e), respectively. The slope of five occurrence rates are shown by black lines as references to see rates from cumulative number lines.

Fig. 3. Occurrence rates and AIC at each Tc for M≥2.5.

(a) Daily occurrence rate of before Tc (Blue line) and after Tc (Red line) terms are shown at each Tc. Black line shows the average rate of the whole term.

(b) M-T plot of M≥2.5 for the same period.

(c) AIC values for each Tc are plotted at Tc. The black line shows the AIC for the model without Tc, i.e. the constant rate through the whole term. The part in the red broken square are expanded in (d).

Fig. 4. Occurrence rates and AIC at each Tc for M≥2.5 without one month data after the M9 event.

Tc in July 2011 gives the smallest AIC. See the caption of Fig. 3.
Fig. 5. Occurrence rates and AIC at each Tc for M\geq3.0 without one month data after the M9 event.

Tc in Aug. 2011 gives the smallest AIC. See the caption of Fig. 3.

Fig. 6. Temporal changes of the isotropic strain due to the M9 event.

The vertical section of the isotropic strain changes along the line A-A’ in Fig. 1 at t=0 (coseismic), 5, 10, 20, 30, 50, and 100 years after the M9 event are shown by color and contours. The red and blue color scales represent expansion, and contraction, respectively. Contours of $5\times10^{-5}$, $\pm2\times10^{-5}$, $\pm1\times10^{-5}$, $\pm5\times10^{-6}$, $\pm2\times10^{-6}$ are also shown by thin lines. The thick solid line indicates the PAC plate interface shallower than 50km.

The thin horizontal line at 40km-depth indicates the interface between elastic and viscoelastic layers. The analyzed area is shown by the blue dotted rectangle in the top figure. The green star in the top figure shows the position of the point whose stress change is plotted in Fig. 8. [made after Hashima et al. (2014)]
Fig. 7. Deviatoric shear strain changes due to the M9 event.

The vertical section of the deviatoric strain fields along the line A-A’ in Fig. 1 at t=0 (coseismic), 5, 10, 20, 30, 50, and 100 years after the M9 event.

The deviatoric maximum shear strain is shown by color, and contours of $5 \times 10^{-5}$, $2 \times 10^{-5}$, $1 \times 10^{-5}$, $5 \times 10^{-6}$, and $2 \times 10^{-6}$. The black and white bars show the extension and contraction directions with those magnitudes at each point, respectively. See the caption of Fig. 6.

Fig. 8. Changes of the mean stress (extension positive), and the maximum shear stress at the point of (422km-west from the trench axis, 10km-depth) shown in Fig. 6 due to the M9 event, for 50 years.

Since the point is in the elastic layer, dilatation and the maximum shear strain are proportional to the mean stress, and the maximum shear stress, respectively. With the bulk and shear moduli in Table 3, these are converted to stresses. The values at t=0 are coseismic values.
| Date (JST)       | JMA M | Mw  | depth (km) | type   |
|------------------|-------|-----|------------|--------|
| 1997/11/23 12:50| 5.8   | 5.5 | 8          | thrust |
| 2011/3/12 4:46  | 6.4   | 6.1 | 5          | strike slip |
| 2019/6/18 22:22 | 6.7   | 6.4 | 11         | thrust |

Mw and depth are from F-net.

| Tc in 2011 days after the M9 | AIC2.5  | AIC3.0w/c | AIC2.5 w/c | λ_{left}2.5 | λ_{right}2.5 | λ_{left}3w/c | λ_{right}3w/c | λ_{right}2.5 |
|------------------------------|---------|-----------|------------|-------------|-------------|-------------|-------------|-------------|
| July 3 113                   | 7176.4  | 3563.4    | 7354.8     | 0.20        | 0.10        | 0.073       | 0.036       | 0.21        |
| July 24 134                  | 7176.5  | 3562.1    | 7355.0     | 0.20        | 0.10        | 0.073       | 0.035       | 0.21        |
| Aug. 10 151                  | 7178.4  | 3561.9    | 7357.1     | 0.20        | 0.10        | 0.073       | 0.035       | 0.21        |

Underlined value is the smallest AIC for each data set. A numerical subscript for AIC and λ represents Mth of each data set. “w/c” represents that the data without a month after the M9 event is used. All λs are occurrence rates per one day.

| Table 3. The structural parameter of the elastic-viscoelastic layered half-space model used for the simulation (after Hashima et al., 2014). |
| Layer No. | Thickness (km) | Bulk modulus (10^{10} Pa) | Shear modulus (10^{10} Pa) | Density (10^3 kg/m^3) | Viscosity (10^{19} Pa s) |
|-----------|----------------|--------------------------|----------------------------|-----------------------|-------------------------|
| 1         | 40             | 5.1                      | 3.2                        | 2.6                   | ∞                       |
| 2         | ∞              | 13                       | 6.9                        | 3.4                   | 1                       |
Figure 1

The map of the examined area, and the distribution of examined shallow earthquakes. All M>=2.0 earthquakes of depth=<60km in JMA catalog from Oct. 1st, 1997, to Dec. 31st, 2019 in the black dotted square of the left map are shown by gray crosses in the right large map. Red crosses are analyzed earthquakes. M6.4 on 2012 Mar. 12 (JST) in the north, and M6.7 on 2019 June 18 in the southeast are the only two M>=6.0 events. Source area of the megathrust M9 event in 2011 is after Hashimoto et al. (2012). Ticks for each 100km are shown for the A-A’ line, which is parallel to the PAC-plate motion, is the same as the line in Fig. 7 of Hashima et al. (2014).
Cumulative number of events shown by red crosses in Fig. 1. (a) M-T plot of events. (b) Cumulative numbers of the whole term with three thresholds of M. For the period around the occurrence time of the M9 event (shown by gray squares on each line) are expanded in (c), (d) and (e), respectively. The slope of five occurrence rates are shown by black lines as references to see rates from cumulative number lines.
Figure 3

Occurrence rates and AIC at each Tc for M≥2.5. (a) Daily occurrence rate of before Tc (Blue line) and after Tc (Red line) terms are shown at each Tc. Black line shows the average rate of the whole term. (b) M-T plot of M≥2.5 for the same period. (c) AIC values for each Tc are plotted at Tc. The black line shows the AIC for the model without Tc, i.e. the constant rate through the whole term. The part in the red broken square are expanded in (d).
Occurrence rates and AIC at each Tc for M≥2.5 without one month data after the M9 event. Tc in July 2011 gives the smallest AIC. See the caption of Fig. 3.

Figure 4
Figure 5

Occurrence rates and AIC at each Tc for M≥3.0 without one month data after the M9 event. Tc in Aug. 2011 gives the smallest AIC. See the caption of Fig. 3
Temporal changes of the isotropic strain due to the M9 event. The vertical section of the isotropic strain changes along the line A-A’ in Fig. 1 at $t=0$ (coseismic), 5, 10, 20, 30, 50, and 100 years after the M9 event are shown by color and contours. The red and blue color scales represent expansion, and contraction, respectively. Contours of $5 \times 10^{-5}$, $±2 \times 10^{-5}$, $±1 \times 10^{-5}$, $±5 \times 10^{-6}$, $±2 \times 10^{-6}$ are also shown by thin lines. The thick solid line indicates the PAC plate interface shallower than 50km. The thin horizontal line at 40km-
depth indicates the interface between elastic and viscoelastic layers. The analyzed area is shown by the blue dotted rectangle in the top figure. The green star in the top figure shows the position of the point whose stress change is plotted in Fig. 8. [made after Hashima et al. (2014)]

Figure 7

Deviatoric shear strain changes due to the M9 event. The vertical section of the deviatoric strain fields along the line A-A’ in Fig. 1 at t=0 (coseismic), 5, 10, 20, 30, 50, and 100 years after the M9 event. The deviatoric maximum shear strain is shown by color, and contours of $5 \times 10^{-5}$, $2 \times 10^{-5}$, $1 \times 10^{-5}$, $5 \times 10^{-6}$, and $2 \times 10^{-6}$. The black and white bars show the extension and contraction directions with those magnitudes at each point, respectively. See the caption of Fig. 6.

Figure 8

Changes of the mean stress (extension positive), and the maximum shear stress at the point of (422km-west from the trench axis, 10km-depth) shown in Fig. 6 due to the M9 event, for 50 years. Since the point is in the elastic layer, dilatation and the maximum shear strain are proportional to the mean stress, and
the maximum shear stress, respectively. With the bulk and shear moduli in Table 3, these are converted to stresses. The values at t=0 are coseismic values.

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