Time-Independent Forecast Model For Large Crustal Earthquakes in Southwest Japan Using GNSS Data

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- 1 **Time-Independent Forecast model for Large Crustal Earthquakes in Southwest**
- 2 **Japan using GNSS Data**
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Abstract

In this study, we developed a regional likelihood model for crustal earthquakes using geodetic strain rate data from southwest Japan. First, smoothed strain rate distributions were estimated from continuous GNSS measurements. Second, we removed the elastic strain rate attributed to interplate coupling on the subducting plate boundary, including the observed strain rate, under the assumption that it is not attributed to permanent loading on crustal faults. We then converted the geodetic strain rates to seismic moment rates and calculated the 30-year probability for $M \geq 6$ earthquakes in $0.2 \times 0.2^\circ$ cells, using a truncated Gutenberg–Richter law and time-independent Poisson process. Likelihood models developed using different conversion equations, seismogenic thicknesses, and rigidities were validated using the epicenters and moment distribution of historical earthquakes. The average seismic moment rate of crustal earthquakes recorded during 1583–2020 was only 13–20 % of the seismic moment rate converted from the geodetic data, which suggests that the observed geodetic strain rate includes considerable inelastic strain. Therefore, we introduced an empirical coefficient to calibrate the moment rate converted from geodetic data with the moment rate of the

earthquakes. Several statistical scores and the Molchan diagram showed that all models could predict real earthquakes better than the reference model, in which earthquakes occur uniformly in space. Models using principal horizontal strain rates exhibited better predictive skill than those using the maximum horizontal shear strain rate. There was no significant difference in the predictive skill between uniform and variable distributions for seismogenic thickness and rigidity. The preferred models suggested high 30-year-probability in the Niigata–Kobe Tectonic Zone and central Kyushu, exceeding 1% in more than half of the analyzed region. Model predictive skill was also verified by a prospective test using earthquakes recorded during 2010–2020. This study suggests that the proposed forecast model based on geodetic data can improve the regional likelihood model for crustal earthquakes in Japan in combination with other forecast models based on active faults and seismicity.

Keywords

regional earthquake likelihood model, long-term forecast, crustal earthquake, global navigation satellite system, southwest Japan

37 **Introduction**

38 The development of a regional earthquake likelihood model (RELM) is a practical
39 product of earthquake science that can be used to assess earthquake hazards and
40 enhance human preparedness for earthquake disasters. Most RELMs use either active
41 faults or past seismicity to estimate long-term earthquake rates (e.g., Zechar et al.,
42 2013). Crustal deformation measured by geodetic instruments including global
43 navigation satellite system (GNSS) can also provide useful information on future
44 earthquakes because earthquakes convert elastic deformation to inelastic permanent
45 deformation according to Reid's (1911) elastic rebound theory (Rhoades et al., 2017).
46 For example, Ward (1994) stated that geodetic data can be used to quantify the
47 earthquake potential of poorly known faults during seismic hazard analysis in southern
48 California. Forecast models using GNSS data have successfully forecast large
49 earthquakes on both global (e.g., Bird and Kreemer, 2015) and regional scales (e.g.,
50 Shen et al., 2007).
51 The Japanese Islands are situated in a region of complex tectonics, where four tectonic
52 plates converge (e.g., Taira, 2001). Regional tectonic stress leads to numerous

53 earthquakes, which can be categorized into two types: subduction-type earthquakes and
54 crustal earthquakes. The Headquarters for Earthquake Research Promotion (HERP),
55 which is an administrative branch of the Japanese government, evaluates the long-term
56 activity of both earthquake types, and develops national seismic hazard maps of Japan
57 (Fujiwara et al., 2006). Their evaluation of crustal earthquakes is typically based on
58 geological and geomorphological data from major active faults with the potential for M
59 ≥ 7 earthquakes. However, several damaging crustal earthquakes, including the 2008
60 $M_{7.3}$ Iwate–Miyagi Inland earthquake (Ohta et al., 2008) have occurred on faults that
61 are not recognized as major active faults. The HERP has recently began conducting
62 regional evaluations of active faults to assess $M \geq 6.8$ earthquakes using short active
63 fault and seismicity data. The HERP also considers earthquakes on unspecified faults
64 based on seismicity data for national seismic hazard maps. However, the HERP does
65 not currently use geodetic data, although contemporary deformation of the Japanese
66 Islands is monitored by a permanent dense GNSS network (e.g., Sagiya, 2004). Only a
67 few pioneering studies have developed forecast models for the Japanese Islands using
68 geodetic data (Sagiya, 2015; Takahashi and Shinohara, 2015; Triyoso and Shimazaki,

2012). Therefore, in this study, we utilize GNSS data to develop an RELM for crustal earthquakes in southwest Japan and compare it with the distribution of actual earthquakes to verify its predictive ability.

Data and Method

GNSS data

We used velocity data from permanent GNSS stations in southwest Japan, as estimated by Nishimura (2017). The secular velocity was estimated using the daily coordinates from April 2005 to December 2009. Nishimura (2017) removed the elastic deformation attributed to interplate coupling between the continental plate and the subducting Philippine Sea plate along the Nankai Trough from the observed velocity from the GNSS stations. They noted that the distribution of crustal earthquakes is correlated with that of strain rates after removal. Here, we assume that the stress causing crustal earthquakes in southwest Japan is not directly loaded by coupling of the subduction megathrust but by permanent inelastic deformation below seismogenic faults (e.g., Iio and Kobayashi, 2002). In other words, elastic deformation attributed to interplate

coupling is fully released by interplate megathrust earthquakes; therefore, it can modulate the timing of crustal earthquakes but does not permanently load crustal faults (e.g., Hori and Oike, 1999; Mitogawa and Nishimura, 2020). Therefore, we used the corrected velocity after the removal of elastic deformation and estimated the strain rate distribution using the method proposed by Okazaki et al. (2021), in which the velocity field is subjectively optimized by the expansion of the bicubic B-spline basis function. Figure 1 shows the estimated strain rate distribution at $0.2 \times 0.2^\circ$ cells. The plotted strain component is the maximum of $|\dot{\varepsilon}_{h1}|$, $|\dot{\varepsilon}_{h2}|$, and $|\dot{\varepsilon}_{h1} + \dot{\varepsilon}_{h2}|$, where $\dot{\varepsilon}_{h1}$ and $\dot{\varepsilon}_{h2}$ are the maximum and minimum principal strain rates in the horizontal plane, respectively, which are used in the conversion to seismic moment rates in the next subsection. The other strain components are shown in Figure S1. These generally indicate that many $M \geq 6$ crustal earthquakes occur in cells with high GNSS strain rates. We regard this strain rate distribution as a proxy for the long-term average value of strain accumulation causing crustal earthquakes.

Method for calculating earthquake probability

First, we converted the observed strain rates to seismic moment rates, $\dot{m}_0$. Several equations for this conversion have been proposed, of which the following were tested (Savage and Simpson, 1997; Ward, 1994):

$$\dot{m}_0 = \mu H A \beta \dot{\gamma} \quad (1)$$

$$\dot{m}_0 = 2\mu H A \beta \text{Max}(|\dot{\varepsilon}_{h1}|, |\dot{\varepsilon}_{h2}|) \quad (2)$$

$$\dot{m}_0 = 2\mu H A \beta \text{Max}(|\dot{\varepsilon}_{h1}|, |\dot{\varepsilon}_{h2}|, |\dot{\varepsilon}_{h1} + \dot{\varepsilon}_{h2}|), \quad (3)$$

where μ , H , and A are the rigidity, thickness of the seismogenic layer, and surface area, respectively. $\dot{\varepsilon}_{h1}$, $\dot{\varepsilon}_{h2}$, and $\dot{\gamma}$ are the maximum and minimum principal strain rates, and the maximum engineering shear strain rate in the horizontal plane, respectively. Here, we add the empirical correction coefficient β to the original equations proposed by Ward (1994) and Savage and Simpson (1997). This coefficient calibrates the moment rates converted from the geodetic strain rates to those of actual crustal earthquakes. The most important reason for introducing the empirical coefficient is that the geodetic strain rates were much higher than the seismic and geological strain rates in Japan, as reported in previous studies (e.g., Shen-Tu et al., 1995). A part of this discrepancy can be explained by elastic deformation attributed to interplate coupling on

the subduction megathrust fault (e.g., Ikeda, 2014). The discrepancy remains after we removed the elastic strain attributed to interplate coupling, which suggests that the observed strain includes considerable inelastic strain. The inelastic strain is attributed to ongoing permanent aseismic processes, including fault creep, slow slip events, active folding, and numerous small earthquakes occurring in the seismogenic layer. We estimate β by comparing the moment rates converted from geodetic strain rates (hereafter, geodetic moment rates) with those of past earthquakes in the following subsection.

Bird and Liu (2007) proposed another conversion equation

$$\dot{m}_0 = \begin{cases} 2\mu H A \dot{\varepsilon}_3, & \dot{\varepsilon}_2 < 0 \\ -2\mu H A \dot{\varepsilon}_1, & \dot{\varepsilon}_2 \geq 0 \end{cases} \quad (4)$$

where $\dot{\varepsilon}_1$, $\dot{\varepsilon}_2$, and $\dot{\varepsilon}_3$ are the principal strain rates in three dimensions. Because GNSS data can provide only horizontal strain rates, the three principal strain rates are derived by assuming the conservation of volume (e.g., $\dot{\varepsilon}_1 + \dot{\varepsilon}_2 + \dot{\varepsilon}_3 = 0$) and a vertical orientation of one principal strain rate. Using these assumptions, equation (4) is equivalent to equation (3), with $\beta = 1$.

The rigidity, μ , and seismogenic thickness, H , in equations (1)–(3) generally exhibit

regional variations. Therefore, we used D90, the depth above which 90% of earthquakes occurred, as a proxy for the seismogenic thickness (Figure 2a). The D90 distribution of Omuralieva et al. (2012) was used after interpolation and extrapolation with adjustable tension continuous curvature splines (Wessel et al., 2013). We calculated the average rigidity of the seismogenic thickness based on the deep subsurface structure model of the Japan Seismic Hazard Information Station (J-SHIS) (NIED, 2019) (Figure 2b). Hereafter, we refer to the model that uses variable μ and H as the VARI model. The VARI models developed using equations (1), (2), and (3) are termed VARI1, VARI2, and VARI3. The product of μ and H , which controls the geodetic moment rates, ranges between 51 GPa km and 979 GPa km, with an average of 351 GPa km. Moreover, we selected 30 GPa and 12 km as uniform μ and H values in the UNI model. The UNI models developed using equations (1), (2), and (3) are termed UNI1, UNI2, and UNI3.

The earthquake magnitude used in this study was the Japan Meteorological Agency (JMA) scale. The empirical relationship between the JMA magnitude (M) and seismic moment (m_0) was used for shallow crustal earthquakes (Takemura, 1990):

149 $\log m_0 = 1.17M + 10.72.$ (5)

150 We then used a truncated Gutenberg–Richter law for the relationship between the
 151 magnitude (M) and number of earthquakes (n):

152
$$\begin{cases} \log n(M) = a - bM & (M \leq M_{max}) \\ n(M) = 0 & (M > M_{max}), \end{cases}$$

 153 (6)

154 where M_{max} is the maximum magnitude of the analyzed region. The number of
 155 earthquakes $N(M)$ with magnitude M and larger is given by

156
$$N(M) = 10^{a-\log(b \ln 10)-bM} - 10^{a-\log(b \ln 10)-bM_{max}}.$$
 (7)

157 The total seismic moment of earthquakes per unit time, $\int_{-\infty}^{M_{max}} m_0(M)n(M) dM$,
 158 following a truncated Gutenberg–Richter law, is assumed to be equal to the geodetic
 159 moment rate, $\dot{m}_0$, converted from the strain rate (equations (1)–(3)). Then, a in
 160 equations (6) and (7) can be given by

161
$$a = \log[\dot{m}_0(1.17 - b) \ln 10] - [10.72 + (1.17 - b)M_{max}],$$
 (8)

162 Although the other parameters in equation (6) may be dependent on the region (e.g.,
 163 Hirose and Maeda, 2011), we used 8.0 and 0.9 for M_{max} and b as spatially uniform
 164 typical values for crustal earthquakes, respectively. M_{max} was derived from the

165 magnitude of the 1891 Nobi earthquake.

166 Assuming a stationary Poisson process, the probability of $p(l, t)$ having l events in
167 period t is given by:

$$168 \quad p(l, t) = \frac{(\dot{N}t)^l}{l!} \exp(-\dot{N}t), \quad (9)$$

169 where $\dot{N}$ is the rate of earthquakes in the cell, which is a temporal derivative of the
170 number of earthquakes. Then, the probability of one or more events can be expressed as

$$171 \quad p(l, t; l \geq 1) = 1 - p(0) = 1 - \exp(-\dot{N}t). \quad (10)$$

172 We used equations (7) and (10) to obtain the probability for a certain magnitude
173 threshold and a certain time period.

174

175 **Historical earthquake data**

176 For calibration and validation of the RELM, we used a catalog of historical earthquakes
177 before 1919 (Utsu, 1990, 1992). We also used an earthquake catalog determined using
178 seismograms instrumentally recorded by the JMA in 1919, with a focus on large crustal
179 earthquakes with depths ≤ 20 km and $M \geq 6$. The depth of historical earthquakes
180 before 1919 is poorly understood. Therefore, we used earthquakes denoted as very

181 shallow or shallow during 1885–1918 and all earthquakes before 1885 in Utsu’s
182 catalog. We manually excluded six M 6.0–7.4 historical earthquakes that the
183 Earthquake Research Committee (2004) regarded as intraslab earthquakes similar to the
184 2001 M_w6.8 Geiyo earthquake (Takehi, 2004). A total of 151 earthquakes (indicated by
185 red circles in Figure 1) were employed for further analysis.

186 The number of earthquakes was counted using the number of epicenters in each cell.
187 Therefore, only a single cell is responsible for an earthquake, although the source area
188 of a large earthquake can occupy multiple cells. Because detailed source models for
189 most historical earthquakes are unavailable, we simply distributed the seismic moment
190 of an earthquake to surrounding cells to ensure that it was proportional to the area of a
191 circle with a diameter of L in each cell. L in kilometers was calculated from the
192 length of the fault in the empirical scaling law of Takemura (1998) as follows:

$$193 \quad \log L = 0.6M - 2.97. \quad (11)$$

194 The epicenters and moment distribution of historical earthquakes (Figure 3a) suggest
195 that historical earthquakes are concentrated in high-strain-rate areas, including the
196 Niigata–Kobe Tectonic Zone (Sagiya et al., 2000), the San-in Shear Zone (Nishimura

and Takada, 2017), and central Kyushu (Nishimura et al., 2018), which have all been identified as strain concentration zones in previous studies. Temporal evolution of the total seismic moment in the analyzed area shows that the moment rate increased with time (Figure 3b). The total moment was 8.68×10^{20} Nm and 6.46×10^{20} Nm during 599–2020 and 1586–2020, respectively. It is preferable to take a longer time to ensure a stable estimate of the average moment rate. However, the much higher rate in the later period suggests that many $M \geq 6$ earthquakes were not documented before the 16th century. The moment rate, including two largest earthquakes during 1586–2020, was approximately equal to that during 1919–2020, i.e., the era of instrumental recorded seismograms, in which no $M \geq 6$ earthquakes were likely missed (e.g., Ohta et al., 2002). Therefore, we used the period between 1586 and 2020 to calculate the average moment rate of long-term seismicity (1.49×10 Nm/yr). We β determined the correction coefficient β to balance the average moment rate of historical earthquakes with the geodetic moment rates derived from equations (1)–(3), as listed in Table 1.

Results and Discussion

Estimated probability distribution of crustal earthquakes

We calculated the probability of $M \geq 6$ crustal earthquakes within 30 years for a total of six models using three conversion equations and two structures (Figures 4 and S2). The highest probability in each model ranged from 2.9 to 3.7% and was found in Kyushu. The lowest probability was between 0.027% and 0.11%. More than half of the cells had a probability of $\geq 1\%$ in all models. The calculated probability distribution for the UNI models (Figure 4b) reflected the strain rate distribution (Figure 1). Although the effect of variable thickness and rigidity on the probability was rather minor, we observed an increase in the probability due to a thick seismogenic layer in Hiroshima and Okayama Prefectures ($132.5\text{--}134^\circ$ E and $34\text{--}35^\circ$ N) (Figures 2a and 4a).

Retrospective testing of the forecast models

We calculated several statistical scores to examine and validate the performance of the forecast models (Table 2). All $M \geq 6$ crustal earthquakes during 599–2020 (Figures 1 and 3a) were used for the analysis. The first score, which was the correlation coefficient between the geodetic moment rate and the moment of past earthquakes, suggested weak

positive correlations for all models. Scatter plots (Figure S3) showed no large moment release of past earthquakes in cells with low geodetic moment rates, and the maximum moment release of past earthquakes increased with the geodetic moment rates. Although our forecast model is based on the proportionality between earthquake moment rates and geodetic moment rates on a long-term average, the period of the earthquakes employed in the model was apparently shorter than the average recurrence intervals of crustal earthquakes (more than hundreds to thousands of years), as manifested by the null moment of past earthquakes in many cells. The VARI models exhibited slightly higher correlation coefficients than the UNI models. Moreover, the models with maximum shear strain rates (i.e., VARI1 and UNI1) had lower correlation coefficients than those with principal strain components (i.e., VARI2, VARI3, UNI2, and UNI3). The second score was the probability gain per earthquake (G) for the models relative to a reference model in which earthquakes are uniformly distributed (e.g., Helmstetter et al., 2007):

$$G = \exp\left(\frac{L - L_{ref}}{N}\right), \quad (12)$$

where L and L_{ref} are the log-likelihood of the present model and reference model,

245 respectively, and N is the number of earthquakes. The probability gains per earthquake
246 exceeded 1.13 for the models with principal strain-rate components (i.e., VARI2,
247 VARI3, UNI2, and UNI3), but were approximately 1.05 for models with the maximum
248 shear strain rate (i.e., VARI1 and UNI1). This is attributed to the various focal
249 mechanisms of crustal earthquakes in southwest Japan, including normal, strike-slip,
250 and reverse faulting (Terakawa and Matsu'ura, 2010). These gains may be less than our
251 expectation, when compared with the values of 1.17–7.08 obtained in a forecast model
252 based on seismicity in California (Helmstetter et al., 2007). However, all examined
253 models were significantly better than the uniform density model because the probability
254 gains of all 151 earthquakes exceeded 1,800, even for models using the maximum shear
255 strain rate.

256 The Molchan error diagram (Molchan, 1997) is often used to demonstrate the
257 performance of an alarm-based forecast. It represents the relationship between the miss
258 rate, that is, the proportion of unforecasted earthquakes that do not satisfy a certain
259 forecast threshold, and the proportion of forecasted space/time. In our case, the
260 horizontal axis of Figure 5 is the cell number in descending order of the geodetic

261 moment rate, normalized by the total number of cells. We can arbitrarily choose a
262 forecast threshold, such as 1% of the 30-year probability, and the probability at the cells
263 with the upper 25% probability and alert the cells satisfying the threshold. The vertical
264 axis represents the number and moment of earthquakes in the cells without the alert,
265 normalized by the total number and moment of earthquakes, respectively. We also
266 plotted the normalized geodetic moment rates in the corresponding cells. If there is no
267 correlation between the model forecast and past earthquakes, the error curve is expected
268 to be a diagonal line from the upper-left corner to the lower-right corner in the Molchan
269 diagram. This indicates that the forecast model has no predictive skill. On the other
270 hand, a model with predictive skill has an error curve to the lower left of the diagonal
271 line, which indicates that earthquakes are concentrated in the cells with higher
272 earthquake probability. We plotted the 95% confidence level of a non-correlation model
273 simulated by a random cell number. The error curves for the number and moment of
274 past earthquakes in all forecast models generally traced to the lower left of the 95%
275 confidence level of the non-correlation model, which suggests a significant positive
276 correlation between the geodetic moment rate and past earthquakes (Figure 5).

277 Additionally, we used the proportion of forecasted earthquakes in the number and the
278 moment at $x = 0.25$ in the Molchan diagram as a third score (e.g., Shen et al., 2007).
279 The remainder was obtained by subtracting the proportion of unforecasted earthquakes,
280 as indicated by the error curves in Figure 5, from one. Accordingly, 36–46% of the
281 epicenters of past earthquakes were located in cells of the upper 25% of high
282 probability/geodetic moment rates (Table 2). This proportion increased to 46–64% for
283 the moment of past earthquakes. The UNI1 model had a smaller proportion of past
284 earthquake concentrations than the other models. The fourth score was the area skill
285 score (ASS), that is, the area above the error curve inside the unit square of the Molchan
286 diagram. The ASS was used to indicate the overall performance of the covariate in
287 earthquake forecasting models (Zechar and Jordan, 2010). The diagonal line of the
288 Molchan diagram had $ASS = 0.5$ and the predictive model gave $ASS > 0.5$. The ASS
289 for the epicenters of past earthquakes ranged from 0.62 to 0.65, whereas that for the
290 moment ranged from 0.69 to 0.75. The ASS of models with the maximum shear strain
291 rate was smaller than that of models with principal strain rate components for both UNI
292 and VARI models.

293 These scores indicated that past earthquakes were concentrated in a high-strain-rate
 294 zone observed by GNSS and that the forecast model based on GNSS observations
 295 exhibited predictive ability for earthquakes. The models using the strain-rate component
 296 of $\text{Max}(|\dot{\varepsilon}_{h1}|, |\dot{\varepsilon}_{h2}|)$ or $\text{Max}(|\dot{\varepsilon}_{h1}|, |\dot{\varepsilon}_{h2}|, |\dot{\varepsilon}_{h1} + \dot{\varepsilon}_{h2}|)$ (i.e., UNI2, UNI3, VARI2, and
 297 VARI3) exhibited better performance than models using the maximum shear strain rate.
 298 There was no substantial difference between models with variable or uniform
 299 distributions of rigidity and seismogenic thickness. Considering that equation (3), which
 300 was proposed by Savage and Simpson (1997), uses $\text{Max}(|\dot{\varepsilon}_{h1}|, |\dot{\varepsilon}_{h2}|, |\dot{\varepsilon}_{h1} + \dot{\varepsilon}_{h2}|)$ as an
 301 improved expression between the seismic moment and surface strain rate after
 302 examining equations (1) and (2), we used the UNI3 and VARI3 models as
 303 representative models for further analysis.
 304 Triyoso and Shimazaki (2012) constructed a forecast model using GNSS data and
 305 compared it with previous 400-year-long seismicity. They showed that their GNSS-
 306 based model did not effectively reproduce the distribution of past crustal earthquakes
 307 and that its predictive skill was approximately equal to that of the uniform density
 308 model. Conversely, our study demonstrated that forecast models using GNSS data have

better predictive skill. These contrasting findings can be attributed to notable differences between the data analysis procedures. That is, we used a high-resolution distribution of the GNSS strain rate derived from a larger number of GNSS stations, optimal smoothing of the strain rate distribution (Okazaki et al., 2021), and a finer coupling model on the subducting plate interface (Nishimura et al., 2018). Moreover, the analyzed region was limited to southwest Japan in this study, but covers most of Japan in the work of Triyoso and Shimazaki (2012). The minimum magnitudes of verified earthquakes were 6.0 and 6.8 in this study and in the work of Triyoso and Shimazaki (2012), respectively. A comparison of the corrected strain-rate distribution suggests that the different coupling model had a large impact on the results.

Prospective performance of the forecast models

In the previous subsection, most earthquakes occurred before the geodetic data period because the data periods for seismicity and geodetic data were 599–2020 and 2005–2009, respectively. Although we assume time independence of seismicity, it remains unclear whether the validation results are applicable to future earthquakes. Triyoso and

325 Shimazaki (2012) suggested that the strain concentration zone observed by GNSS was
326 not a steady long-term feature, but a temporal one caused by past large earthquakes. A
327 simple simulation of postseismic deformation due to viscoelastic relaxation
328 demonstrates significant temporal variation in the strain rates around a fault (e.g., Wang
329 et al., 2021). Therefore, one may doubt our assumption that the strain rate distribution
330 used is a proxy for the long-term average value of strain accumulation. As such, we
331 used earthquakes that occurred only after the geodetic data period to examine the
332 prospective performance of the forecast models. Only eight $M \geq 6$ crustal earthquakes
333 occurred in the analyzed area during 2010–2020. Three of them were foreshocks and
334 the mainshock of the 2016 Kumamoto earthquake (Kato et al., 2016). Because a small
335 number of tested earthquakes leads to uncertainty and instability in the statistical test,
336 we lowered the magnitude threshold to examine a total of 51 $M \geq 5$ earthquakes with a
337 depth of ≤ 20 km, as shown in Figure 4.

338 The VARI3 and UNI3 models forecast approximately 21 $M \geq 5$ earthquakes over 11
339 years, with a total moment of $\sim 1.3 \times 10^{19}$ Nm. These numbers and moments are
340 approximately one third of the actual values (i.e., 51 and 3.42×10^{19} Nm), which is

mainly attributed to seismic activity of the M7.3 Kumamoto earthquake. The probability gains per earthquakes were 1.15 and 1.33 for the VARI3 and UNI3 models, respectively. The error curves in the Molchan diagram show the concentration of epicenters and earthquake moments in both models (Figure 6). They also indicate that the UNI3 model had better predictive ability than VARI3 as they were close to the 95% confidence limits of the no-correlation model. The ASSs for the earthquake number and moment were 0.650 and 0.810 for the VARI3 model, respectively. Conversely, these values were 0.734 and 0.833 for the UNI3 model, respectively.

Implications of forecast model validation

In both retrospective and prospective examinations, the statistical scores for the moment distribution of past earthquakes were better than those for the number of earthquakes (Table 2), which means that our models forecast the source areas of earthquakes better than their epicenters. This may be reasonable because geodetic measurements observe the interseismic strain that accumulates around the earthquake source region, not only its epicenter. Because the dimensions of the cell used in this study (0.2°) are

357 approximately equal to the fault length of an M7.2 earthquake, the source area of a large
358 earthquake must occupy multiple cells. Thus, using only the epicenter of large
359 earthquakes can bias the validation test for a high-resolution forecast model with a small
360 cell size.

361 Comparisons of error curves between the moments of past earthquakes (red curve) and
362 the geodetic moment rate (blue curve) in the Molchan diagram (Figures 5 and 6)
363 indicate that the moment distribution of large earthquakes observed geodetically was
364 more concentrated in cells with a high strain rate. For example, 64% of the seismic
365 moment was concentrated in the upper quarter of high-strain-rate cells for the VARI3
366 model, whereas 43% of the geodetic moment rate was observed in the same cells
367 (Figure 5c). Several factors likely contributed to this apparent concentration. First,
368 surface deformation in the interseismic period was more distributed than the coseismic
369 deformation concentrated immediately above the source fault. The elastic dislocation
370 theory demonstrates that interseismic strain rates are distributed around the fault,
371 depending on the down-dip limit of the locked part of the fault (cf. Segall, 2010).

372 Second, the distribution of the GNSS stations was too sparse to capture the real

heterogeneous distribution of interseismic strain rates. For example, a high-strain-rate zone along the coast of the Japan Sea, called the San-in Shear Zone (Figure 1), was revealed by the velocity data after significant enhancement of the GNSS network in 2002 (Nishimura and Takada, 2017). A regional dense GNSS array (e.g., Meneses-Gutierrez and Nishimura, 2020; Sagiya et al., 2004) and InSAR observations (e.g., Takada et al., 2018) near active faults is useful for improving the spatial resolution of interseismic deformation. Third, noise included in GNSS velocity data generally increases the “observed” strain rates from those of tectonic deformation. Thus, we speculate that the real tectonic strain rates may be reduced in cells with low strain rates and concentrated in cells with higher strain rates.

Conclusion and Prospects

In this study, we developed time-independent forecast models for crustal earthquakes using GNSS data from southwest Japan. In the forecast models, optimally smoothed GNSS strain rates from 2005 to 2009 were employed after removing the elastic deformation attributed to interplate coupling on the megathrust fault along the Nankai

389 Trough. Then, we converted the strain rates to geodetic moment rates using three
390 equations proposed in previous studies. Finally, we constructed uniform and variable
391 structure models for different values of seismogenic thickness and rigidity in the
392 conversion equations. The derived geodetic moment rate was ~5–8 times larger than the
393 seismic moment rate of historical earthquakes during 1586–2020. Therefore, we
394 introduced an empirical factor to calibrate the geodetic moment rate with the seismic
395 moment rate. Finally, we calculated the probability of $M \geq 6$ crustal earthquakes over
396 30 years, assuming a stationary Poisson process and truncated Gutenberg–Richter law
397 with values of 0.9 and 8.0 as the uniform b-value and maximum earthquake magnitude,
398 respectively. The estimated probability exceeded 1% in more than half of the analyzed
399 area and exhibited significant spatial variation of two orders of magnitude.

400 Furthermore, we validated the forecast models using retrospective and prospective
401 earthquake catalogs with several score indexes and the Molchan diagram. These
402 analyses suggested that the models using the absolute value of principal horizontal
403 strain rates and areal strain rates better forecast the real seismicity than models using the
404 maximum shear strain rates. Models using the absolute value of only the principal

405 horizontal strain rates exhibited equal predictive ability. There was no substantial
406 difference in the forecast performance between models using uniform or variable
407 seismogenic thickness and rigidity. All models explained the real seismicity
408 significantly better than the uniform earthquake distribution model. This study
409 demonstrates that RELMs based on GNSS data can provide enhanced preparedness for
410 earthquake disasters.

411 Although parameters b and β , which control the earthquake probability, were
412 assumed to be spatially uniform in this study, they clearly exhibit regional variation in
413 nature. Many studies (e.g., Hirose and Maeda, 2011) have estimated the heterogeneous
414 b -value distribution of the Gutenberg–Richter law for the Japanese Islands. However, it
415 remains practically difficult to estimate stable values because they can change not only
416 spatially but also temporally (e.g., Ogata et al., 2018). A small β value is expected in a
417 region with ongoing inelastic deformation, including active folding and fault creep. It is
418 also difficult to distinguish between inelastic strain and elastic strain in the observed
419 insufficient data, although a few methods have been proposed (e.g., Noda and
420 Matsu'ura, 2010). Estimating these variable parameters is a challenge for future

421 research.

422 Previous studies have shown that a model combining different types of data can

423 improve forecast performance on both global (e.g., Bird et al., 2015) and regional scales

424 (e.g., Rhoades et al., 2017). GNSS data has the advantage of a relatively uniform spatial

425 resolution throughout Japan. Active fault data are crucial for time-dependent forecast

426 models because they provide a history of past earthquakes. We propose that a

427 combination of multidisciplinary data, including GNSS, seismicity, and active faults, is

428 essential for improving RELMs for long-term earthquake forecasting in Japan.

429

430 **Declarations**

431 **Ethics approval and consent to participate**

432 Not applicable

433 **Consent for publication**

434 Not applicable

435 **List of abbreviations**

436 ASS: Area skill score

437 GNSS: Global navigation satellite system

438 HERP: Headquarters for Earthquake Research Promotion

439 JMA: Japan Meteorological Agency

440 RELM: Regional earthquake likelihood model

441 **Availability of data and materials**

442 Subsurface structures, including rigidity distributions, are available at the J-
443 SHIS website (<https://www.j-shis.bosai.go.jp/en/>). The earthquake catalogs
444 by Utsu (1990, 2002) and JMA are available at the website of Dr. Tatsuhiko
445 Hara of the Building Research Institute
446 (https://iisee.kenken.go.jp/utsu/index_eng.html) and the JMA website
447 (<https://www.data.jma.go.jp/svd/eqev/data/bulletin/index.html>),
448 respectively.

449 **Competing interests**

450 The authors declare that they have no competing interests.

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Authors' contributions

TN designed the research, performed the analyses, and wrote the article. The authors read and approved the final manuscript.

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468   **References**

- 469   Bird P, Jackson DD, Kagan YY, Kreemer C, Stein RS (2015) GEAR1: A global
470   earthquake activity rate model constructed from geodetic strain rates and
471   smoothed seismicity. *Seismol Soc Am Bull* 105(5):2538-2554.
472   doi:10.1785/0120150058
- 473   Bird P, Kreemer C (2015) Revised tectonic forecast of global shallow seismicity based
474   on version 2.1 of the global strain rate map. *Seismol Soc Am Bull* 105(1):152-
475   166. doi:10.1785/0120140129
- 476   Bird P, Liu Z (2007) Seismic hazard inferred from tectonics: California. *Seismol Res*
477   Lett 78(1):37-48. doi:10.1785/gssrl.78.1.37
- 478   Earthquake Research Committee (2004) Evaluation of seismicity in Hyuganada and
479   along the Nansei-shoto Trench. Headquarters of Earthquake Research
480   Promotion, https://www.jishin.go.jp/main/chousa/kaikou_pdf/hyuganada.pdf (in
481   Japanese), Accessed 13 Sep 2021
- 482   Fujiwara H, Kawai S, Aoi S, Morikawa N, Senna S, Kobayashi K, Ishii T, Okumura T,
483   Hayakawa Y (2006) National seismic hazard maps of Japan. *Bulletin of*

484 Earthquake Research Institute, University of Tokyo 81:221-232

485 Helmstetter A, Kagan YY, Jackson DD (2007) High-resolution time-independent grid-
 486 based forecast for $M \geq 5$ earthquakes in California. *Seismol Res Lett* 78(1):78-
 487 86. doi:10.1785/gssrl.78.1.78

488 Hirose F, Maeda K (2011) Earthquake forecast models for inland Japan based on the G-
 489 R law and the modified G-R law. *Earth Planets Space* 63(3):239-260.
 490 doi:10.5047/eps.2010.10.002

491 Hori T, Oike K (1999) A physical mechanism for temporal variation in seismicity in
 492 Southwest Japan related to the great interplate earthquakes along the Nankai
 493 trough. *Tectonophysics* 308(1-2):83-98. doi:10.1016/S0040-1951(99)00079-7

494 Iio Y, Kobayashi Y (2002) A physical understanding of large intraplate earthquakes.
 495 *Earth Planets Space* 54(11):1001-1004. doi:10.1186/Bf03353292

496 Ikeda Y (2014) Strain buildup in the Northeast Japan orogen with implications for
 497 gigantic subduction earthquakes. *Episodes* 37(4):234-245.
 498 doi:10.18814/epiiugs/2014/v37i4/003

499 Kakehi Y (2004) Analysis of the 2001 Geiyo, Japan, earthquake using high-density

500 strong ground motion data: Detailed rupture process of a slab earthquake in a
 501 medium with a large velocity contrast. J Geophys Res: Solid Earth 109(B8).
 502 doi:10.1029/2004jb002980

503 Kato A, Nakamura K, Hiyama Y (2016) The 2016 Kumamoto earthquake sequence.
 504 Proc Jpn Acad Ser B Phys Biol Sci 92(8):358-371. doi:10.2183/pjab.92.359

505 Meneses-Gutierrez A, Nishimura T (2020) Inelastic deformation zone in the lower crust
 506 for the San-in Shear Zone, Southwest Japan, as observed by a dense GNSS
 507 network. Earth Planets Space 72(1). doi:10.1186/s40623-020-1138-z

508 Mitogawa T, Nishimura T (2020) Coulomb stress change on inland faults during
 509 megathrust earthquake cycle in southwest Japan. Earth Planets Space 72(1).
 510 doi:10.1186/s40623-020-01174-6

511 Molchan GM (1997) Earthquake prediction as a decision-making problem. Pure Appl
 512 Geophys 149(1):233-247. doi:10.1007/bf00945169

513 National Research Institute for Earth Science and Disaster Resilience (2019) J-SHIS,
 514 National Research Institute for Earth Science and Disaster Resilience,
 515 doi:10.17598/nied.0010.

516 Nishimura, T (2017) Strain concentration zones in the Japanese Islands clarified from
517 GNSS data and its relation with active faults and inland earthquakes. Active
518 Fault Research, 46:33-39, doi:10.11462/afr.2017.46_33 (in Japanese)

519 Nishimura T, Takada Y (2017) San-in shear zone in southwest Japan, revealed by GNSS
520 observations. Earth Planets Space 69(1). doi:10.1186/s40623-017-0673-8

521 Nishimura T, Yokota Y, Tadokoro K, Ochi T (2018) Strain partitioning and interplate
522 coupling along the northern margin of the Philippine Sea plate, estimated from
523 Global Navigation Satellite System and Global Positioning System-Acoustic
524 data. Geosphere 14(2):535-551. doi:10.1130/ges01529.1

525 Noda A, Matsu'ura M (2010) Physics-based GPS data inversion to estimate three-
526 dimensional elastic and inelastic strain fields. Geophys J Int 182(2):513-530.
527 doi:10.1111/j.1365-246X.2010.04611.x

528 Ogata Y, Katsura K, Tsuruoka H, Hirata N (2018) Exploring magnitude forecasting of
529 the next earthquake. Seismol Res Lett 89(4):1298-1304.
530 doi:10.1785/0220180034

531 Ohta, K, Fujihara, Y, Maeda, K (2002) Spatiotemporal variation of minimum

532 magnitude of completeness in the JMA catalog. Q J Seismol 65:111-122. (in
 533 Japanese)
 534 Ohta Y, Ohzono M, Miura S, Iinuma T, Tachibana K, Takatsuka K, Miyao K, Sato T,
 535 Umino N (2008) Coseismic fault model of the 2008 Iwate-Miyagi Nairiku
 536 earthquake deduced by a dense GPS network. Earth Planets Space 60(12):1197-
 537 1201. doi:10.1186/Bf03352878
 538 Okazaki T, Fukahata Y, Nishimura T (2021) Consistent estimation of strain-rate fields
 539 from GNSS velocity data using basis function expansion with ABIC. Earth
 540 Planets Space 73(1). doi:10.1186/s40623-021-01474-5
 541 Omuralieva AM, Hasegawa A, Matsuzawa T, Nakajima J, Okada T (2012) Lateral
 542 variation of the cutoff depth of shallow earthquakes beneath the Japan Islands
 543 and its implications for seismogenesis. Tectonophysics 518-521:93-105.
 544 doi:10.1016/j.tecto.2011.11.013
 545 Reid HF (1911) The elastic-rebound theory of earthquakes. Univ Calif Publ Bull Dept
 546 Geol 6(19):413-444
 547 Rhoades DA, Christophersen A, Gerstenberger MC (2017) Multiplicative earthquake

548 likelihood models incorporating strain rates. Geophys [J Int](#)
 549 doi:10.1093/gji/ggw486
 550 Sagiya T (2004) A decade of GEONET: 1994-2003 - The continuous GPS observation
 551 in Japan and its impact on earthquake studies. Earth Planets Space 56(8):Xxix-
 552 Xli. doi:10.1186/Bf03353077
 553 Sagiya T, Nishimura T, Iio Y (2004) Heterogeneous crustal deformation along the
 554 central-northern Itoigawa-Shizuoka Tectonic Line Fault system, Central Japan.
 555 Earth Planets Space 56(12):1247-1252. doi:10.1186/Bf03353347
 556 Sagiya, T (2015) Proposal of the long-term earthquake forecast based on crustal strain
 557 rate and its problems, Abstract presented at the 2015 fall meeting, the
 558 seismological Society of Japan, Kobe International Conference Center, Kobe,
 559 26-28 October 2015 (in Japanese)
 560 Savage JC, Simpson RW (1997) Surface strain accumulation and the seismic moment
 561 tensor. Seismol Soc Am Bull 87(5):1345-1353
 562 Segall P (2010) Earthquake and volcano deformation. Princeton University Press,
 563 Princeton; Oxford

564 Shen ZK, Jackson DD, Kagan YY (2007) Implications of geodetic strain rate for future
 565 earthquakes, with a five-year forecast of M5 earthquakes in southern California.
 566 Seismol Res Lett 78(1):116-120. doi:10.1785/gssrl.78.1.116

567 Shen-Tu B, Holt WE, Haines AJ (1995) Intraplate deformation in the Japanese Islands:
 568 A kinematic study of intraplate deformation at a convergent plate margin. J
 569 Geophys Res: Solid Earth 100(B12):24275-24293. doi:10.1029/95jb02842

570 Taira A (2001) Tectonic evolution of the Japanese island arc system. Annu Rev Earth
 571 Planet Sci 29:109-134. doi:10.1146/annurev.earth.29.1.109

572 Takada Y, Sagiya T, Nishimura T (2018) Interseismic crustal deformation in and around
 573 the Atotsugawa fault system, central Japan, detected by InSAR and GNSS. Earth
 574 Planets Space 70(1). doi:10.1186/s40623-018-0801-0

575 Takahashi, T, and D. Shinohara (2015) Inland earthquake long-term occurrence
 576 probability evaluation using crustal deformation strain rate data, Abstract
 577 presented at the 2015 fall meeting, the seismological Society of Japan, Kobe
 578 International Conference Center, Kobe, 26-28 October 2015 (in Japanese)

579 Takemura M (1998) Scaling law for japanese intraplate earthquakes in special relations

580 to the surface faults and the damages. Zisin (Journal of the Seismological
 581 Society of Japan 2nd ser) 51(2):211-228. doi:10.4294/zisin1948.51.2_211 (in
 582 Japanese)
 583 Terakawa T, Matsu'ura M (2010) The 3-D tectonic stress fields in and around Japan
 584 inverted from centroid moment tensor data of seismic events. Tectonics 29(6).
 585 doi:10.1029/2009tc002626
 586 Triyoso W, Shimazaki K (2012) Testing various seismic potential models for hazard
 587 estimation against a historical earthquake catalog in Japan. Earth Planets Space
 588 64(8):673-681. doi:10.5047/eps.2011.02.003
 589 Wang K, Zhu Y, Nissen E, Shen ZK (2021) On the relevance of geodetic deformation
 590 rates to earthquake potential. Geophys Res Lett 48(11).
 591 doi:10.1029/2021gl093231
 592 Ward SN (1994) A multidisciplinary approach to seismic hazard in southern California.
 593 Seismol Soc Am Bull 84(5):1293-1309
 594 Wessel, P, Smith, WHF, Scharroo, R, Luis, J, Wobbe F (2013) Generic mapping tools:
 595 improved version released. EOS Trans Am Geophys Union 94(45), 409-410,

596   doi:10.1002/2013EO450001

597   Zechar JD, Jordan TH (2010) The area skill score statistic for evaluating earthquake

598   predictability experiments. *Pure Appl Geophys* 167(8-9):893-906.

599   doi:10.1007/s00024-010-0086-0

600   Zechar JD, Schorlemmer D, Werner MJ, Gerstenberger MC, Rhoades DA, Jordan TH

601   (2013) Regional earthquake likelihood models i: first-order results. *Seismol Soc*

602   *Am Bull* 103(2A):787-798. doi:10.1785/0120120186

603

604 **Figure Legends**

605 Figure 1 GNSS strain rates and historical earthquakes in southwest Japan. Color scale
606 indicates strain rates corrected for elastic deformation attributed to interplate coupling
607 along the Nankai Trough from April 2005 to December 2009. Red circles indicate
608 epicenters of $M \geq 6$ crustal earthquakes from 599 to 2020, whereas purple circles
609 indicate subduction-type and/or offshore earthquakes beyond the scope of this study.
610 Gray lines indicate major active faults (Earthquake Research Committee, 2021).

611 Figure 2 Seismogenic layer thickness and rigidity distribution used in the conversion to
612 seismic moment rates. Gray lines indicate major active faults (HERP, 2021). (a)
613 Thickness of the seismogenic layer derived from D90, the depth above which 90% of
614 earthquakes occur (Omuralieva et al., 2012). (b) Average rigidity in the elastic thickness
615 calculated from the deep subsurface structure model of J-SHIS ([https://www.j-](https://www.jshis.bosai.go.jp/en/)
616 [shis.bosai.go.jp/en/](https://www.jshis.bosai.go.jp/en/)). (c) Product of elastic thickness and average rigidity.

617 Figure 3 Seismic moment of past $M \geq 6$ crustal earthquakes from 599 to 2020. (a)
618 Moment distribution of earthquakes in 0.2° cells. Red circles indicate epicenters of
619 earthquakes. (b) Moment evolution of earthquakes. Note that the seismic catalogue is

620 based on historical documents for 599–1918 (Utsu et al., 2008) and instrumental
 621 seismograms from 1919 (JMA, 2021).

622 Figure 4 Probability of $M \geq 6$ crustal earthquakes over 30 years. Purple circles indicate
 623 epicenters of $M \geq 5$ earthquakes with a depth of ≤ 20 km for 2010–2020. (a) VARI3
 624 model and (b) UNI3 model.

625 Figure 5 Comparison of cumulative moment/number between GNSS strain rates and all
 626 $M \geq 6$ earthquakes (599–2020). Horizontal axis is the grid number in descending order of
 627 GNSS strain rates. Blue, red, and green lines indicate normalized moments converted
 628 from GNSS strain rates, normalized moments for all earthquakes, and the number of all
 629 earthquakes, respectively. Broken green and red lines indicate 95% confidence intervals
 630 of the non-correlation model. The moment and number are cumulative values from the
 631 first cell (e.g., the highest strain rate) to the corresponding cell, respectively. (a) VARI1
 632 model, (b) VARI2 model, (c) VARI3 model, and (d) UNI3 model.

633 Figure 6 Comparison of cumulative moment/number between GNSS strain rates and
 634 $M \geq 5$ retrospective future earthquakes (2010–2020). Line styles are the same as those in
 635 Figure 4. (a) VARI3 model and (b) UNI3 model.

637 Table 1 Correction coefficient β used to balance the seismic moment calculated from
 638 geodetic strain rates to that of past large earthquakes.

	$\dot{\gamma}$	$\text{Max}(\dot{\varepsilon}_{h1} , \dot{\varepsilon}_{h2})$	$\text{Max}(\dot{\varepsilon}_{h1} , \dot{\varepsilon}_{h2} , \dot{\varepsilon}_{h1} + \dot{\varepsilon}_{h2})$
	(Eq. 1)	(Eq. 2)	(Eq. 3)
UNI model	0.193	0.125	0.129
VARI model	0.198	0.130	0.127

639

640 Table 2 Statistical scores for retrospective forecasts of $M \geq 6$ crustal earthquakes.

	VARI1	VARI2	VARI3	UNI1	UNI2	UNI3
Correlation coefficient	0.260	0.343	0.339	0.223	0.313	0.316
Probability gain per earthquake (G)	1.059	1.130	1.133	1.051	1.138	1.144
Proportion of epicenter concentration*	0.464	0.437	0.430	0.357	0.464	0.464
Proportion of moment concentration*	0.622	0.654	0.639	0.456	0.622	0.625
ASS for epicenter**	0.620	0.636	0.638	0.621	0.647	0.649
ASS for moment**	0.711	0.746	0.744	0.691	0.738	0.735

641 *Proportion of epicenters/moments of past earthquakes in cells of the upper 25% of
642 high probability.

643 ** ASS = area skill score; see main text for explanation.

Figures

Figure 1

GNSS strain rates and historical earthquakes in southwest Japan. Color scale indicates strain rates corrected for elastic deformation attributed to interplate coupling along the Nankai Trough from April 2005 to December 2009. Red circles indicate epicenters of $M \geq 6$ crustal earthquakes from 599 to 2020, whereas purple circles indicate subduction-type and/or offshore earthquakes beyond the scope of this study. Gray lines indicate major active faults (Earthquake Research Committee, 2021).

Figure 2

Seismogenic layer thickness and rigidity distribution used in the conversion to seismic moment rates. Gray lines indicate major active faults (HERP, 2021). (a) Thickness of the seismogenic layer derived from D90, the depth above which 90% of earthquakes occur (Omuralieva et al., 2012). (b) Average rigidity in the elastic thickness calculated from the deep subsurface structure model of J-SHIS (<https://www.j-shis.bosai.go.jp/en/>). (c) Product of elastic thickness and average rigidity.

Figure 3

Seismic moment of past $M \geq 6$ crustal earthquakes from 599 to 2020. (a) Moment distribution of earthquakes in 0.2° cells. Red circles indicate epicenters of earthquakes. (b) Moment evolution of earthquakes. Note that the seismic catalogue is based on historical documents for 599–1918 (Utsu et al., 2008) and instrumental seismograms from 1919 (JMA, 2021).

Figure 4

Probability of $M \geq 6$ crustal earthquakes over 30 years. Purple circles indicate epicenters of $M \geq 5$ earthquakes with a depth of ≤ 20 km for 2010–2020. (a) VARI3 model and (b) UNI3 model.

Figure 5

Comparison of cumulative moment/number between GNSS strain rates and all $M \geq 6$ earthquakes (599–2020). Horizontal axis is the grid number in descending order of GNSS strain rates. Blue, red, and green lines indicate normalized moments converted from GNSS strain rates, normalized moments for all earthquakes, and the number of all earthquakes, respectively. Broken green and red lines indicate 95%

confidence intervals of the non-correlation model. The moment and number are cumulative values from the first cell (e.g., the highest strain rate) to the corresponding cell, respectively. (a) VARI1 model, (b) VARI2 model, (c) VARI3 model, and (d) UNI3 model.

Figure 6

Comparison of cumulative moment/number between GNSS strain rates and $M \geq 5$ retrospective future earthquakes (2010–2020). Line styles are the same as those in Figure 4. (a) VARI3 model and (b) UNI3 model.

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