Spatiotemporal Functional Modeling of Postseismic Deformation After the 2011 Tohoku-Oki Earthquake

Satoshi Fujiwara (✉ fujiwara-s2vq@mlit.go.jp)

Geospatial Information Authority of Japan <https://orcid.org/0000-0002-7541-9266>

Mikio Tobita

Geospatial Information Authority of Japan

Shinzaburo Ozawa

Geospatial Information Authority of Japan

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3   **2011 Tohoku-Oki earthquake**

4   Author #1: Satoshi Fujiwara*, Geospatial Information Authority of Japan, 1 Kitasato,
5   Tsukuba, Ibaraki 305-0811, Japan; fujiwara-s2vq@mlit.go.jp

6   Author #2: Mikio Tobita, Geospatial Information Authority of Japan, 1 Kitasato,
7   Tsukuba, Ibaraki 305-0811, Japan; tobita-m96mh@mlit.go.jp

8   Author #3: Shinzaburo Ozawa, Geospatial Information Authority of Japan, 1 Kitasato,
9   Tsukuba, Ibaraki 305-0811, Japan; ozawa-s96sa@mlit.go.jp

10

11   * Corresponding author

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13

14   **Abstract**

15   Postseismic deformation continues for a long duration after major earthquakes. A
16   previous study has shown that temporal changes in postseismic deformation can be
17   approximated through simple functions. Almost 10 years have passed since the 2011
18   M9 Tohoku-Oki earthquake, and data at continuously operating global navigation
19   satellite system stations have accumulated. We performed statistical processing of the
20   data on postseismic deformations of this earthquake and obtained and verified their
21   spatiotemporal distribution. We were able to approximate the postseismic deformations
22   over a wide area with a standard deviation of 1 cm for approximately 10 years using
23   two logarithmic and one exponential functions. However, the residuals from the
24   functional model showed a sharp deviation from 2015. Although the pattern of
25   postseismic deformation did not change after the earthquake, a change in steady-state
26   velocity occurred from 2015 and continues till date. By improving the functional model
27   to incorporate this steady-state velocity, we can reduce the overall standard deviation of
28   the residuals of more than 200 stations distributed over more than 1000 km to less than
29   0.4 cm in the horizontal component. Furthermore, the spatial distributions of the

coefficients of each time constant are not random and have a natural spread, which makes it possible to grid model them in terms of a spatial function. The spatial distributions of the short- and long-period components of the functional model and the afterslip and viscoelastic relaxation calculated by a physical model are similar to each other, respectively. Each time function has a meaning related to the physical processes in the underground, which provides an understanding of the physical phenomena involved in seismogenesis.

Keywords

2011 Tohoku-Oki earthquake, crustal deformation, postseismic deformation, slip, global navigation satellite system time series, predicting model.

Main Text

Introduction

On March 11, 2011, an earthquake of M9 occurred off the Pacific coast near Tohoku, Japan (hereinafter, the 2011 Tohoku-Oki earthquake) and caused coseismic crustal deformation of > 5 m in the horizontal direction and > 1 m in the vertical direction. Even after the earthquake, large postseismic crustal deformations of > 1 m continue depending on the location (Ozawa et al. 2011; 2012). Tobita (2016) used simple logarithmic and exponential functions to approximate the time series of the postseismic deformation to predict its future trend over a wide area accurately. This suggests that the changes occurring underground after a major earthquake are driven by simple physical laws.

Postseismic deformation of earthquakes is mainly considered to be caused by afterslip at the plate boundary and viscoelastic relaxation of the upper mantle (e.g., Sun and Wang 2015). Therefore, understanding the spatiotemporal distribution of postseismic deformations will enable accurate estimation of geophysical processes. Such functional models are useful for predicting seismic activity and understanding the geophysical

processes of large earthquakes and for discerning small crustal deformations caused by other sources by removing the large postseismic deformation through a simple model. The functional model by Tobita (2016) has been used by Ozawa et al. (2016), Sakaue et al. (2019), and others to discern crustal deformations other than postseismic deformations of large earthquakes.

Tobita (2016) shows that the time function created is common to all observation stations over a wide area. The commonality of the time function implies that a particular geophysical phenomenon occurs underground and is observed in the same way at every station above the ground. Therefore, it is expected that the distribution of the spatial function is closely related to the distribution of geophysical phenomena underground. In this study, we compare the spatial function with geophysical phenomena estimated by physical modeling. In particular, the creation of a functional model by statistical processing that is independent of the geophysical process can be clarified by comparing it with the geophysical model constructed by methods such as the finite element method.

In this study, we apply the method of Tobita (2016) to the crustal deformation data

obtained from the global navigation satellite system's (GNSS) continuous observation stations on the ground for approximately 10 years after the 2011 Tohoku-Oki earthquake to verify its effectiveness in describing postseismic deformation and improve its accuracy.

Data and methods

In this study, we used the daily coordinates of the GEONET F3 solution (Nakagawa et al. 2009) operated by the Geospatial Information Authority of Japan (GSI) as the postseismic deformation data of the 2011 Tohoku-Oki earthquake. In addition to Tobita's (2016) consideration, we added stations in Hokkaido, in the northeast of Japan, to the analysis to understand the phenomena over a wider area. The Fukue GNSS station (station ID: 950462) in Nagasaki Prefecture, located approximately 1500 km west–southwest of the epicenter area, was used as the fixed reference station. The original GNSS time series contains offsets caused mainly by large aftershocks. Therefore, in addition to the nine earthquakes considered by Tobita (2016), we have corrected the coseismic variations of the following earthquakes: M7.4 November 22, 2016

Fukushimaken-Oki, M6.3 December 28, 2016 Ibarakiken-Hokubu, M6.7 September 6,

2018 Hokkaido-Iburi-Tobu, and M6.7 June 18, 2019 Yamagataken.

Tobita (2016) presented several combinations of logarithmic and exponential functions for use. We used a mixed model, which contains two logarithmic and one exponential functions, that showed the best performance as reported by Tobita (2016) and represented by equation (1).

$$D(t) = a \ln(1 + t/b) + c + d \ln(1 + t/e) - f \exp(-t/g) + Vt, \quad (1)$$

where $D(t)$ is each component of the postseismic deformation time series, t is the number of days after the earthquake, $\ln$ is the natural logarithm, b , e , and g are the relaxation time constants of logarithmic or exponential functions common to all stations, and V is the steady velocity of each station before 2011. It has been shown that this equation can be used to predict short- and medium-term time trends and postseismic deformation changes that vary with location with high accuracies.

The time constants for the time series of four stations, namely, Miyako, Yamoto, Minase, and Choshi were determined (Fig. 1) and they show representative variability as in Tobita (2016). For the other stations, the determined time constants are given in

common. For the fitting period, the coefficients of a , c , d , and f , which are unique to each station and for each component, are calculated using the least-squares method.

Because the nonlinear least-squares method is used to determine the time constants b , e , and g , it is computationally time-consuming and can lead to local solutions. Tobita (2016) showed that the fit of the functional model using the determined time function was good even at stations other than where the time function was determined.

Therefore, after careful and rigorous determination of the time constants at four observation stations, it is reasonable to determine the coefficients a , c , d , and f at each station using the linear least squares method, which can determine the solution in a short time. In addition, once the time constants are determined, they can be easily applied to other observations and spatial expansions. This can be expressed as follows:

$$F(t, x, y) = \sum time\_f(t) \cdot space\_f(x, y) \quad (2)$$

where $time\_f(t)$ is the term in Eq. (1) (time function), and $space\_f(x, y)$ is the spatial function at the coordinate (x, y) for each time function. The time function can be statistically solved using the principal component analysis as suggested by Mune Kane (2012). However, in this study, we follow Tobita (2016) and verify the method of

limiting the time function to logarithmic and exponential functions and discuss the spatial function using more than 200 observation stations.

Results

Time function

In the functional model of Tobita (2016), the time constants, b , e , and g are effective over a wide area and are common to each component. Table 1 shows the calculated results for the fitting periods of 2.0, 3.9, 5.8, and 8.9 years. The fitting period started on the day after the earthquake. For b and e , the time constant tended to increase as the fitting period increased, but no significant differences were observed. In contrast, the values of g for 2.0- and 3.9-year fittings do not change significantly, but the values of g for the next 5.8-year fitting jump significantly. The time constant of 450,000 days for g of the 5.8- and 8.9-year fittings is more than 1200 years, and it is unlikely that it can be calculated correctly only with a limited number of years for fitting.

Table 1 Results of data fitting for each fitting period

Fitting period (year)	End of fitting period	Relaxation time constant (days)		
		b for log1	e for log2	g for exp
2.0	Mar 2013	1.3784	82.00	3217.0
3.9	Feb 2015	1.5929	148.63	3645.4
5.8	Dec 2016	1.9827	128.71	449999.9

8.9	Feb 2020	2.1176	287.45	450005.2

Figure 2 shows the time series predicted by the functional model for different fitting periods for the Kawai and Shizugawa stations that are close to the epicenter of the 2011 Tohoku-Oki earthquake (see Fig. 1) and the Kaminokuni and Nadachi stations that are distant from the epicenter (see Fig. 1). Figure 2 shows the predicted time series of the functional model for different fitting periods and the extrapolated predictions up to 2026.5.

First, we checked the time series of the short fitting periods of 2.0 years and 3.9 years. At all the stations, the 2.0-year fitting of the NS component was shifted to the northern side of the 3.9-year fitting. Figure S1 shows the distribution of the short-period logarithmic term (the first term in Eq. (1)) for the 2.0-year and 3.9-year fitting periods on March 11, 2014, three years after the earthquake, and the difference between them.

Although the two are in general agreement, the eastward component of the 2.0-year fitting is smaller near Miyako and south of Yamoto, and the southward and upward components of the 2.0-year fitting are larger for the entire region. The southward and upward components of the 2.0-year fitting were affected by local variations of the fixed reference station Fukue in 2013. Since simple correction of gaps in Fukue's time series

cannot improve the result, complex changes in Fukue were included. It is difficult to avoid errors in the predictions owing to the deterioration of the signal-to-noise ratio caused by the shortening of the fitting period. Particular attention should be paid to the noise contained in the fixed reference station, for example, using the average of multiple stations as the reference. However, we did not improve the handling of fixed reference stations in this study. Despite the noise in the fixed reference station, Fig. 2 shows that the time series of the 2.0-year and 3.9-year fittings are parallel in the future, and their long-term trends are likely to be similar. In other words, the long-term trend is correctly included in both and it does not shift over time. In addition, although the 2.0-year fitting is susceptible to small-scale noise due to the short period of time over which the values were obtained, for a prediction period of 10 years, the error is only several centimeters, which is sufficient for some purposes that can tolerate a lower precision.

It is natural that the 8.9-year fitting period, which is the longest fitting period, represents the time series with the smallest residuals throughout the entire period. In addition, as there is almost no difference between the 5.8- and 8.9-year fittings, a fitting period of 5.8 years is sufficient for the functional model. Even though the 2.0- and 3.9-

169 year fittings and the 5.8- and 8.9-year fittings are aligned and draw similar curves, it is
170 found that there is a difference between these two groups. This suggests that a
171 systematic change occurs between 3.9 and 5.8 years. This is consistent with the fact that
172 the value of g cannot be calculated correctly after the 5.8-year fitting as shown in Table
173 1.

174 To investigate the reason for this change in trend with the fitting period, Fig. 3 shows
175 the residuals based on the predictions for the 3.9-year fitting (until February 2015). The
176 predicted values agreed with the observed values within 1 cm until February 2015;
177 however, the residuals accumulated in a certain direction after the M6.9 Sanriku-Oki
178 earthquake that occurred on February 17, 2015 (hereinafter, 2015 Sanriku-Oki
179 earthquake) and the M6.8 Miyagiken-Oki earthquake that occurred on May 13, 2015
180 (hereinafter, 2015 Miyagiken-Oki earthquake). In other words, since 2015, the residuals
181 that progress at a constant rate have occurred over a wide area and includes all the
182 components over 1000 km from Hokkaido to central Japan. This indicates that another
183 event that was different from the previously occurring postseismic deformation
184 occurred in 2015, and its continuation has broken the original setting conditions of the

185 functional model, and the value of g has also become abnormal. Therefore, a period
186 longer than 3.9 years should not be adopted as the fitting period to use the functional
187 model in Eq. (1).

188 A closer look at the EW components with the most pronounced changes since 2015
189 shows that the linear changes in Kaminokuni and Nadachi started in the beginning of
190 2015, while the sluggish changes in Kawai and Shizugawa occurred from February to
191 July 2015. Shizugawa showed an eastward change in 2020, which was caused by the
192 M6.2 Miyagiken-Oki earthquake that occurred on April 20, 2020. The common change
193 of approximately 5 mm in the NS component in July 2013 was caused by the fixed
194 reference station Fukue.

195 From Fig. 3, we can see that a linear component appeared after the beginning of 2015
196 at all the stations and components. To model this new component as a function, a
197 straight line was fitted using the least-squares method for the five-year period from
198 December 2015 to December 2020 considering the existence of an annual component.
199 Of course, there is a possibility that the new component after 2015 is a function with
200 non-linear properties, but we have not found any changes that suggest a function more

complex than linear, and hence, it can be expressed with a minimum of simple functions. In this study, we propose Eq. (3) as a modified functional model of Tobita (2016) for 2015 and beyond.

$$D(t) = a \ln(1 + t/b) + c + d \ln(1 + t/e) - f \exp(-t/g) + Vt + c' + vt, \quad (3)$$

where c' and v are constants for each observation station and are components calculated by linear fitting. Figure 4 shows a magnified view of the EW components of the three stations that show characteristic changes from 2015 to the beginning of 2016 (see Fig. 5 for the locations of the three stations). The characteristics of the changes before and after 2015 are as follows. First, the EW component is almost flat before January 2015, and the functional model in Eq. (1) works well. Second, coseismic deformations associated with the 2015 Sanriku-Oki earthquake, the 2015 Miyagiken-Oki earthquake, and the M6.7 Urakawa-Oki earthquake that occurred on January 14, 2016 (hereinafter, 2016 Urakawa-Oki earthquake) appear at observation stations near each earthquake. Third, there is a widespread inclusion of linear variability with a constant trend between February and July 2015. Fourth, the variability stabilizes after February 2016 for all stations. As shown in Figs. 4a and 4c, the second coseismic variation is large in the

vicinity of the epicenters; however, in most locations, the third gradual variation from February to July is prominent (Fig. 4). The total displacement due to these two fluctuations (the second and the third characteristic changes) was calculated as the difference between the values on July 1, 2015 in Eq. (3) and the value on February 16, 2015 in Eq. (1). Here, February 16 is the day before the 2015 Sanriku-Oki earthquake, and July 1 is the reading from Fig. 4. This amount corresponds to the dashed lines with arrows drawn on July 1, 2015 in Fig. 4. In this study, we refer to the gap as the “gap in 2015.” Although the changes caused by the 2016 Urakawa-Oki earthquake did not occur in 2015, they are closely related to the v term in Eq. (3), which is described in detail in the section Discussion. In addition, because the value of v is small at observation stations affected by the 2016 Urakawa-oki earthquake, the error in the amount of gap caused by the different timing of the coseismic deformation is small. Therefore, we include these in the series of “gap in 2015” in our discussion. Based on the above, the new component of Eq. (3) from 2015 can be described as follows:

$$c' + vt = gap_{2015} + v(t - t_0) \quad (4)$$

where, gap_{2015} is the “gap in 2015” described above, t_0 is July 1, 2015, and this equation

233 is applicable after t_0 . The variation from 2015 to early 2016 cannot be modeled as a
234 simple function. Therefore, for convenience, the “gap in 2015” is assumed to have
235 occurred linearly between February 17 and July 1, 2015, and Eqs. (1) and (3) are
236 connected so that there is no step change during February to July. Therefore, when
237 using the improved functional model, it should be noted that discontinuities are
238 included in the period from February 2015 to January 2016.

239 The date and time of the beginning of the third characteristic change mentioned above
240 cannot be determined exactly because of variability and errors in the daily GNSS
241 observations; however, it seems to have started before the 2015 Sanriku-Oki earthquake
242 (February 17, 2015) as shown in Fig. 4b. This is consistent with the fact that a slow-slip
243 event (SSE) occurred in Sanriku-Oki at the end of January 2015 (Honsho et al. 2019)
244 suggesting that the 2015 Sanriku-Oki earthquake was not the trigger for the series of
245 events but some silent event started in the area at the end of January 2015. The 2015
246 Sanriku-Oki earthquake may have been triggered by the same phenomenon.

247 To verify the validity of Eq. (3), Figs. 5a and 5b show the spatial distribution of the
248 “gap in 2015” (gap_{2015}) and v , respectively. Figure 5b shows a uniform spread of

249 variability over a wide area. Applying a straight line, vt , to each component of each
250 station individually may result in over-fitting of the line to local phenomena that is
251 unique to each station. However, Fig. 5 shows that both gap_{2015} and v are spatially
252 distributed smoothly, and it can be considered that systematically occurring phenomena
253 in a wide area are captured, which is a corroboration of the validity of the assumption of
254 Eq. (3).

255 Figure 6 shows the time series for each station using Eqs. (3) and (4). Based on the
256 results so far, the value of the 3.9-year fitting is used for the overall time constant, and
257 vt , which is a linear variation after 2015, is added. As a graph, the initial value of each
258 term on the day after the earthquake is drawn starting from zero, and a constant is added
259 to the exponential term (the fourth term in Eq. (3)). Figure 3 also shows their residuals.
260 For the four observation stations for which the time function was obtained, the time
261 series based on Eq. (1) are shown in Fig. S2 and based on Eq. (3) are shown in Fig. S3.
262 Table 2 lists the standard deviations for each fitting period. The overall standard
263 deviations for all the 222 stations based on Eq. (3) are shown in the bottom row of
264 Table 2. The standard deviation of the NS component is < 3 mm, for the total horizontal

component it is < 4 mm, and for the UD component it is < 8 mm. These low standard deviation values indicate that the functional model presented by Eq. (3) is the best.

Table 2 Standard deviation and AIC of residuals for each fitting period

Equation	Fitting period (year)	Standard deviation (cm) of components			AIC*
		EW	NS	UD	
(1)	2.0	1.4654	1.0531	2.0407	-34254
	3.9	1.5275	0.7472	1.1327	-34584
	5.8	0.9759	0.5632	0.9918	-36853
	8.9	0.8075	0.5044	0.9724	-37262
(3)	3.9	0.2585	0.2619	0.7831	-40012

*AIC: Akaike information criterion

Figure 6 shows the total functional model values as well as the components of the two logarithmic terms, the exponential term, and the two constant velocity terms. Each term is well mixed in the horizontal component, although it varies depending on the observation station and component and the exponential term is dominant in the vertical (UD) component.

Notably, the displacement rate of the overall crustal deformation has not returned to the pre-earthquake trend (the V term in Eq. (1)) even 10 years after the earthquake.

Figure 6 also shows the extrapolated predictions for the near future, which do not predict a return to the pre-earthquake trend even after several more years.

280 *Spatial function*

281 In this section, we show the spatial distribution of the components of the functional
282 model. Figure 7 shows the distribution of the two logarithmic terms, the exponential
283 term, and the steady velocity V term three years after the earthquake (March 11, 2014).
284 The term vt is zero at this time, and the v term after 2015 is shown in Fig. 5b. When the
285 5-year post-earthquake period is plotted, as in Fig. 7, the short-period logarithmic term,
286 long-period logarithmic term, exponential term, and V term are 1.08, 1.22, 1.52, and
287 1.67 times larger than those of the 3-year post-earthquake period, respectively, and the
288 contribution of the longer-period term becomes larger.

289 The spatial distribution of all the terms shows a systematic spatial extent rather than a
290 random one. The spatial wavelengths are shorter for a shorter relaxation time constant
291 of each term, with the shortest at approximately 100 km. Although it cannot be easily
292 expressed as a mathematical function, a gridded spatial function can be obtained by
293 simple spatial interpolation even for points for which no observation is available.

294 These spatial distributions are caused by geophysical phenomena in the underground
295 and are separated by time functions with different time constants suggesting that

postseismic deformations are caused by phenomena that are related to time and underground location (Tobita 2016). For example, in Fig. 7a, the short-period logarithmic term has a more complex spatial distribution than that of the other terms suggesting that it is influenced by phenomena occurring in a shallower and narrower area.

Discussion

Comparison between functional and physical models

The postseismic deformation of large earthquakes is largely caused by afterslip and viscoelastic relaxation (e.g., Sun and Wang 2015). Because our spatiotemporal model is divided by the time constant of the time function and its spatial distribution is also smoothly spread over a wide area, we will explore the meaning of the time constant and other factors by comparing them with those of a physical model.

Freed et al. (2016) and Suito (2017) constructed a 3D viscoelastic relaxation model using the finite element method for the postseismic deformation of the 2011 Tohoku-Oki earthquake. The difference between the viscoelastic relaxation model and the

312 observed data is supposed to represent the afterslip. Figures 8a and 8b show the short-
313 period logarithmic term (the first term in Eq. (3)) and the afterslip component based on
314 Suito (2017), respectively, as of March 11, 2014, three years after the earthquake. Here,
315 we assume that the observed data include the afterslip, viscoelastic relaxation, and
316 constant velocity (V term), and the afterslip component from the physical model is the
317 observed data minus the V term and the viscoelastic relaxation model component.

318 In Figs. 8a and 8b, the eastward and subsidence components near Miyako and the
319 southeastward and uplift components near Choshi are in good agreement qualitatively
320 and quantitatively with the functional and physical models. In the central part, a north–
321 northeast–south–southeast sequence of subsidence components extending for several
322 hundred kilometers is observed, which is in agreement with both the models. This may
323 be due to a post-earthquake volcanic subsidence (Takada and Fukushima 2013). The
324 physical model is based on the differences in the observed data, and hence, it is a
325 manifestation of the original observed data and not that of the modeled data. Although
326 they show a good agreement in many places, e.g., near Yamoto, the functional model
327 has a large east component, while the physical model has an almost zero horizontal

328 component.

329 The remaining two terms of the functional model, that is, the long-period logarithmic
330 term (the third term in Eq. (3)) and the exponential term (the fourth term in Eq. (3)), are
331 not related to the physical model of Suito (2017). The sum of these two and the
332 viscoelastic relaxation model of the physical model are shown in Figs. 8c and 8d,
333 respectively. The horizontal component is generally eastward, with a southward
334 component in the north and a northward component in the south, and the vertical
335 component is uplifted along the Pacific coast and subsided along the Japan Sea coast.
336 Contrary to Figs. 8a and 8b, however, the physical model has a large eastward
337 component near Yamoto. The differences between Figs. 8c and 8d are shown in Fig.
338 S3d, and the difference near Yamoto is large.

339 Because the physical model does not take into account time dependence, it is natural
340 to assume that the difference between the two models is caused by the shorter time
341 phenomenon in viscoelastic relaxation near Yamoto than in the other areas, and this
342 leaks into the short-period logarithmic term of the functional model, which is mainly the
343 afterslip component (Tobita 2016). This process can be explained as follows: the

344 coseismic slip zone of the main shock of the 2011 Tohoku-Oki earthquake is located
345 close to Yamoto, and the slip zone extends to just near Yamoto (Iinuma et al. 2016;
346 Ozawa et al. 2012; Suito 2017). Therefore, after the main shock, the afterslip is small in
347 this area, and the displacement due to viscoelastic relaxation is dominant. According to
348 Suito (2017), the viscoelasticity of the mantle wedge, which is just below the land
349 observation stations, is approximately one-fifth that of the ocean mantle. The lower
350 viscoelasticity increases flowability, which leads to a shorter period of viscoelastic
351 relaxation, and it is certain that this effect occurs near Yamoto.

352 Figure 8 shows that there is a clear difference in the horizontal component between
353 the above functional model and the physical model, but no significant difference is
354 found in the vertical component. The vertical components show a large contribution of
355 the exponential term (Fig. 6), and this fact can be used to improve the accuracy of the
356 physical model. In addition, it is necessary to consider the effect of viscoelastic
357 relaxation to discuss the long-term (~1000 years) inter-seismic vertical change
358 (Nishimura 2014).

359 Here, we discuss why the viscoelastic relaxation term in the physical model is the

sum of the long-period logarithmic term and the exponential term in the functional model. Compared to the long-period logarithmic term, the time constant of the exponential term is more than 20 times longer (Table 1). Therefore, the time constants of the phenomena causing viscoelastic relaxation are very wide, ranging from short to long. Furthermore, the short-period logarithmic term contains large viscoelastic relaxation components near Yamoto suggesting that the variation of time constants for viscoelastic relaxation is extremely wide (several days to thousands of days). The functional and physical models do not match because although both the models simplify the phenomena, there is a fundamental difference in the way the models are created in terms of time or physical phenomena. A physical model can be constructed according to the time constant, which will lead to more advanced modeling by incorporating the differences in underground properties.

Slip distribution on the plate surface

Next, using inversion simulations, we discuss the extent and location of the movement of the source area. The discussions here have two limitations. First, viscoelastic

376 relaxation is complex not only in terms of where it occurs, but also in terms of the
377 direction of motion at each location (e.g., Agata et al. 2019). In contrast, sliding on a
378 plate surface can be simulated with constraints on the location and direction of sliding.
379 Therefore, we mainly deal with phenomena that can be considered as a slip on the plate
380 surface. The second limitation is that our data are only available on the land side, and
381 we are trying to build a model without using data from the ocean side because seafloor
382 crustal movement data do not have adequate time series. Hence, offshore slip that is far
383 from land cannot be estimated from onshore data alone (Iinuma et al. 2016) and the
384 certainty of the model decreases as the distance from land increases.

385 We estimated the slip distribution on the plate by applying geodetic inversion using
386 the Markov chain Monte Carlo method (Fukuda and Johnson 2008).

387 Figure 9a shows the slip on the plate surface as the driving force for the short-period
388 logarithmic term (Fig. 7a) at three years after the earthquake. As discussed above, this
389 term also includes deformations caused by viscoelastic relaxation of the mantle wedge.
390 The moment magnitude of this term in the three years was 8.3.

391 Figures 9b and 9c show the slips on the plate surface of the term gap_{2015} in Eq. (3)

(Fig. 5a) and term v in Eq. (3) (Fig. 5b), respectively. The symbols from B to E in the figures indicate the locations of the characteristic variations shown in Fig. 9c. Although there are errors due to the above two restrictions in all the three parameters of Fig. 9, these mutual comparisons are meaningful because the data are analyzed under the same conditions. For example, it is worth discussing that there is no slip at B in Fig. 9a compared to 9b and 9c, and that there is a slip spread northeast of C in Fig. 9b.

Although it is possible to calculate the long-period logarithmic term and the exponential term as slip on the plate surface, we do not discuss them here because they are mainly composed of viscoelastic relaxation components, not afterslip, as described above.

Gap in 2015

Figure 9b is a unique slip that occurred from February 2015 to January 2016 apart from the original postseismic deformation that started just after the earthquake, and it includes the coseismic slips caused by the three earthquakes with a magnitude of > 6.5 as well as the variation that proceeded at a constant rate during the period. Figure 9b

408 shows that these variations can be attributed to two locations: Miyagiken-Oki (*C*),
409 which is associated with the occurrence of the 2015 Sanriku-Oki earthquake and the
410 2015 Miyagiken-Oki earthquake. The location Urakawa-Oki (*B*) to the north
411 corresponds to the 2016 Urakawa-Oki earthquake.

412 The moment magnitude of the slip is M_w 7.0 for the Urakawa-Oki (*B*) area and M_w
413 7.3 for the Sanriku-Oki to Miyagiken-Oki (*C*) area indicating that they are large and
414 cannot be explained by the main shock and its postseismic deformation alone.

415

416 *Linear slip after 2015*

417 The temporal changes in the residuals (cf. Fig. 3) between the observed values and the
418 functional model based on Eq. (1) occurred systematically and simultaneously over a
419 wide area from Hokkaido to the Chubu region after 2015 and continued at almost
420 constant speeds, and are expressed as v terms in Eq. (3). To investigate the cause of this
421 phenomenon, a model of the slip rate on the plate surface is shown in Fig. 9c, which
422 shows a few centimeters of slip per year in large areas. It is controversial whether the
423 slip in this term is partially caused by viscoelastic relaxation in the upper mantle, rather

than only on the plate surface. However, the temporal change shown in Fig. 3 is proceeding at a steady speed, which is unlikely to be due to the viscoelastic relaxation, and it is more likely that the constant slip on the plate surface is continuing.

The location of the new slip can be roughly divided into two areas: Miyagiken-Oki (*C*) to Fukushima-Okai (*D*) and Urakawa-Okai (*B*). In the Miyagiken-Okai to Fukushima-Okai area, the slip is spread in the afterslip area (Fig. 9a) and its deeper area of *gap*₂₀₁₅, and it is considered to have occurred with a constant velocity to add to the afterslip. In contrast, no significant slip occurred in the Urakawa-Okai area before 2015, and it occurred after 2015. In addition, the total moment magnitudes of these areas from 2015 to 2020 are integrated to M_w 7.4 for *B* and M_w 7.8 for *C* and *D*.

The relationship between the new steady velocity v term after 2015 (Fig. 5a) and the steady velocity V term that existed before 2011 (cf. Fig. 7d) is interesting. v and V have almost opposite directions, and the ratio of their magnitudes is approximately 0.4 at most. Since both have an almost stationary velocity, we may assume that the value of V changed in 2015. However, the spatial extent of the distributions of V (Fig. 7d) and v (Fig. 5b) are different, and even if v is a change in V , it is only a small part of the

440 change in the physical mechanism that formed V . Moreover, at this point, we have not
441 found any major event that triggered the start of v in 2015. If there is a large event, it
442 should occur with a time constant as a secondary after-effect fluctuation, and it is
443 unlikely that it will have a constant velocity as in v . Notably, there were no major events
444 in 2015, and a silent shift to a stable steady state occurred.

445 The cause for this phenomenon, which started silently and continued without any
446 major events, is unknown. However, the steady-state nature of the phenomenon leads to
447 a hypothesis that suggests that the site probably returned to its ‘original’ tectonic state
448 long before the earthquake. In other words, the steady velocity V before the 2011
449 Tohoku-Oki earthquake was itself an anomaly (e.g., Nishimura 2014), and it recovered
450 after the earthquake and returned to its original state in 2015, suddenly but silently.
451 Further observations and analyses are required to verify this hypothesis.

452

453 *Evolution of slip zone on the plate*

454 Figure 10 shows a series of changes in the location of the sliding zone on the plate
455 surface from before 2011 to 2020 based on Fig. 9. Figures 10a, 10b, 10d, and 10e show

two phenomena at the same time, one before and one after each epoch.

Figure 10a shows the distribution of slip on the plate surface of the steady velocity V term (Eqs. (1) and (3), item 5) (> 10 cm/year) before 2011, and the main shock (coseismic) slip of the 2011 Tohoku-Oki earthquake (Ozawa et al. 2012; > 10 m). The slip of the steady velocity V term is not quantitatively meaningful because it is not caused by the slip on the plate surface but by the continental plate (Japanese archipelago side) that is being pushed as the plate surface is fixed. The 2011 Tohoku-Oki earthquake occurred on the shallow side of the plate surface with a strong adhesion before 2011.

Figure 10b shows the coseismic slip of the 2011 Tohoku-Oki earthquake and slip of the short-period logarithmic term (> 2 m) during the three years after the earthquake, which is mainly the afterslip. The afterslip occurred adjacent to the deep side of the coseismic slip of the earthquake.

Figure 10d shows the slip of gap_{2015} (> 5 cm), which occurred while the afterslip was occurring. The slip occurred on the northeast side of the afterslip area partially overlapping it. The slip of gap_{2015} is also observed in the Urakawa-Oki (B) area, which is far from the afterslip area. Considering the time series of the gap_{2015} , the SSE

472 occurred at the end of January 2015 near the 2015 Sanriku-Oki earthquake (EQ2 in Fig.
473 10d) (Honsho et al. 2019) followed by the occurrence of a steady-state velocity event
474 from February to July in a wide area, EQ2 in February, EQ3 (the 2015 Miyagiken-Oki
475 earthquake) in May, and EQ1 (the 2016 Urakawa-Oki earthquake) in January 2016.
476 Regarding the variation in the Urakawa-Oki (*B*) area, although EQ1 occurred in 2016,
477 Fig. 4a shows that the slow variation started, albeit slightly, in February 2015. Thus,
478 EQ1, EQ2, and EQ3 are associated with a series of events, and it is unlikely that these
479 earthquakes themselves or their postseismic deformations are the main phenomena that
480 are likely associated with the silent event.

481 Figure 10e shows a steady slip v term (> 2 cm/year) that occurred at the same time as
482 gap_{2015} , and it is continuing in 2020. The Urakawa-Oki (*B*) area is slightly shifted
483 southwest of the gap_{2015} distribution. Note that the Boso Peninsula offshore (*E*) area
484 was affected by the SSE that occurred in 2018 and it was not a steady-state continuous
485 variation within this period (Ozawa et al. 2019).

486 Areas *C* and *D* were stationary before 2011, show post-earthquake afterslip, and
487 continue with the new stationary slip added after 2015. In addition, *B*, *C*, and *D* have

488 few earthquakes in common (Figs. 10c and 10f). *B* is similar to *C* and *D* but does not
489 show afterslip just after the main shock.

490 Next, we focus on the areas where slip is smaller compared to the surroundings in Fig.
491 10 such as east of *B* (Tokachi-Oki), between *C* and *D* (Miyagiken-Oki), and *F*
492 (Aomoriken-toho-Oki). In these areas the afterslip of the 2011 Tohoku-Oki earthquake
493 and the steady-state slip since 2015 were not observed. To the east of *B* is the 2003
494 Tokachi-Oki earthquake (Yamanaka and Kikuchi 2003), between *C* and *D* is the 2011
495 Tohoku-Oki earthquake (Fig. 10a, Ozawa et al. 2012) and its afterslip (Fig. 10b), and *F*
496 is the 1994 Sanriku-Oki earthquake (Yamanaka and Kikuchi 2004) that have caused
497 asperities. These locations are unlikely to move except during their unique earthquakes.

498

499 *Error estimation and prediction performance*

500 Tobita (2016) listed six elements of the functional model's prediction limit. They are as
501 follows: (1) uncertainty of the steady velocity *V*, (2) limitation of function fitting, (3)
502 status change of postseismic deformation mechanisms, (4) variable (inconstant) inter-
503 seismic velocity, (5) future coseismic deformations, and (6) observation errors.

504 Based on the observed data (Fig. 6), the effects of (1), (2), and (4) are sufficiently
505 small because they have not been detected explicitly in the last 10 years. The coseismic
506 variation in (5) has an effect at stations close to the epicenter of an earthquake with a
507 magnitude > 6 but it does not have much of an effect at some distance from the
508 epicenter. In the case of (6), although there is always an error due to environmental
509 factors such as GNSS signal shielding by trees at the observation station, the influence
510 on the model can be minimized by using stations with a good observation environment.
511 These two factors that deteriorate the accuracy of the functional model found in this
512 study are widespread phenomena that occur in the middle of the time series (from 2015)
513 and the phenomena are caused by the fixed reference station (Fukue). The largest error
514 factor was the steady velocity v term after 2015, which would be category (3) stated
515 above. This may not be caused by a change in the mechanism itself but it is because of
516 the start of a new sliding phenomenon in a wide area that was not predicted at all,
517 resulting in an error of several centimeters in a few years. In addition, errors related to
518 the fixed reference station are always associated with such observations, and a
519 fundamental solution is required.

520 Therefore, the evaluation of the prediction performance depends on the existence of
521 the steady velocity v . The v term itself is small, but because it is a steady velocity, it
522 accumulates in one direction over time, resulting in an error of a maximum of 10 cm in
523 10 years. However, the model in Eq. (3), which takes v into account, can be modeled
524 with an error of less than a few centimeters in 10 years. What will happen in the future?
525 This depends on whether the assumption of Eq. (3) holds, and if a phenomenon such as
526 v occurs, the error will increase with time. Therefore, in the practical operation of the
527 functional model, the residuals from the time series at each station in time should be
528 examined, and the functional model should be adjusted as needed. There has been no
529 sudden large shift in the past 10 years, and hence, even if the functional model does not
530 change, it will not pose a practical problem if it is operated in such a way that the
531 change graph shifts parallel to the current observed values using the relative values of
532 time change (e.g., NS component of 2.0-year and 3.9-year fittings in Fig. 2).

533

534 *Use case of the functional model*

535 There are three main purposes of using the spatiotemporal functional model developed

536 in this study: understanding the geophysical processes underground after a large
537 earthquake, discerning small variations other than those of the postseismic deformation,
538 and modeling for precise positioning such as the International Terrestrial Reference
539 Frame (Altamimi et al. 2017) and semi-dynamic datum (Tanaka et al. 2007).

540 The advantages of these applications are that our model can handle a wide area at the
541 same time and can be computed using only the location and time to predict the future.

542 In this section, we present two examples of discerning minute crustal deformations. In
543 general, to discern small crustal deformations from time series, it is necessary to set a
544 fixed station as a reference in the vicinity according to the target location and period and
545 estimate the trend for each observation station to eliminate fluctuations over a wide
546 area.

547 Crustal deformations of the Boso Peninsula offshore SSE that occurred from the end
548 of May to July 2018 (Ozawa et al. 2019) are shown in Fig. 11 as an example of local
549 variability extraction. In Fig. 11a, which is a simple difference between the two periods,
550 the postseismic deformations of the 2011 Tohoku-Oki earthquake are scattered, and the
551 pattern is not uniform. However, in Fig. 11b, where the temporal variation is calculated

552 using the spatiotemporal model obtained in this study, only the SSEs in the Boso
553 Peninsula are clearly extracted, and the extraction power of crustal deformation is
554 incomparable to that of the simple difference.

555 This functional model is effective for extracting various small displacement
556 phenomena. It can also be used for local phenomena, but since the widespread
557 phenomenon of the postseismic deformation of a major earthquake appears uniformly
558 within the local range, the simple difference within the local range is often sufficient.

559 Therefore, the value of this model is in the extraction of small phenomena over a wide
560 area. As an example of discerning such small changes over a wide area, the load
561 deformation due to snow accumulation (Heki 2001) is shown in Fig. 12. In this figure,
562 the residuals of the functional model are calculated from the observed values on March
563 11 of each year after the earthquake (except for 2015), and the average values are drawn
564 because the deepest snow cover usually occurs in early March. To create such a figure
565 for a very small change of 1–2 mm, it would require complicated operations such as
566 modeling the change at each station, but such a figure can be easily drawn by simply
567 subtracting the functional model. It is the power of the functional model that led to the

568 discovery of the existence of v after 2015, and it is a powerful tool with a wide range of
569 applications for discerning small and gradual changes over a wide area.

570

571 **Concluding remarks**

572 The functional model for the postseismic deformation of large earthquakes by Tobita
573 (2016) with statistical processing using a model with two logarithmic functions and one
574 exponential function allows us to draw the following conclusions:

575 (1) The functional model by Tobita (2016) can predict the postseismic deformation of
576 the 2011 Tohoku-Oki earthquake with good accuracy even after 10 years in a wide area
577 exceeding 1000 km.

578 (2) However, from the residuals of this functional model, it was found that a linear
579 change began silently over a wide area in 2015. The pattern is in a form in which a new
580 change in steady-state velocity has been added, and it continues as of 2020 and
581 accumulates at a maximum of approximately 1 cm per year. This phenomenon has been
582 observed over a wide area and uniformly, and when simulated as a slip on the plate
583 surface, in addition to the afterslip area north of Fukushima-Oki and its vicinity, a

584 new slip has appeared in the Urakawa-Oki area. The slip has continued until 2020.

585 (3) The areas where new slip has sparsely occurred since 2015 coincide with the

586 asperity areas that cause unique earthquakes.

587 (4) The new slip since 2015 started silently without any major events, and a closer look

588 shows that the displacement progressed at a constant rate from February to July 2015,

589 and then continued after July with a slight change in trend.

590 (5) Three earthquakes of magnitude > 6.5 have occurred in this new slip zone, but these

591 did not trigger the new slip since 2015, and they themselves were triggered by some

592 silent phenomena.

593 (6) The functional model was improved by incorporating the new slip since 2015 in a

594 linear approximation, and the overall prediction performance of the functional model

595 was significantly improved.

596 (7) The spatial distribution of the functional model for each time constant is similar to

597 that of the afterslip and the viscoelastic relaxation by an independently computed

598 physical model; that is, each time function has a meaning related to the time-dependent

599 physical processes in the underground.

(8) The comparison of the functional and physical models shows that the viscoelastic relaxation near the land has a relatively shorter time constant, and that the fluctuations caused by the viscoelastic relaxation have a very wide range of time constants ranging from a few days to more than 1000 days.

(9) The evolution of the slip zone on the plate surface since before the 2011 earthquake shows that the main shock occurred on the shallow side of the pre-2011 sticking zone, and the afterslip occurred adjacent to the deeper side of the main shock. Subsequently, a temporary slip was observed on the northeast side of the afterslip area and Urakawa-Oki in the first half of 2015, which was followed by the occurrence of a new slip after 2015 that spread to the entire deeper side of the plate surface.

(10) The residuals of the functional model from the observed data are very effective in discerning the occurrence of other events that are not postseismic deformations, and hence can be used in various fields.

Declarations

Ethics approval and consent to participate

616 *Not applicable*

617

618 **Consent for publication**

619 *Not applicable*

620

621 **List of abbreviations**

622 **GNSS:** Global navigation satellite system

623 **SSE:** Slow-slip event

624

625 **Availability of data and materials**

626 The datasets used and/or analyzed during the current study are available from the

627 corresponding author upon reasonable request.

628

629 **Competing interests**

630 The authors declare that they have no competing interests.

631

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633   *Not applicable*

634

635   **Authors' contributions**

636   SF analyzed the data and drafted the manuscript. MT coded the calculation programs.

637   SO calculated the model simulations. All the authors have read and approved the final
638   manuscript.

639

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641   *Not applicable*

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739

740 **Figure captions**

741 Fig. 1 GNSS observation stations considered in this study

742 The four stations, marked as red squares, were used for time series prediction. The four

743 stations, marked as blue squares, in Figs. 2, 3, and 6, and the stations, marked as black

squares, are the other stations. The gray area represents land, and a seafloor topographic map is depicted.

Fig. 2 Observed and predicted postseismic deformation using the functional model

At the four stations of **a** Kaminokuni, **b** Kawai, **c** Nadachi, and **d** Shizugawa (shown in Fig. 1). The three components of EW, NS, and UD were drawn for each station from the day after the earthquake to 2026.5. The black dots represent daily observations. The four broken lines are the time series of predicted values for each fitting period (2.0, 3.9, 5.8, and 8.9-year).

Fig. 3 Residuals between observed values and the 3.9-year fitting values

Each component of **a** EW, **b** NS, and **c** UD were drawn for the four observation stations (Fig. 1). Gray dots are residuals of the 3.9-year fitting based on equation (1). Black dots are residuals of the predicted value by adding a steady velocity term after 2015 to a 3.9-year fitting based on equation (3). Light blue lines are straight lines that fit gray dots from December 2015 to December 2020.

760

761 Fig. 4 Characteristic changes in residuals from 2015 to early 2016

762 The EW components of the three observation stations **a** Erimo, **b** Iwaizumi1, and **c**

763 Oofunato (shown in Fig. 5). Black dots are residuals between the observed values and

764 the 3.9-year fitting values. Red lines are the residuals smoothed with spline. Light blue

765 lines are extensions of straight lines fitted from December 2015 to December 2020. The

766 stars indicate the time of the aftershocks that occurred near each observation station.

767 The double-headed dotted lines are the values of gap_{2015} (see text).

768

769 Fig. 5 Distribution of gaps that occurred in 2015 and steady-state velocity fluctuations

770 that occurred from 2015 to 2020

771 **a** Distribution of gap_{2015} (see text). Red observation stations are shown in Fig. 4. The

772 stars are the epicenters of the aftershocks that affected the time series shown in Fig. 4.

773 **b** Velocity distribution of steady displacement that occurred in 2015 and has continued

774 since then.

775

776 Fig. 6 Observed and predicted postseismic deformation

777 At the four stations of **a** Kaminokuni, **b** Kawai, **c** Nadachi, and **d** Shizugawa (shown in
778 Fig. 1). The three components of EW, NS, and UD were drawn for each station from the
779 day after the earthquake to 2026.5. Gray dots are daily observations used for the 3.9-
780 year fitting. The black dots represent daily observations during the prediction period.
781 The red lines are the predicted values based on Eq. (3), and the other lines are the terms
782 in Eq. (3) (see text).

783

784 Fig. 7 Spatial distribution of each term of the predicted values in three years after the
785 earthquake

786 **a** Short-period logarithmic term, **b** Long-period logarithmic term, **c** Exponential term,
787 and **d** Steady-state velocity term V in Eq. (3). The values for each term are three years
788 after the earthquake (March 11, 2014) when the values immediately after the earthquake
789 were set to zero.

790

791 Fig. 8 Comparison between functional model and physical model

a Short-period logarithmic term of the functional model. **b** Afterslip component based on physical model. **c** Sum of the long-period logarithmic and exponential term of the functional model. **d** Viscoelastic relaxation component of the physical model. The values for each term are three years after the earthquake (March 11, 2014) when the values immediately after the earthquake were set to zero. The physical model was obtained from Suito (2017).

Fig. 9 Slip component models on the plate surface

a Model explaining the short-period logarithmic term at three years after the earthquake. **b** Model explaining *gap*₂₀₁₅. **c** Model explaining the steady-state velocity *v* that occurred from 2015, *B* to *E* represent the locations indicating the characteristic displacement in **c**.

Fig. 10 Evolution of the slip zone on the plate surface

a Orange area shows the slip on the plate surface of the distribution of the steady velocity *V* term (> 10 cm/year) (Eq. (1) and (3), item 5) before 2011, and the blue contours show the coseismic slip of the 2011 Tohoku-Oki earthquake (Ozawa et al.,

808 2012, > 10 m).

809 **b** The blue area shows the coseismic slip (> 10 m) and pink contours show the slip on
810 the plate surface of the short-period logarithmic term (> 2 m) during the three years
811 after the earthquake.

812 **c** Epicenter distribution map from 2011 to 2014. The depth is 15 km or more, and $M >$
813 4.5.

814 **d** The pink area shows the slip on the plate surface of the short-period logarithmic term
815 (> 2 m) and green contours show gap_{2015} (> 5 cm). EQ1 is the Urakawa-Oki earthquake
816 (M6.7) that occurred on January 14, 2016; EQ2 is the Sanriku-Oki earthquake (M6.9)
817 that occurred on February 17, 2015; EQ3 is the Miyagiken-Oki earthquake (M6.8) that
818 occurred on May 13, 2015.

819 **e** Green area shows gap_{2015} (> 5 cm) and red contours show the steady slip (> 2
820 cm/year) that occurred after 2015. The stars represent EQs in **d**.

821 **f** Epicenter distribution map from 2015 to 2018. The depth is 15 km or more, and $M >$
822 4.5. The stars represent EQs in **d**.

823 *B* to *E* represent places indicating characteristic displacements in **e**. *F* represents an area

824 with a small displacement in any of the figures, and *A* represents the location where the
825 maximum displacement was estimated in the main shock.

826

827 Fig. 11 Comparison between simple difference and the functional model in crustal
828 deformation discernment

829 **a** Difference between 10-day averages of May 25 and July 1, 2018

830 **b** Subtracting the functional model of this study from **a**

831

832 Fig. 12 Discernment of crustal deformation caused by snow load using the functional
833 model

834 **a** Vertical component. The green dashed line is a contour of -0.5 mm. The blue lines
835 are the lines where the average annual maximum snowfall is 100 cm (MLIT 2012).

836 **b** Horizontal component. Blue areas are places where the average annual maximum
837 snowfall is more than 100 cm.

838 Both figures used the average values for 10 days on March 11 of each year from 2012 to
839 2020 (excluding 2015).

840

841 **Additional files**

842 Fig. S1 Difference in fitting period and difference in physical model

843 **a** 2.0-year fitting of the short-period logarithmic term, **b** 3.9-year fitting of the short-
844 period logarithmic term, **c** **a** minus **b**.

845 **d** Viscoelastic relaxation component of the physical model minus long-period
846 logarithmic and exponential terms of the functional model.

847 The values for each term are three years after the earthquake (March 11, 2014) when the
848 values immediately after the earthquake were set to zero. The physical model was
849 obtained from Suito (2017).

850

851 Fig. S2 Observed and predicted postseismic deformation using the functional model

852 At the four stations of **a** Minase, **b** Miyako, **c** Yamoto, and **d** Choshi (shown in Fig. 1).

853 The three components of EW, NS, and UD were drawn for each station from the day
854 after the earthquake to 2026.5. The black dots represent daily observations. The four

855 broken lines are the time series of predicted values for each fitting period (2.0, 3.9, 5.8,

856 and 8.9-year).

857

858 Fig. S3 Observed and predicted postseismic deformation

859 At the four stations of **a** Minase, **b** Miyako, **c** Yamoto, and **d** Choshi (shown in Fig. 1).

860 The three components of EW, NS, and UD were drawn for each station from the day

861 after the earthquake to 2026.5. Gray dots are daily observations used for the 3.9-year

862 fitting. The black dots represent daily observations during the prediction period. The red

863 lines are the predicted values based on Eq. (3) and the other lines are the terms in Eq.

864 (3) (see text).

Figures

Figure 1

GNSS observation stations considered in this study. The four stations, marked as red squares, were used for time series prediction. The four stations, marked as blue squares, in Figs. 2, 3, and 6, and the stations, marked as black squares, are the other stations. The gray area represents land, and a seafloor

topographic map is depicted. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Observed and predicted postseismic deformation using the functional model At the four stations of a Kaminokuni, b Kawai, c Nadachi, and d Shizugawa (shown in Fig. 1). The three components of EW, NS, and UD were drawn for each station from the day after the earthquake to 2026.5. The black dots represent daily observations. The four broken lines are the time series of predicted values for each fitting period (2.0, 3.9, 5.8, and 8.9-year).

Figure 3

Residuals between observed values and the 3.9-year fitting values. Each component of a EW, b NS, and c UD were drawn for the four observation stations (Fig. 1). Gray dots are residuals of the 3.9-year fitting based on equation (1). Black dots are residuals of the predicted value by adding a steady velocity term after 2015 to a 3.9-year fitting based on equation (3). Light blue lines are straight lines that fit gray dots from December 2015 to December 2020.

Figure 4

Characteristic changes in residuals from 2015 to early 2016 The EW components of the three observation stations a Erimo, b Iwaizumi1, and c Oofunato (shown in Fig. 5). Black dots are residuals between the observed values and the 3.9-year fitting values. Red lines are the residuals smoothed with spline. Light blue lines are extensions of straight lines fitted from December 2015 to December 2020. The stars

indicate the time of the aftershocks that occurred near each observation station. The double-headed dotted lines are the values of gap2015 (see text).

Figure 5

Distribution of gaps that occurred in 2015 and steady-state velocity fluctuations that occurred from 2015 to 2020 a Distribution of gap2015 (see text). Red observation stations are shown in Fig. 4. The stars are the epicenters of the aftershocks that affected the time series shown in Fig. 4. b Velocity distribution of steady displacement that occurred in 2015 and has continued since then. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 6

Observed and predicted postseismic deformation At the four stations of a Kaminokuni, b Kawai, c Nadachi, and d Shizugawa (shown in Fig. 1). The three components of EW, NS, and UD were drawn for each station from the day after the earthquake to 2026.5. Gray dots are daily observations used for the 3.9-year fitting. The black dots represent daily observations during the prediction period. The red lines are the predicted values based on Eq. (3), and the other lines are the terms in Eq. (3) (see text).

Figure 7

Spatial distribution of each term of the predicted values in three years after the earthquake a Short-period logarithmic term, b Long-period logarithmic term, c Exponential term, and d Steady-state velocity term V in Eq. (3). The values for each term are three years after the earthquake (March 11, 2014) when the values immediately after the earthquake were set to zero. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of

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Figure 8

Comparison between functional model and physical model a Short-period logarithmic term of the functional model. b Afterslip component based on physical model. c Sum of the long-period logarithmic and exponential term of the functional model. d Viscoelastic relaxation component of the physical model.

The values for each term are three years after the earthquake (March 11, 2014) when the values immediately after the earthquake were set to zero. The physical model was obtained from Suito (2017). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 9

Slip component models on the plate surface a Model explaining the short-period logarithmic term at three years after the earthquake. b Model explaining gap2015. c Model explaining the steady-state velocity v that occurred from 2015, B to E represent the locations indicating the characteristic displacement in c. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 10

Evolution of the slip zone on the plate surface a Orange area shows the slip on the plate surface of the distribution of the steady velocity V term (> 10 cm/year) (Eq. (1) and (3), item 5) before 2011, and the blue contours show the coseismic slip of the 2011 Tohoku-Oki earthquake (Ozawa et al., 2012, > 10 m). b The blue area shows the coseismic slip (> 10 m) and pink contours show the slip on the plate surface of the short-period logarithmic term (> 2 m) during the three years after the earthquake. c Epicenter distribution map from 2011 to 2014. The depth is 15 km or more, and $M > 4.5$. d The pink area shows the slip on the plate surface of the short-period logarithmic term (> 2 m) and green contours show gap2015 (> 5 cm). EQ1 is the Urakawa-Oki earthquake ($M6.7$) that occurred on January 14, 2016; EQ2 is the Sanriku-Oki earthquake ($M6.9$) that occurred on February 17, 2015; EQ3 is the Miyagiken-Oki earthquake ($M6.8$) that occurred on May 13, 2015. e Green area shows gap2015 (> 5 cm) and red contours show the steady slip

(> 2 cm/year) that occurred after 2015. The stars represent EQs in d. f Epicenter distribution map from 2015 to 2018. The depth is 15 km or more, and $M > 4.5$. The stars represent EQs in d. B to E represent places indicating characteristic displacements in e. F represents an area with a small displacement in any of the figures, and A represents the location where the maximum displacement was estimated in the main shock. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 11

Comparison between simple difference and the functional model in crustal deformation discernment a Difference between 10-day averages of May 25 and July 1, 2018 b Subtracting the functional model of this study from a Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 12

Discernment of crustal deformation caused by snow load using the functional model a Vertical component. The green dashed line is a contour of -0.5 mm. The blue lines are the lines where the average annual maximum snowfall is 100 cm (MLIT 2012). b Horizontal component. Blue areas are places where the average annual maximum snowfall is more than 100 cm. Both figures used the average values for 10 days on March 11 of each year from 2012 to 2020 (excluding 2015). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

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