Spatiotemporal Slip Distributions Associated with the 2018-2019 Bungo Channel Long-Term Slow Slip Event Inverted from GNSS Data

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Research Article

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Spatiotemporal slip distributions associated with the 2018-2019 Bungo Channel long-term slow slip event inverted from GNSS data

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Abstract

Long-term slow slip events (L-SSEs) have occurred beneath the Bungo Channel with durations of several months to a couple of years repeatedly with a recurrence interval of approximately six years. We estimated the spatiotemporal slip distributions of the 2018-2019 Bungo Channel L-SSE inverted from processed GNSS time series data. This event was divided into two subevents, with the first on the southwest side of the Bungo Channel from 2018.3 to 2018.7 and the second beneath the Bungo Channel from 2018.8 to 2019.4. Tectonic tremors became active on the downdip side of the L-SSE occurrence region when large slow slips took place beneath the Bungo Channel. Compared with the previous Bungo Channel L-SSEs, this spatiotemporal slip pattern and amount were similar to those of the 2003 L-SSE. However, the slip expanded in the northeast-southwest direction in the latter half of the second subevent. We also found that the total duration of the two subevents was 1.0 year, which was the shortest among the four recent L-SSEs beneath the Bungo Channel identified using GNSS time series data. The maximum amount of slip, the maximum slip velocity, the total released seismic moment, and the moment magnitude of the 2018-2019 L-SSE were estimated to be 27 cm, 53 cm/year, $4.1 \times 10^{19}$ Nm, and 7.0, respectively, all of which were the largest among the four L-SSEs.

1. Introduction

In the Bungo Channel, located between Shikoku and Kyushu in southwestern Japan, the Philippine Sea plate is subducting beneath the Amurian plate in the northwest direction at a convergence rate of approximately $58.4 \pm 1.2$ mm/year (Fig. 1). On the plate boundary beneath this region, aseismic interplate slips, which are so-called long-
term slow slip events (hereafter referred to as L-SSEs), have repeatedly occurred with
durations of several months to several years. The GNSS continuous observation system
(GEONET, GNSS Earth Observation Network System) launched by the Geospatial
Information Authority of Japan (GSI) in 1996 has enabled high-precision geodetic
observations with high temporal resolution and detection of such aseismic slow slip
events. GNSS observation stations have been set up at approximately 1,300 locations
throughout the Japanese Islands and play an important role in monitoring crustal
deformation caused by earthquakes and volcanic activities. Previous studies have
analysed the slip distributions of L-SSEs that occurred beneath the Bungo Channel in
1996-1998, 2002-2004, and 2009-2011. Kobayashi and Yamamoto (2011) showed that L-SSEs also occurred in 1980, 1985-1986, and 1991 beneath the Bungo
Channel based on levelling survey and tide gauge station data and that the L-SSEs have
been repeated every 5-6 years since 1980.

Yoshioka et al. (2015) performed inversion analysis of the Bungo Channel L-SSEs
that occurred in 1996-1998, 2002-2004, and 2009-2011 and compared their
spatiotemporal slip distributions. In the 1996-1998 events, the maximum slip amount was
approximately 15 cm with Mw 6.8 and it was estimated that slip occurred beneath the
Ashizuri cape on the east side of the Bungo Channel from 1996.9. The slip area then
shifted to the central part of the Bungo Channel. The maximum slip amount of the 2002-
2004 event was estimated to be approximately 21 cm with Mw 7.0. The L-SSE during
this period consisted of two main subevents. The first subevent occurred on the southwest
side of the Bungo Channel from approximately 2002.1 to 2002.8 with the maximum slip
amount estimated to be approximately 7.3 cm with Mw 6.5. The second subevent
occurred from approximately 2003.1 to 2004.3 with the maximum slip amount estimated
to be approximately 16 cm with Mw 6.8. Furthermore, the second subevent can be divided into three periods: 2003.1-2003.4, 2003.5-2004.0, and 2004.0-2004.3. The first slip occurred in the southwest to central part of the Bungo Channel. The second slip started at the northeast side of the Bungo Channel and expanded to the southwest with the acceleration of the slip. The third slip was observed on the southwest side of the Bungo Channel. In the 2009-2011 event, the maximum slip amount was approximately 19 cm, Mw 6.9, and it was estimated that the slip started at approximately 2009.9 in the central part of the Bungo Channel and then shifted to the southwest of the channel.

Ozawa et al. (2020) analysed the spatiotemporal slip distribution of the Bungo Channel L-SSE that occurred from 2018 to 2019. They found that slip took place at the plate boundary north of Hyuga-nada from June 2018 to October 2018 and at the Bungo Channel from October 2018 to approximately August 2019. The maximum slip amount was estimated to be approximately 30 cm beneath the Bungo Channel and 36 cm in northern Hyuga-nada with Mw 7.0.

In this study, we used the inversion method proposed by Yoshioka et al. (2015) to analyse the Bungo Channel L-SSE that occurred from 2018 to 2019 and compared the results with spatiotemporal slip distributions of the previous Bungo Channel L-SSEs.

2. Data processing of GNSS time series

In this study, we used the daily coordinate positioning values (F3 solutions) of GEONET stations provided by the Geospatial Information Authority of Japan. The data period used for analysis covered 1 January 2016 to 30 June 2020. The number of observation stations used was 114 (Fig. 1) with three components at each station. Six
stations (0075, 0076, 0385, 0387, 0388, and 0407) in the northern Chugoku district (Fig. 1), which are not affected by the L-SSE, were used as reference stations to calculate the common-mode error. The analysis procedure was summarized as follows, according to Yoshioka et al. (2015). First, we calculated the residual, 

\[
\varepsilon_i^S(d) = P_i^S(d) - C_i^S(d) \tag{1}
\]

where \(\varepsilon_i^S(d)\) is the residual, \(P_i^S(d)\) is the time series data of the reference station after removing the coseismic steps and the steps caused by antenna exchange, \(C_i^S(d)\) is the linear trend of the time series data of the reference station, and \(i (= 1, 2, \text{and} 3)\) denote the east-west, north-south, and up-down components, respectively. Next, the residuals of the six stations were averaged to obtain the common-mode error:

\[
\hat{\varepsilon}_i(d) = \frac{1}{6} \sum_{S=1}^{6} \varepsilon_i^S(d) \tag{2}
\]

Assuming that this error component is common to all the stations used in the analysis, we removed the common-mode error from the time series data of each station.

\[
\hat{O}_i^T(d) = \hat{O}_i^T(d) - \hat{\varepsilon}_i(d) \tag{3}
\]

where \(\hat{O}_i^T(d)\) denotes the original time series data of each observation station. After removing the common-mode error, we calculated the crustal movement due to plate motions and annual and semiannual variations and removed these components.

\[
y(t) = \alpha + \beta t + \sin \left(\frac{2\pi t}{T}\right) + d \cos \left(\frac{2\pi t}{T}\right) + e \sin \left(\frac{4\pi t}{T}\right) + f \cos \left(\frac{4\pi t}{T}\right) \tag{4}
\]

where \(T = 1\) year, the first and second terms on the right-hand side represent crustal deformation due to plate motions assuming a linear trend, the third and fourth terms represent annual variations, and the fifth and sixth terms represent semiannual variations. \(\alpha\) to \(f\) are unknown parameters and their optimal values were determined by the least-squares method. The period used for the calculation of equation (4) was from 1 January
2016 to 31 December 2017, when no L-SSEs took place, and these components were
assumed to be invariant during the entire analysis period. After removing the coseismic
steps and the steps caused by antenna exchange, we also removed the crustal deformation
caused by plate motion, annual variations and semiannual variations. The coseismic steps
and the steps caused by the antenna exchange were corrected by taking the difference of
the average of the previous and next 10 days. The corrected time series data were
subjected to curve fitting using a cubic B-spline function using ABIC (Akaike's Bayesian
Information Criterion) minimization principle\textsuperscript{11} to estimate the standard deviation of the
data used for the inversion of the spatiotemporal slip distribution of L-SSE. In addition,
the corrected time series data show larger variations in the vertical displacements than
those in the horizontal displacements.

3. Model

Since the L-SSE is a slip phenomenon occurring on the plate boundary, the
estimation area is placed on the three-dimensional upper surface of the Philippine Sea
plate, as shown in Hirose et al. (2008)\textsuperscript{12} (Fig. 1). The size of the source region at the plate
interface was 200 km × 200 km in the dip and strike directions, respectively, and 11 × 11
B-spline functions were distributed as the basis functions. The number of basis functions
in the time direction was 21. Therefore, the total number of model parameters
representing the spatiotemporal slip distribution was 5082, where the slip was represented
by two components, the dip and strike directions. The means of the standard deviations
used to weight the EW, NS, and UD components during inversion were 0.14 cm, 0.14 cm,
and 0.52 cm, respectively, which were obtained using the optimal curve and daily
corrected positioning time series data, as described in the previous section. In this study, the time step was set to 0.1 year.

4. Results

4-1. Horizontal and vertical displacement rates associated with the L-SSE

The total horizontal and vertical displacements associated with the L-SSE at each station during the analysis period are shown in Figs. S1 (a) and (b), respectively. In the horizontal displacement field, a maximum displacement of approximately 5 cm in the southeast and east-southeast directions was identified at most stations. In the vertical displacement field, a maximum subsidence of approximately 5 cm was identified in eastern Kyushu, and a maximum uplift of approximately 5.5 cm was observed in southwestern Shikoku.

The corrected time series three-component data at some picked-up stations in Fig. S1(a) are shown in Fig. S2. At the stations in Kyushu, southeastward displacements associated with the 2018-2019 Bungo Channel L-SSE began to be observed from the middle of 2018 and subsided in the middle of 2019. The maximum displacements were approximately 1.5 cm in the south direction, approximately 2.9 cm in the east direction, and approximately 2.8 cm in the downward direction among the stations in Kyushu, as shown in Fig. S2. The southeastward displacements also began to be observed at stations in Shikoku in the middle of 2018 and subsided in the middle of 2019. The time when the displacements subsided was almost the same as that in Kyushu. The maximum displacements were approximately 2.6 cm in the south direction, approximately 3.4 cm in the east direction, and approximately 4.6 cm in the upward direction among the stations.
in Shikoku, as shown in Fig. S2. In particular, the uplift at the station located in the southwestern part of Shikoku was approximately 2 to 3 cm larger than that at other stations in Shikoku.

Horizontal displacements at 0.1-year time steps are shown in Fig. 2. Displacement rates in the southeast to east-southeast directions began to be observed at both stations in Kyushu and Shikoku in approximately 2018.4 (Fig. 2(e)). During the period from 2018.5 to 2018.6 (Fig. 2(f)), the displacement rates became larger. The increase in displacement was especially pronounced at the stations in Kyushu, where the maximum displacement rate was approximately 5 cm/year. During the period from 2018.6 to 2018.7 (Fig. 2(g)), the displacement rates decreased, and during the period from 2018.7 to 2018.8 (Fig. 2(h)), almost no displacement was observed. Subsequently, the displacement rates in the east-southeast direction appeared during the period from 2018.8 to 2018.9 (Fig. 2(i)). The displacement rates became the largest during the period from 2019.1 to 2019.2 (Fig. 2(l)), with a maximum displacement rate of approximately 11 cm/year. After that, the displacement rates decreased, and almost no displacement was observed during the period from 2019.4 to 2019.5 (Fig. 2(o)). In contrast to the displacement rates observed during the period from 2018.3 to 2018.7 (Fig. 2(d)-(g)), during the period from 2018.8 to 2019.4 (Fig. 2(i)-(n)), displacement rates in the southeast to east-southeast direction were observed mainly at stations in the northern part of Kyushu, reaching approximately 7 cm/year, and the displacement rates at stations in the southwestern part of Shikoku became larger by approximately 8 cm/year. After southeast to east-southeast displacement rates were observed in both Kyushu and Shikoku during the period from 2018.8 to 2019.4 (Fig. 2(i)-(n)), east-southeastward displacement rates up to approximately 3 cm/year were observed mainly in Shikoku during the period from 2019.5 to 2019.6 (Fig. 2(p)).
The vertical displacement at 0.1-year time steps is shown in Fig. 3. Uplift began gradually in the southwestern part of Shikoku in approximately 2018.9 (Fig. 3(j)) and became the largest during the period from 2019.1 to 2019.3 (Fig. 3(l)-(m)), reaching approximately 14 cm/year. After that, the displacement rates decreased. Subsidence, reaching approximately 5 cm/year, can be identified at most of the stations in Kyushu during the period from 2019.0 to 2019.1 (Fig. 3(k)).

4-2. Spatiotemporal slip distributions associated with the L-SSE inverted from the GNSS data

The inversion analysis of the spatiotemporal slip distribution on the 3-D shaped plate boundary was performed from 2018.0 to 2020.0 using the corrected time series GNSS data of each observation station. The spatiotemporal slip distributions inverted from the horizontal displacement (Fig. 2) and vertical displacement (Fig. 3) data at 0.1-year time steps are shown in Fig. 4. The maximum amount of slip, released seismic moment, and equivalent moment magnitude were estimated to be approximately 27 cm, $4.1 \times 10^{19}$ Nm, and 7.0, respectively (Table S1). The rigidity used in the calculation of seismic moments was 30 GPa. Here, we evaluated the minimum released seismic moment and equivalent Mw, although the seismic moment appears to increase even after the second subevent (Figs. S3). This point will be discussed later.

The L-SSE that occurred during this period consists of two subevents. The first subevent was identified on the southwest side of the Bungo Channel during the period from 2018.3 to 2018.7 (Figs. 4 (d)-(g)). The maximum amount of slip, released seismic moment, and equivalent moment magnitude were estimated to be approximately 8.2 cm,
9.0 \times 10^{18} \text{Nm}, \text{ and } 6.6, \text{ respectively. The maximum slip velocity was approximately 36 cm/year during the period from 2018.5 to 2018.6 (Fig. 4(f)).}

The second subevent was identified beneath the central Bungo Channel area during the period from 2018.8 to 2019.4 (Figs. 4 (i)-(n)). The maximum amount of slip, released seismic moment, and equivalent moment magnitude were estimated to be approximately 19 cm, \( 2.2 \times 10^{19} \text{Nm} \), and 6.8, respectively. The maximum slip velocity was approximately 53 cm/year during the period from 2019.1 to 2019.2 (Fig. 4(l)). In this subevent, the slip area expanded in the northeast-southwest direction during the period from 2019.2 to 2019.3 (Fig. 4(m)). In addition, tectonic tremors appear to have been activated on the downdip side of the L-SSE occurrence region when large slips occurred beneath the Bungo Channel. After the end of the second subevent, a slight slip appears to take place during the period from 2019.4 to 2019.8 (Figs. 4 (o)-(r) and S3).

Here, we compare the calculated values obtained from the slip distributions shown in Fig. 4 with the observed values. In Fig. 2, the directions of the observed and calculated horizontal displacement rates were almost the same at most stations, although the calculated values were more east-southeast than the observed values at some stations. The displacement rates were almost the same, although the calculated values were smaller than the observed values at some stations. During the period from 2019.5 to 2019.7, the observed displacement rates were not clearly identified, but the calculation showed displacement rates from east-southeast to southeast in the southwestern part of Shikoku.

In Fig. 3, we show a comparison between the observed and calculated vertical displacement fields. Agreement in these data is not as good as that of the horizontal displacement fields because the data weight for the latter is larger than that for the former. There was a large difference between the observed and calculated displacement rates at
the stations in Kyushu, but the difference was relatively small at the stations in Shikoku. In particular, the observed and calculated values were almost identical during the period from 2019.1 to 2019.3 (Figs. 3(l) and (m)), when the southwestern part of Shikoku was greatly uplifted.

A similar tendency can also be identified from the time series data at some picked-up stations (Fig. S2). The fitting of the calculation to the corrected horizontal time series data is better than that of the vertical data, and the discrepancy tends to be slightly larger in the vertical component at the stations in Kyushu.

5. Discussion

5-1. Comparison with spatiotemporal slip distributions of the past L-SSEs beneath the Bungo Channel

L-SSEs occurred beneath the Bungo Channel in the past. Here, based on the results obtained by Yoshioka et al. (2015), we compared the characteristics of slips of the L-SSEs that occurred in 1996-1998, 2002-2004, and 2009-2011 with that of the L-SSE estimated in this study (Table S1). The first subevent of the L-SSE estimated in this study occurred on the southwest side of the Bungo Channel and the second subevent took place beneath the central part of the Bungo Channel. The location, magnitude, spatial slip distribution, and relative order in time and space in 2018-2019 were all similar to those of the 2002-2004 L-SSE (Fig. S4).

However, the time interval between the first and second subevents was 0.3 years in the 2002-2004 L-SSE, while it was 0.1 years in the 2018-2019 L-SSE and the slip area expanded in the northeast-southwest direction in the latter half of the second subevent.
(Figs. 4 (m) and (n)) in the 2018-2019 L-SSE. We also found that the total duration time
of the two subevents was 1.0 year, which was the shortest among the four recent L-SSEs
beneath the Bungo Channel identified using GNSS time series data.

The time variation of the cumulative released seismic moment of the 2018-2019
L-SSE is shown in Fig. S3. The released seismic moment and equivalent moment
magnitude of the first and second subevents of the L-SSE estimated in this study were
almost the same as those of the first and second subevents of the 2002-2004 L-SSE. In
addition, the released seismic moment and equivalent moment magnitude of the second
subevent estimated in this study were almost the same as those of the 1996-1998 and
2009-2011 L-SSEs. The duration of the slip was approximately 1.3 years for the 1996-
1998 L-SSE, approximately 0.7 years for the first subevent, approximately 1.2 years for
the second subevent of the 2002-2004 L-SSE, and approximately 1.2 years for the 2009-
2011 L-SSE. On the other hand, the durations of the first and second subevents of the
2018-2019 L-SSE were approximately 0.4 and 0.6 years, respectively. Thus, the total
duration of slips was the shortest for the 2018-2019 L-SSE among the four L-SSEs. In
the 1996-1998 L-SSE, 2002-2004 L-SSE, 2009-2011 L-SSE, and 2018-2019 L-SSE, the
maximum slip velocity was approximately 28 cm/year, 44 cm/year, 39 cm/year, and 53
cm/year, respectively, and the total slip was approximately 15 cm, 21 cm, 19 cm, and 27
cm, respectively. The maximum slip velocities, which also resulted from the shortest
duration, and the total slip of the L-SSEs estimated in this study were the largest among
the four L-SSEs beneath the Bungo Channel. The occurrence interval of L-SSEs in the
past was approximately six years, but the estimated L-SSE in this study was
approximately eight years after the last L-SSE in 2009-2011. This may have affected the
maximum slip rate and total slip.
Hirose et al. (2010) found that tectonic tremors and shallow very low-frequency earthquakes located near the Nankai Trough far to the south were synchronized in the 2002-2004 L-SSE and the 2009-2011 L-SSE. In this study, an increase in tectonic tremors was identified, but synchronization with shallow very low-frequency earthquakes has not yet been investigated.

5-2. Comparison with a previous study on spatiotemporal slip distributions of the 2018-2019 Bungo Channel L-SSE

Next, we compared the spatiotemporal slip distributions of the 2018-2019 Bungo Channel L-SSE obtained in this study with those obtained in a previous study. Ozawa et al. (2020) performed a network filter inversion by McGuire and Segall (2003) and found that the first subevent occurred on the north side of Hyuga-nada from June 2018 to October 2018 and the second subevent was identified beneath the Bungo Channel from October 2018 to August 2019. The locations of the two subevents were almost the same as those obtained in this study. In Ozawa et al. (2020), the second subevent also expanded in the northeast-southwest direction. The maximum amount of slip was estimated to be approximately 30 cm by Ozawa et al. (2020), which was almost the same as that estimated in this study. The moment magnitude of the L-SSE was estimated to be 7.0, which was consistent with the results of this study.

However, there were also some discrepancies between the two studies. First, the start time of the first subevent was different from that of this study. In addition, during the period from 1 April 2019 to 1 June 2019, the slip near the centre of the Bungo Channel weakened, and slip was identified on the southwest side of Shikoku and the north side of Hyuga-nada in Ozawa et al. (2020), whereas there was no weakening of the slip near
the centre of the Bungo Channel in this study. Furthermore, the slip weakened in the
period from June 2019 to August 2019 in Ozawa et al. (2020), but in this study, a slight
slip was identified in the period from 2019.4 to 2019.8 (Figs. 4 (o)-(r)). This suggested
that the slip may have continued even after August 2019. Another possibility is that this
difference may originate from the fact that the postseismic deformations associated with
the 2011 Tohoku earthquake, especially eastward slight continuous displacements, as seen
in Fig. S3 (b), have not been completely removed in this study, in which a linear trend is
assumed and detrended, resulting in superficial slight slip in Figs. 4 (o)-(r).

These differences may be caused by differences in the temporal resolution of the
slip distributions, the difference in the correction of the GNSS time series data, and the
difference in the inversion method. With regard to the temporal resolution, Ozawa et al.
(2020) explained the temporal change in slip using the slip distribution every two
months, while in this study, we used the slip distribution every 0.1 year. In Ozawa et al.
(2020), the period of the time step was longer than that of this study, so the slip amount
at each time step was expected to be larger. For the correction of the GNSS time series
data, Ozawa et al. (2020) used the estimation period of the annual variations from 2000
to 2018 and the linear trend from 1 January 2017 to 1 January 2018, while in this study,
the estimation period of both the annual and semiannual variations and the linear trend
was from 1 January 2016 to 31 December 2017. For the inversion method, Ozawa et al.
(2020) used the constraints that the aseismic slip vector and slip vector at the plate
interface should be within 10° from the direction opposite to the relative motion of the
Philippine Sea plate to the Amurian plate and did not give any constraints in the time
direction, while in this study, we used the three prior constraints as described in the
“Methods” section.
6. Conclusions

In this study, we analysed the spatiotemporal slip distributions of the long-term slow slip event that occurred on the plate boundary beneath the Bungo Channel from 2018 to 2019 using GNSS time series data. We used the inversion method proposed by Yoshioka et al. (2015) with the three prior constraints. Significant results obtained in this study can be summarized as follows:

(1) Regarding the 2018-2019 L-SSE analysed in this study, the total duration time of 1.0 year was the shortest, and the slip velocity of 53 cm/year, slip amount of 27 cm, total amount of released seismic moment of $4.1 \times 10^{19}$ Nm, and equivalent moment magnitude of 7.0 were all the largest among the four L-SSEs which were recorded by GNSS. The latter may be related to the longest recurrence interval of eight years since the occurrence of the last L-SSE.

(2) The 2018-2019 L-SSE consists of two subevents. The first subevent occurred on the southwest side of the Bungo Channel, with a maximum slip of approximately 8.2 cm, released seismic moment of $9.0 \times 10^{18}$ Nm, equivalent Mw of 6.6, and maximum slip velocity of approximately 36 cm/year during the period from 2018.5 to 2018.6. The second subevent took place near the centre of the Bungo Channel, with a maximum slip of approximately 19 cm, a released seismic moment of $2.2 \times 10^{19}$ Nm, an equivalent Mw of 6.8, and a maximum slip velocity of approximately 53 cm/year during the period from 2019.1 to 2019.2.

(3) Tectonic tremors appear to have been activated on the downdip side of the L-SSE occurrence region when large slips occurred beneath the Bungo Channel.
Compared with the past L-SSEs beneath the Bungo Channel, the first subevent occurred on the southwest side of the Bungo Channel and the second subevent took place near the centre of the Bungo Channel, which is similar to the 2002-2004 L-SSEs. The released seismic moment and equivalent Mw were almost the same.

**Methods**

We performed an inversion analysis for the crustal deformation associated with the 2018-2019 Bungo Channel L-SSE by the following procedure using corrected GNSS time series data. The medium is assumed to be a semi-infinite homogeneous perfect elastic body.

In this study, we used the inversion method proposed by Yoshioka et al. (2015) with three prior constraints: 1) the spatial slip distribution is smooth, 2) the slip directions are oriented in the direction of plate convergence, and 3) the temporal change in the slip is smooth. The slip distribution is represented by a superposition of bicubic B-spline functions, and the temporal evolution is represented by a superposition of first-order B-spline functions. In the following, we briefly summarize the inversion method according to Yoshioka et al. (2015). The relationship between the model parameters representing the spatiotemporal slip distribution and the observed data can be expressed by the following equation:

\[
\begin{bmatrix}
\mathbf{d} \\
\mathbf{0} \\
\mathbf{0} \\
\mathbf{0}
\end{bmatrix} = 
\begin{bmatrix}
\mathbf{H} \\
\mathbf{A} \\
\mathbf{B} \\
\mathbf{G}
\end{bmatrix}
\begin{bmatrix}
\alpha \\
\beta \\
\gamma
\end{bmatrix}
\]

where \( \mathbf{d} \) is the vector of observed displacement data, \( \mathbf{H} \) is a matrix representing the relationship between the unit slip on the fault plane and the displacement at each GNSS
observation station, \( a \) is a vector of model parameters, \( A \), \( B \), and \( G \) are matrices representing the above-described first, second and third constraints, respectively. \( \hat{a} \), \( \hat{\beta} \), and \( \hat{\gamma} \) are the optimal values of the hyperparameters and represent the optimal values of the weight of the constraints. These hyperparameters are determined uniquely and objectively based on the ABIC minimization principle\(^\text{11}\). A covariance matrix \( C \) of the estimation error for the estimated model parameter vector can be obtained as follows:

\[
C = \hat{\sigma}^2 (H^T H + \hat{\alpha}^2 A^T A + \hat{\beta}^2 B^T B + \hat{\gamma}^2 G^T G)^{-1}
\]

where \( \hat{\sigma}^2 \) is described in Yoshioka et al. (2015)\(^\text{7}\). A resolution matrix can be defined as

\[
R = (H^T H + \hat{\alpha}^2 A^T A + \hat{\beta}^2 B^T B + \hat{\gamma}^2 G^T G)^{-1} H^T H
\]

The value of the resolution at each solved point on the plate boundary is defined by the diagonal component of the resolution matrix as

\[
R = \sqrt{\left(R^P\right)^2 + \left(R^S\right)^2} / 2
\]

where \( R^P \) and \( R^S \) are the resolutions in the plate convergence direction and perpendicular to the plate convergence direction, respectively.

In this study, we evaluated the reliability of the inverted slip distributions using the calculated estimation errors and resolutions.

The optimal values of the hyperparameters representing the weights of the three prior constraints \( \hat{a} \), \( \hat{\beta} \), and \( \hat{\gamma} \) used in this study were obtained as \( 7.4 \times 10^{-2} \), \( 6.7 \times 10^{-1} \), and \( 7.4 \times 10^{-2} \), respectively.

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were created by using the Generic Mapping Tools (GMT)\textsuperscript{16} (version: GMT 4.5.7, URL link: https://www.generic-mapping-tools.org/download/). This work was partly supported by Japan Society for the Promotion of Science grants KAKENHI 16H04040 and 16H06477. The part of this research is also supported by The Project for Hazard Assessment of Large Earthquakes and Tsunamis in the Mexican Pacific Coast for Disaster Mitigation, SATREPS funded by JST-JICA (#1554361).

\textbf{Author Contributions statement}

Y.S. carried out the data processing of GNSS time series and carried out the inversion analyses, and wrote the paper; S.Y. organized and instructed this study, pointing out possible problems and advised the solutions to those in this study. Both authors reviewed and commented on the paper as well as declare no competing interests in relation to the work.
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Figure captions

Figure 1  Tectonic map in and around the Bungo Channel, southwest Japan. The thin black lines represent isodepth contours of the upper surface of the Philippine Sea plate subducting from the Nankai Trough, represented by the thick barbed black line. The 10 km, 20-50 km, and > 60 km contour lines are taken from Baba et al. (2002)\textsuperscript{17}, Hirose et al. (2008)\textsuperscript{12}, and Nakajima and Hasegawa (2007)\textsuperscript{18}, respectively. The arrows indicate the plate motion velocity vector of the Philippine Sea plate with respect to the Amurian plate estimated by DeMets et al. (2010)\textsuperscript{1}. The light-blue solid circle denotes the approximate location where the Bungo Channel slow slip events took place. The red solid circles and blue solid squares denote the GNSS stations used for the inversion analysis in this study and reference stations to calculate the common-mode error, respectively. The grey squared area is the study region in the map of the Japanese islands.

Figure 2  Spatial distribution of horizontal displacement fields associated with the Bungo Channel L-SSE at each 0.1-year time step during the period from 2018.0 to 2020.0. The red and blue arrows indicate the observed displacements and the calculated displacements obtained from the spatiotemporal slip distributions shown in Fig. 4, respectively. (a) 2018.0-2018.1. The scale of 0.5 cm for the arrow is shown. (b) 2018.1-2018.2. (c) 2018.2-2018.3. (d) 2018.3-2018.4. (e) 2018.4-2018.5. (f) 2018.5-2018.6. (g) 2018.6-2018.7. (h) 2018.7-2018.8. (i) 2018.8-2018.9. (j) 2018.9-2019.0. (k) 2019.0-2019.1. (l) 2019.1-2019.2. (m) 2019.2-2019.3. (n) 2019.3-2019.4. (o)
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Figure 4  Slip distributions of the Bungo Channel L-SSE for the 0.1-year time step during the period from 2018.0 to 2020.0. The arrows indicate the directions and amounts of the slip, and the circles at the tips of the arrows indicate the estimation errors of 1σ. The contour lines with yellowish colour show the amounts of slip with an interval of 1 cm. Areas with a resolution of less than 0.15 are masked in grey. The light blue dots indicate the epicentres of tectonic tremors that occurred during each period. (a) 2018.0-2018.1. (b) 2018.1-2018.2. (c) 2018.2-2018.3. (d) 2018.3-2018.4. (e) 2018.4-2018.5. (f) 2018.5-2018.6. (g) 2018.6-2018.7. (h) 2018.7-2018.8. (i) 2018.8-2018.9. (j) 2018.9-2019.0. (k) 2019.0-2019.1. (l) 2019.1-2019.2. (m) 2019.2-2019.3. (n) 2019.3-2019.4. (o) 2019.4-2019.5. (p) 2019.5-2019.6. (q) 2019.6-2019.7. (r) 2019.7-2019.8. (s) 2019.8-2019.9. (t) 2019.9-2020.0.
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