Repetitive long-term slow slip events beneath the Bungo Channel, southwestern Japan, identified from leveling and sea level data from 1979 to 2008

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Abstract

Leveling and sea level data for the period from 1979 to 2008 around the Bungo Channel, southwestern Japan, were investigated to characterize vertical deformation patterns. We found evidence of discrete events that may have occurred beneath the Bungo Channel before the two most recent long-term slow slip events (SSEs) (1996–1997 and 2003) detected from GPS data. GPS-derived steady-state vertical displacements related to ongoing subduction of the Philippine Sea plate were subtracted from the vertical displacements observed by leveling surveys. The spatial pattern of the residual vertical displacements observed by leveling was similar to that observed by GPS in the periods including recent long-term SSEs. This suggests that discrete vertical displacements, which might represent long-term SSEs, have occurred in each of four intervals between leveling surveys before GPS deployment. We calculated differences of sea level between tidal stations near the Bungo Channel after some corrections, and then cross-correlated them with the GPS-derived vertical displacements of the recent long-term SSE to estimate the timing of the events. These cross correlations and the discrete vertical displacements derived from leveling suggest that long-term SSEs may have occurred around 1980, around 1985–1986, and around 1991.

1. Introduction

On plate interfaces, there are stable sliding areas and asperities [*Lay and Kanamori*, 1981]. The interface is locked and strain and stress build up during the plate subduction at the asperities. There are also the transition areas which have characteristics between the stable sliding area and the asperities. In the transition areas, slow slip events (SSEs) have been reported from subduction margins in the world [e.g., *Schwartz and Rokosky*, 2007].

The deployment of the GEONET GPS observation network [*Miyazaki et al.*, 1997] and the Hi-net high-sensitivity seismograph network [*Okada et al.*, 2004] has led to the detection of SSEs on the plate boundary under Japan [e.g., *Ozawa et al.*, 2003; *Obara et al.*, 2004]. The SSEs in Japan are classified into two types according to duration. One is a short-term SSE with duration of a few days, and the other is a long-term SSE which lasts from several months to several years. Short-term SSEs are accompanied with non-volcanic deep low-frequency tremors, and are distributed in a belt-like zone from central to southwestern Japan [*Obara and Hirose*, 2006]. Long-term SSEs have been observed both in the Tokai region, central Japan, from 2001 to 2005 [*Ozawa et al.*, 2002; *Geographical Survey Institute*, 2007], and in the Bungo Channel region, southwestern Japan, from 1996 to 1997 [*Hirose et al.*, 1999] and in 2003 [*Ozawa et al.*, 2004; *Ozawa et al.*, 2007] after the deployment of the GEONET. Both of these areas lie along the Nankai Trough where the Philippine Sea plate is subducting beneath the Eurasian plate (Figure 1). The source areas of the long-term SSEs were located around the marginal area of the locked zones of faults that may cause future large earthquakes. The short-term SSEs locate at the downdip edge of the plate interface, a bit deeper than the source area of the long-term SSEs. This relative location is also seen in the other slow slips in the world [*Schwartz and Rokosky*, 2007]. The generation of the long-term SSEs will cause stress change in neighboring areas. Actually, the short-term SSEs became active during the period of long-term SSEs [*Hirose and Obara*, 2005; *Kobayashi et al.*, 2006]. Therefore, the stress change should also extend to the locked zones of future source area of large earthquakes.

A future large earthquake has been considered in the Tokai region [*Ando*, 1975a; *Ishibashi*, 1981], and observation system for the earthquake prediction has been built up. Along the Nankai Trough, large earthquakes occurred with recurrence intervals of 100–200 years [e.g., *Ando*, 1975b]. The latest events are the 1944 Tonankai (*M7.9*) and the 1946 Nankai (*M8.0*) earthquakes. More than half a century has passed since the last large earthquakes. Because the next great earthquakes are expected to occur in the near future, observation systems began to be installed in the region. Recent numerical simulations produce large earthquakes and various types of slip phenomena including slow slips [e.g., *Mitsui and Hirahara*, 2006; *Kato*, 2008; *Hirose et al.*, 2009]. Discrete crustal deformation due to aseismic interseismic slip events is predicted in results of the simulation, and this aseismic slip could become the useful information for earthquake prediction. It is necessary to raise the accuracy of the simulation for more reliable earthquake prediction. However, the observation period of the GPS is too short compared with the period between earthquakes. Sufficient observation data necessary for improvement of the simulation have not been obtained. Therefore, it is necessary to estimate the crustal deformation before GPS deployment by leveling and sea level observations.

Some long-term SSEs that occurred before the deployment of GEONET have been reported in the Tokai region. *Kimata et al.* [2001] reported two SSEs from 1978 to 1983 and from 1987 to 1991 on the basis of leveling and electronic distance meter data. *Nagoya University* [2004] inferred transient deformation during the same time periods from leveling and sea level data. *Kobayashi and Yoshida* [2004] estimated from sea level data in the Tokai region that long-term SSEs occurred there from 1980 to 1982 and from 1988 to 1990. *Yamamoto et al.* [2005] inferred that a change in the tilt record in the Tokai region from 1988 to 1989 was caused by a long-term SSE. The occurrence time of these long-term SSEs beneath the Tokai region from different data sets roughly agree. In the Bungo Channel, *Teraishi et al.* [2007] reported that strain measured by an extensometer at Sukumo, in southwestern Shikoku, changed during the two recent long-term SSEs (1996–1997 and 2003). They also recognized a similar change of strain in 1991. However, there have been no further investigations of the long-term SSEs beneath the Bungo Channel.

Because leveling surveys are time and resource intensive, there is generally a long interval between surveys. But the precision of the leveling data is good and they provide long-term data that is very useful for investigation of past crustal deformation. The precision of vertical crustal deformation estimated from sea level data is inferior, and sea level data provide information about deformation only at the locations of the tidal stations. However, unlike leveling data, sea level data is continuous over decades, so it is useful for constraining the time range of possible long-term SSEs. In this paper, we show that long-term SSEs may have occurred repeatedly beneath the Bungo Channel by considering long-term vertical crustal displacements in terms of both leveling data and sea level data. Understanding the history of long-term SSEs beneath the Bungo Channel may provide important information for prediction of future large earthquakes along the Nankai Trough, and the regions where the similar short-term and long-term SSEs are observed in the world.

2. Long-term slow slip events beneath the Bungo Channel observed by GPS

2.1. Crustal deformation during the long-term slow slip event of 2003

We used GPS daily coordinate data from GEONET [*Miyazaki et al.*, 1997]. The analytical procedure of the GPS data is described in detail by *Hatanaka et al.* [2003] and some new procedures were introduced [*Nakagawa et al.*, 2009]. GPS 24 hour data are analyzed with Bernese GPS software version 5.0 using IGS final ephemerides and earth rotation parameters based on the ITRF2005 (IGS05). The improved strategy includes the estimation of atmospheric gradients. GPS coordinate data after 21 March 1996 was recomputed using the new analytical procedure [*Nakagawa et al.*, 2009].

Displacements derived from the GPS data include those from steady crustal deformation due to subduction of the Philippine Sea plate as well as those caused by the discrete events, namely, large earthquakes and SSEs. The 2001 Geiyo earthquake (*M6.7*) and long-term SSEs beneath the Bungo Channel from the period 1996–1997 and in 2003 have influenced the crustal deformation on western Shikoku since 1996, when the GPS coordinate data became available. Because little postseismic deformation was recognized for the 2001 Geiyo earthquake [*Geographical Survey Institute*, 2002], the vertical displacements for this event were estimated from the difference of the mean heights five days before and five days after the earthquake. The displacements by the earthquake were subtracted from the GPS data. We estimated the steady deformation rate at each GPS station by averaging the rates for the periods from April 1998 to April 2002, and between April 2004 and April 2008, avoiding the period of the long-term SSEs. Annual and semiannual terms are often seen in GPS coordinates [*Mao et al.*, 1999]. Though these terms became small by the introduction of the new analysis method [*Nakagawa et al.*, 2009], the terms are yet observed. Correction for the annual variation has not been conducted here. Therefore, we used the difference of the coordinates of the same month of the years so as to avoid the influence of these terms. Then we removed the estimated steady rate from the raw data for the entire period. Such detrended displacements (residual after the subtraction of the steady rate) for the period between January 2003 and January 2004 are shown in Figure 2. The ellipse at the tip of each arrow represents three times the standard deviation (3σ) of the displacements. The error of the vertical component is bigger than that of the horizontal components. The procedure for calculating the standard deviations are as follows. Standard deviations of the daily coordinates were calculated from the data during periods of 1998–1999 and 2006–2007. The displacements were derived from the difference of the mean coordinates in one month of start and end of the assigned period. Standard deviations of the monthly mean coordinates were evaluated by dividing that of the daily data by $\sqrt{n/2}$ where n is the days of the month and $\sqrt{2}$ expresses the effect of the two ends. One standard deviation (σ) of each vertical displacement ranges from 1 to 3 mm. In Figure 2, the southeastward displacement around the Bungo Channel and the upward displacement near the Sukumo Bay caused by the long-term SSE are recognized. The displacements exceed three times the standard deviation (3σ). Figure 3 shows detrended time series of north-south (NS), east-west (EW), and up-down (UD) displacements at the selected GPS stations. These locations are plotted in Figure 2. We can clearly see the displacements due to SSEs in both the period of 1996–1997 and 2003.

The slip distribution on the plate interface estimated by the inversion technique of *Yabuki and Matsu'ura* [1992] using detrended GPS displacement is shown in Figure 4. We used 8 × 10 point sources on the plate interface to calculate slip distribution. Theoretical displacements are calculated with the formulation for point source by *Okada* [1992]. Calculated vertical displacement distribution from the estimated slip is also shown. The center of the uplift area is near the Sukumo Bay, and the amount of the uplift is 2-3 cm.

2.2. Steady and Discrete Displacements Estimated from GPS Data

Since the observation point density and the distribution are different between GPS and leveling, the displacements of the GPS stations were interpolated in order to compare it with leveling data. The numeral at each station in Figure 5 is the steady vertical deformation rate. We fit a curved surface with a minimum curvature to the displacement rates with GMT [*Wessel and Smith*, 1995]. Contours of the vertical displacement rates are shown in Figure 5. The contour lines are smooth and the observed values are generally consistent with the contour values. The interpolation procedure seems to be performed adequately. Then we subtracted this rate from the interpolated GPS-derived vertical crustal displacement for 2003 to determine the vertical displacement caused by the known long-term SSE in the year (Figure 6). The interpolation procedure was the same as Figure 5. We applied a vertical shift to the data for both Figures 5 and 6 to reflect zero value of leveling at BM4542. In the areas except western Shikoku, the displacement by the SSE should become zero in Figure 6. However, residuals of about 1 cm are actually seen in Figure 6. It is thought that these residuals would include colored noise [e.g., *Mao et al.*, 1999], and the displacements less than 1 cm are meaningless after this subtraction procedure. The steady vertical crustal displacement rate obtained here (Figure 5) is consistent with that determined by *Murakami and Ozawa* [2004] using GPS data. Our calculations show that there has been steady subsidence of 0.6–0.8 cm relative to BM4542 each year since 1998 in the region of Sukumo Bay (Figure 5), and that there was uplift of 4–5 cm in 2003, the year of the long-term SSE occurrence beneath the Bungo Channel area (Figure 6).

3. Vertical Crustal Displacement Estimated from Leveling Data

3.1. Leveling Survey in Western Shikoku

The routes of the leveling surveys and the first-order leveling benchmarks used in this study are shown in Figure 7. The duration of each of the leveling surveys are provided in Table 1. Benchmarks along the Sadamisaki Peninsula are not included because a leveling survey was carried out there only in 1991. Therefore, we were not able to determine crustal deformation there. First-order leveling surveys have been conducted repeatedly every several years since the 1960s

(Table 1), although the leveling routes have differed slightly for some repeat surveys [*Kunimi et al.*, 2001]. The pre-1998 leveling data were obtained from the dataset provided by *Sagiya et al.* [2003] and the 2007 leveling data were obtained from the *Geographical Survey Institute* [2008]. Closure error of the leveling circuit was adjusted by distributing the error to the circuit giving weight inversely proportion to distance between benchmarks [*Sagiya et al.*, 2003]. The surveying dates of leveling routes of the same number in Table 1 are different by about one year. The surveying dates (Year in Table 1) are represented as the date when the survey near Sukumo Bay (routes 291 and 292) was conducted, where a large crustal deformation caused by the recent long-term SSE was observed (Figure 2, Figure 6). We determined crustal displacements by comparing leveling data from successive surveys.

The estimation of the error of the leveling survey is difficult. The threshold for closure error for a round trip survey in Japan was $1.5 \times \sqrt{S}$ (mm) until 1965 and $2.0\times\sqrt{S}$ (mm) after 1965 [*Kunimi et al.*, 2001], where S is the length of the leveling route in km. *Murakami and Ozawa* [2004] used multiplied the value by $\sqrt{2}$, because the crustal movement is calculated from the difference of the leveling of two times. They divided the value by the survey interval and considered it to be a standard of the error. The length of the leveling route around Shikoku is 930 km, and the threshold for closure error is 61.0 mm. The closure errors for the actual surveys of 1979.0, 1982.5, 1990.6, 1999.0, and 2007.7 are 6.4, 3.2, 7.2, 13.1, and 12.3 mm [*Geographical Survey Institute*, 1983, 1992, 2000, 2008]. These values are all under the threshold, and the average of them is about 1/7.2 of the threshold. We apply this ratio to the threshold of western Shikoku. The threshold for closure error calculated from the length of the leveling route of western Shikoku is 40.4 mm. We evaluate threshold for a survey interval by multiplying the value of 40.4 mm by $\sqrt{2}$ and 1/7.2, which becomes about 7.9 mm for an interval.

Considerable coseismic and postseismic crustal deformation caused by the 1946 Nankai earthquake was observed on Shikoku [e.g., *Thatcher*, 1984]. *Savage and Thatcher* [1992] inferred that the decay time for the postseismic transient is about 5 years and the linear trend described the deformation reasonably well after the first decade post-earthquake. *Ito and Hashimoto* [2004] reported that the postseismic afterslip lasted 20 years after the earthquake. Figure 8 shows the annual mean sea level differences between Komatsushima and Takamatsu, Hosojima and Tosashimizu, and Hosojima and Uwajima. There were sea level difference changes which reflect the postseismic vertical displacements after the 1946 Nankai earthquake. The curves in the figure are the result of smoothing with Friedman's supersmoother [*Friedman*, 1984], and the lines are fitted about after 1970 when the postseismic afterslip ended [*Ito and Hashimoto*, 2004]. Though postseismic changes are observed by 1970s, it is not observed after 1980s. The deviations from the lines include the influences of oceanic phenomena. At least, the relative vertical deformation seems less than 1 cm after 1980. Considering the error of the leveling survey of about 7.9 mm for an interval, observed deformation by leveling of more than 1 cm is meaningful. For this study, we used the post-1979 leveling data, when the postseismic vertical displacements were relatively small and the intervals between surveys were short.

3.2. Estimation of Discrete Vertical Crustal Displacement

Vertical crustal displacements during the periods between the leveling surveys from 1979 to 2008 are shown in Figure 9. We excluded data points that differed by more than 5 cm from adjacent data points as outliers. We applied a vertical shift to all data points to make the displacement at BM4542 zero (same as Figures 5 and 6). The 2001 Geiyo earthquake was the only earthquake that caused crustal deformation on western Shikoku between 1979 and 2008. The mechanism of this earthquake is a normal fault with strike, dip, and rake parameters of 172, 57, and -84 degrees respectively [*Japan Meteorological Agency*, 2001a, 2001b]. GPS data indicate that subsidence of approximately 2 cm was caused by this earthquake near Matsuyama. Theoretical vertical displacement calculated by formulation of *Okada* [1992] was used to adjust the vertical crustal displacement from the leveling data set that spanned the time of the 2001 earthquake.

Figure 10 shows the distribution of vertical crustal displacements during the four periods between leveling surveys with correction for subduction-related component (Figure 5). If any discrete events have not occurred, Figure 10 should show little spatial variation around zero vertical displacement. However, the residual data clearly show uplift on the southwestern Shikoku coastal area bordering the Bungo Channel for all four periods. This suggests that there were some kind of discrete events for each period.

The estimated discrete uplifts near Sukumo Bay (see Figure 10) are: (period 1) 5–6 cm from 1979.0 to 1982.5, (period 2) 4–5 cm from 1982.5 to 1990.6, (period 3) 8–9 cm from 1990.6 to 1999.0, and (period 4) about 4 cm from 1999.0 to 2007.7. We know that a long-term SSE of 2003 occurred during period 4, therefore the vertical displacement in this period shown in Figure 10 should represent the crustal deformation due to one long-term SSE. Though the two peaks of uplift are recognized, the center of these peaks is located around Sukumo Bay. Indeed, the uplift of about 4 cm near Sukumo Bay derived from leveling data agrees with the uplift determined from GPS data (Figure 6).

4. Vertical Crustal Displacement Estimated from Sea level Data

4.1. Crustal Displacement Estimation Method

We used sea level data from the Ōita, Misakiko, Uwajima, Mishouko, and Tosashimizu tidal stations (Figure 7). Data availability at each station is shown in Table 2. We used the data from 1971 to 2008 to include the time span of the leveling data. The Mishouko tidal station is located near the Sukumo Bay, where the largest vertical displacement was expected from the result of GPS observation (see Figure 2). This station was established in February 1954 [*Coastal Movements Data Center*, 1994]. Unfortunately, sea level data only after 1993 is available.

Sea level data from the Misakiko and Mishouko stations were recorded hourly values and compiled as monthly tables with calculated daily and monthly means. The data from these stations (Misakiko in particular) had the following problems. (1) There were differences of 50 cm or 100 cm between adjacent hourly entries in some cases. We attributed these differences to reading errors caused by ambiguous 50-cm scale marks on the original recording paper. We corrected clearly erroneous data. (2) Daily means were calculated even when there were missing data among the hourly records. When we found missing data at the flood tide or ebb tide, we discarded the daily mean. Otherwise, we recalculated the daily mean after interpolating the missing values taking into account the sea level data from Uwajima, which lies between Misakiko and Mishouko. (3) There were some considerable data offsets before and after the periods of missing data at Misakiko. Maintenance downtime may have explained the offset. However, no information about maintenance was provided in the monthly tables. For these cases, we corrected the offsets by referring to the sea levels recorded at Uwajima and Misakiko, assuming that the offsets were not the result of abrupt local crustal deformation. There was a long period of data defect at Misakiko in 1992, so the vertical displacement there for this period is uncertain. (4) We corrected simple mistakes in some of the daily and monthly mean sea level calculations for both Misakiko and Mishouko. In addition, we discarded monthly mean sea level data of which daily data for more than 11 days of the month were missing.

The sea level data include the effects of meteorological and hydrographic phenomena as well as those of crustal deformation. To isolate the crustal deformation signal, we tried to remove other effects. Because the duration of crustal deformation related to long-term SSEs is several months to one year, we used the monthly mean sea level data. The sea level data along the Japanese coast include annual variation mainly due to the sea water density and atmospheric pressure change [*Nomitsu and Okamoto*, 1927]. The monthly data were corrected for atmospheric pressures using the theoretical coefficient of 1 cm/hPa according to monthly samples measured at the meteorological observatory closest to each tidal station. The annual component was calculated for each station by superimposing the monthly means of each year, which is the method used by *Tsumura* [1963, 1970]. The annual component was subtracted from the monthly sea level data for each station. The corrected monthly mean sea level data (Figure 11) show sea level changes that exceed 10 cm and appear to have occurred at approximately the same time at all stations. We attributed these to hydrographic effects.

We used a method developed by *Tsumura* [1963, 1970] to remove the effect of hydrographic phenomena. In this method, the effect of atmospheric pressure, a linear trend, and the annual component are removed from the sea level data at first. After these corrections, the hydrographic effect for tidal stations within a region of similar sea environment should be represented by similar deviations at all tidal stations. The regional hydrographic component is removed by subtracting the regional average deviation from the sea level data at individual tidal stations. This method by Tsumura has the property of removing the vertical displacement of the common direction in the same sea region as a hydrographic component. The vertical displacements caused by the long-term SSE beneath the Bungo Channel will not be removed by this method, because the displacements are not in the same direction in this region (Figure 4).

The five tidal stations used in this study are within an area divided by *Tsumura* [1963, 1970] for which the hydrographic effect on sea level change would be similar. Therefore, we assumed that the difference between the meteorologically corrected sea levels for pairs of stations represents relative vertical crustal displacement. We chose pairs of the five stations to use for the comparisons with considering their periods of data coverage and the quality of the data. The pairs we used were Ōita and Mishouko, Uwajima and Misakiko, Tosashimizu and Misakiko, and Tosashimizu and Ōita. *Kobayashi* [2008] suggested that the coastal environment of Tosashimizu station is different from that of the other stations we used. Therefore, for our pairing of Tosashimizu with both Misakiko and Ōita, the sea level comparisons were made after applying hydrographic corrections using the stations used by *Kobayashi* [2008]. The stations used for hydrographic correction are shown in Table 2. Because Misakiko was not included in the stations used by *Kobayashi* [2008], we used the stations for Ōita instead. Because the duration of long-term SSEs beneath the Bungo Channel is several months to one year, we evaluated errors of sea level differences using one-year change. Standard deviations of the one-year changes of Ōita–Mishouko, Uwajima–Misakiko, Tosashimizu–Misakiko, and Tosashimizu–Ōita are 24, 23, 31, and 25 mm.

4.2. Detection of Slow Slips by the Sea Level Difference

We also compared the relative heights recorded at the GPS stations closest to each pair of tidal stations. We used the detrended GPS coordinate data described in section 2.1. Figure 12 shows the corrected differences of sea level between pairs of tidal stations and differences between the relative heights recorded at the GPS stations nearest to the tidal stations. Steady-state subduction-related vertical displacement rates derived from GPS have been also removed from sea level differences. An increase of sea level difference represents relative ground uplift of the second-mentioned tidal station of each pair. For example, an increase of the Ōita–Mishouko in Figure 12 means a relative ground uplift of Mishouko.

Due to the missing values in the monthly sea level of Misakiko, there are corresponding missing values in the sea level differences of Misakiko with both Uwajima and Tosashimizu. As we have already described, the monthly mean sea level data were not included when there were more than 11 missing daily mean sea level data in a month. In order to utilize more data, we also show in Figure 12 the one-year moving median of the daily mean sea level differences for these pairs of tidal stations. These values were calculated when more than one third of the one-year data were available. Standard deviations of the one-year changes of the moving median of Uwajima–Misakiko and Tosashimizu–Misakiko are 14 and 17 mm.

The gray shaded time bands in Figure 12 show the periods of long-term SSEs known from GPS data. The GPS height difference for Ōita–Mishouko shows uplift of about 4 cm at Mishouko at the time of the 2003 long-term SSE. The GPS station near Ōita was deployed in 1997, during the period in which the 1996–1997 long-term SSE occurred, but the uplift can still be seen. In addition, the GPS height differences for Uwajima–Misakiko and Tosashimizu–Misakiko show subsidence of 2–3 cm at Misakiko at the time of the 2003 long-term SSE. Furthermore, subsidence of approximately 2 cm at Ōita at the time of the 2003 long-term SSE is indicated by the GPS data from Tosashimizu–Ōita. Other than at these times of abrupt change, the graphs of GPS-derived data are approximately horizontal.

Ideally, the variation of the sea level differences should agree with the variation of the GPS height differences. However, the standard deviations of the one-year changes of sea level differences are almost equivalent to the changes expected by the SSEs. Therefore, the changes of sea level differences caused by the SSEs in the gray periods are not as clear as in the GPS data. It may be considered that this is based on the effect of the local hydrographic condition. However, we can see changes in sea level differences similar to the GPS height differences when comparing the differences of average sea level several years before and several years after the gray bands.

4.3. Cross Correlation between the Sea Level Difference and the GPS

Now we examine the sea level differences in the pre-GPS period. After subtracting the GPS-derived steady vertical displacements, the sea level difference curves shown in Figure 12 should be horizontal, when there is no discrete slip event. However, the sea level difference curves for Tosashimizu–Ōita show locations with non-zero slopes. The sea level differences curves for Uwajima–Misakiko and Tosashimizu–Misakiko show a long-term trend change around the middle 1990s. There are also some shorter-wavelength slope trends in these sea level difference curves. These slope trends may indicate the existence of some discrete events.

In section 3.2, it is suggested that there are some kind of discrete events for each period between leveling surveys. Our aim in this study is to extract discrete events and to estimate the timing of the events. However, sea level differences we examined include variations of several centimeters caused by local hydrographic phenomena. Therefore, they mask the vertical crustal displacements as was described in the previous section. Here we try to identify periods when the discrete events possibly occurred. From Figure 12, we can see relatively steep slopes of the sea level difference of Tosashimizu–Ōita in the periods of known long-term SSEs. We can also see similar slopes in the pre-GPS period. Because the deformation patterns of the discrete events in the pre-GPS period would be similar to that of the 2003 long-term SSE, as is described in the next section, we used cross-correlation analysis between the GPS height difference curves and the sea level difference curves. The period of GPS height difference for this analysis was fixed for the six years from 2001.05 to 2007.05. The center of this period is 2004.05, which is the center of the period of the

2003 long-term SSE reported by *Ozawa et al.* [2007]. The GPS height difference of this period represents a typical time series of vertical displacement of a SSE. Then, we calculated cross-correlation values between the period-fixed GPS height difference and the time series for six years of the sea level differences shifting every month for all period (Figure 13). We used monthly mean sea level data for Ōita–Mishouko and Tosashimizu–Ōita. For Uwajima–Misakiko and Tosashimizu–Misakiko, we used a one-year moving median of daily mean sea levels (as previously discussed).

The cross-correlation values range from –1 to +1. A high positive value means that the changes in the time series of the sea level difference matches well the time series of the GPS height difference. The cross correlation for Uwajima–Misakiko is generally low in the period preceding the mid-1990s, reflecting the previously described long-term trend. The periods of the known long-term SSEs that were observed at GPS stations in 1996–1997 and 2003 are also shown on Figure 13 as dark-gray shaded time bands. The two known events produce relatively high cross-correlation values, which suggests that the methodology we have used here can be used to identify long-term SSEs.

5. Evidence for Past Long-Term Slow slip Events beneath the Bungo Channel

The distribution of vertical displacement derived from leveling surveys for period 4 (1990.0–2007.7) (Figure 10) is similar to the distribution of vertical displacement of the 2003 long-term SSE recorded in GPS data (Figure 6). As discussed in section 3.2, the amount of vertical displacement derived from leveling surveys due to discrete events in period 4 is consistent with the GPS height data. The centers of the uplift area for periods 1–3 are all located in the southwestern Shikoku. The amount of uplift around the Sukumo Bay for periods 1 and 2 is the same level as that for period 4. The amount of uplift around the Sukumo Bay for period 3 is almost two times for period 4. The patterns of the discrete displacement derived from leveling surveys for periods 1–3 are similar to the pattern of period 4 in which 2003 long-term SSE was included. Because no large earthquakes have caused crustal deformation on western Shikoku since 1979, the discrete vertical displacements derived from leveling surveys before the availability of GPS data suggest displacements associated with long-term SSEs beneath the Bungo Channel.

We do not know when the discrete events occur in the periods only by the result of the leveling surveys. Therefore, frequency and time of the discrete events are estimated by the cross correlations of the sea level differences. In Figure 13, total is a sum of four cross-correlation values. The periods before and after one year of the local maxima of the total value of the cross correlations before GPS deployment are shown as light-gray bands. In comparison with these local maxima and the four periods of the leveling, there is one maximum in periods 1, 2, 4 and there are two maxima in period 3. In the following, frequency and time of the discrete events in each period are examined.

In period 4 (1999.0–2007.7), one long-term SSE of 2003 observed by the GPS is included. The amount of uplift around the Sukumo Bay by leveling surveys is about 4 cm, and a cross-correlation peak of sea level difference is also 2003. There is no contradiction in the three observation results.

In period 3 (1990.6–1999.0), at least one long-term SSE of 1996-1997 observed by the GPS is included. The amount of uplift around the Sukumo Bay by leveling surveys is 8-9 cm, and there are two cross-correlation peaks of sea level difference around 1991 and 1997. The crustal displacements caused by the long-term SSEs of 1996–1997 and 2003 were of similar magnitude [*Ozawa et al.*, 2004]. Considering these, we infer a discrete event around 1991 other than the long-term SSE of 1996–1997. *Teraishi et al.* [2007] suggested that changes in extensometer data at Sukumo in 1991 resembled those associated with recent long-term SSEs, which supports our inference of a discrete event in 1991.

In period 2 (1982.5–1990.6), the amount of uplift around the Sukumo Bay by leveling surveys is 4-5 cm, and a cross-correlation peak of sea level difference is around 1985–1986. From these, one discrete event is inferred around 1985–1986.

In period 1 (1979.0–1982.5), the amount of uplift around the Sukumo Bay by leveling surveys is 5-6 cm, and a cross-correlation peak of sea level difference is around 1980. From these, one discrete event is inferred around 1980.

If these discrete events were long-term SSEs, there was one long-term SSE for periods 1 and 2, and two long-term SSEs for period 3. The amount of uplift around the Sukumo Bay is 4-6 cm for one SSE. This indicates that the size of long-term SSE beneath the Bungo Channel is almost the same in every event, if the same region on the plate interface is slipping. Based on the occurrence time of the long-term SSEs estimated here, the recurrence time is rather stable and it is about 5-6 years. Six years passed from the 2003 long-term SSE, continuous GPS data suggest that a repeat of the Bungo Channel SSEs began occurring at the end of 2009 [*Geospatial Information Authority of Japan*, 2010].

6. Summary

We estimated vertical crustal displacements around the Bungo Channel by using leveling survey data in western Shikoku and sea level data recorded at tidal stations around the Bungo Channel. Two long-term slow slip events that were recorded in 1996–1997 and 2003 in GPS data were recognized also in the leveling survey and sea level data. Analysis of the leveling survey and sea level data revealed possible vertical crustal displacements similar to those of the 1996–1997 and 2003 events around 1980, around 1985–1986, and around 1991. These may represent crustal displacements caused by long-term slow slip events beneath the Bungo Channel.

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We thank the Ehime prefectural government for providing sea level data from Misakiko and Mishouko. We also used sea level data obtained from the Coastal Movements Data Center and the Japan Oceanographic Data Center, and leveling data from the Geospatial Information Authority of Japan. We thank the Associate Editor and reviewers for their careful and constructive reviews. We used R software [*R Development Core Team*, 2006] for our calculations and GMT software [*Wessel and Smith*, 1995] for drafting our figures.

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Table 1. Leveling survey data available for use in this study.

Table 2. Tidal observation data available for use in this study.

Figure 1. Regional tectonic setting and location of study area. The solid lines indicate plate boundaries. The dotted rectangular is the region of Figure 2, and the other rectangular is the region of Figure 7.

Figure 2. Detrended displacements for the period between January 2003 and January 2004. The ellipses at the tips of arrows indicate 3σ errors.

Figure 3. Detrended time series of the coordinates at selected GPS stations. The locations of these stations are plotted in Figure 2. NS, EW, and UD represent north-south, east-west, and up-down components with northward, eastward and upward motions being positive. The crossbar on the top shows the periods used to calculate the steady displacement rate.

Figure 4. Slip distribution of 2003 long-term SSE on the plate interface (black bars). The green bars indicate horizontal displacements at GPS stations while the blue bars indicate calculated values using slip distribution.

Figure 5. Smoothed, interpolated vertical rate of crustal movement (in mm/yr) determined for the periods between slow slip events (between April 1998 and April 2002, and between April 2004 and April 2008). Vertical rates are shown relative to a leveling benchmark BM4542. Black points and red numerals show the position of the GPS stations and the displacements there.

Figure 6. Smoothed, interpolated vertical crustal displacements (in mm) related to the 2003 Bungo

Channel long-term SSE derived from the GPS data relative to BM4542. Black points and blue numerals show the position of the GPS stations and the displacements there.

Figure 7. Enlarged map of the rectangular area in Figure 1. Open circles show locations of tidal stations and squares show benchmarks of leveling surveys. R287, R290, R291, R292, R293, R294, and R296 indicate the leveling survey routes on western Shikoku. The cross marks the epicenter of the 24 March 2001 Geiyo earthquake.

Figure 8. Annual mean sea level differences from 1947 to 2008. The curves are the result of smoothing with Friedman's supersmoother [*Friedman*, 1984], and the lines are fitted about after 1970.

Figure 9. Vertical crustal displacements relative to BM4542 during the four periods between leveling surveys.

Figure 10. Vertical crustal displacements relative to BM4542 during the four periods between leveling surveys after subtraction of the steady-state displacements due to subduction of the Philippine Sea plate.

Figure 11. Monthly mean sea level data after correction for atmospheric pressure and the annual component. The offset applied to the sea level data from Misakiko is also shown.

Figure 12. Differences of monthly mean sea levels between selected pairs of tidal stations around the Bungo Channel. The one-year moving median of the differences of daily mean sea levels for Uwajima–Misakiko and Tosashimizu–Misakiko, and the height differences from the GPS stations nearest to the tidal stations are also shown. The steady subduction-related vertical displacement

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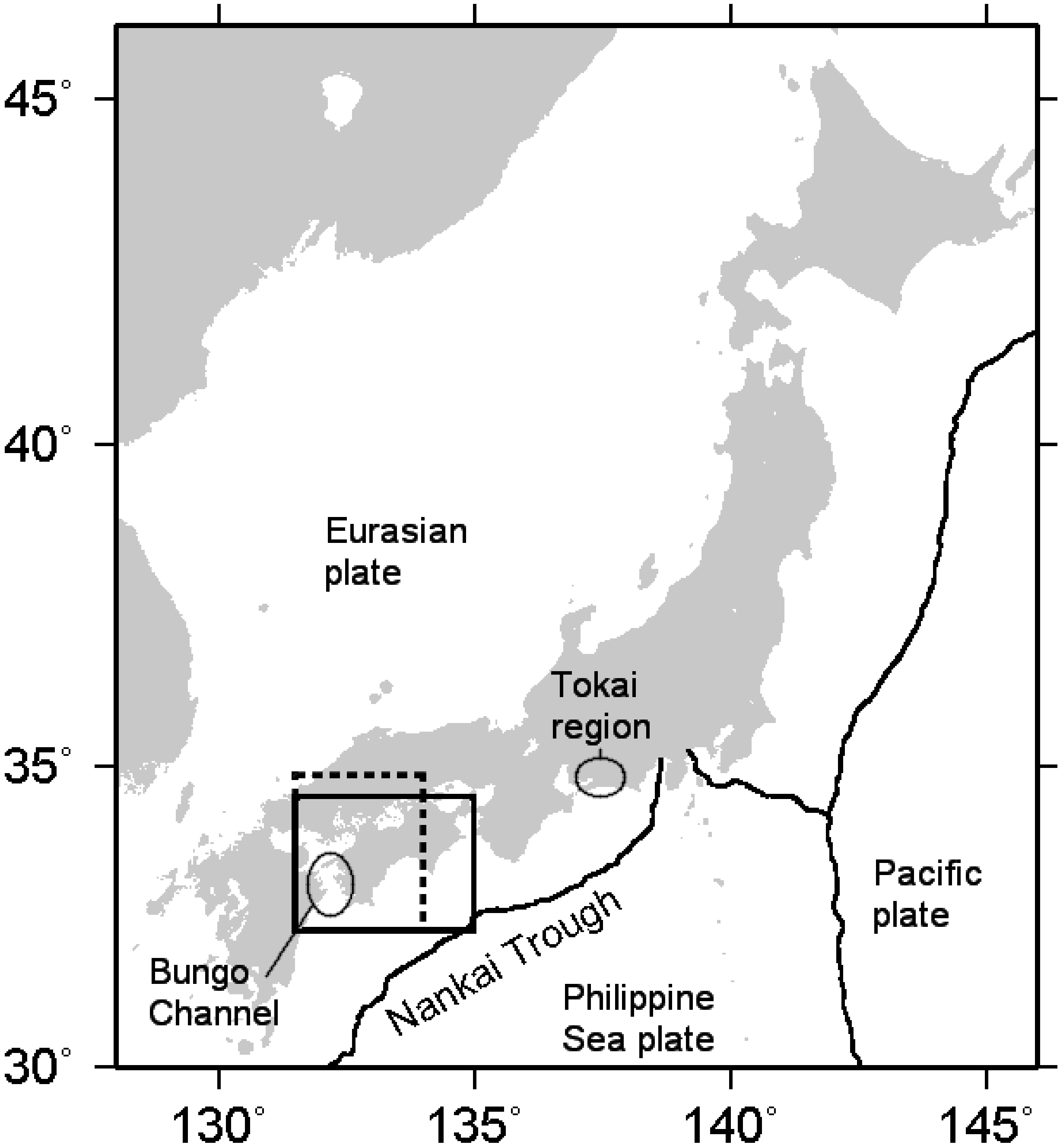
Figure 13. Time series of cross correlations of GPS-derived height differences from 2001.05 to 2007.05 with six-year time segments of sea level differences. Total is a sum of four cross-correlation values, and offset is adjusted according to the number of summation. The two dark-gray shaded time bands show the periods of long-term SSEs known from GPS data, and the three light-gray shaded time bands highlight the pre-GPS periods in which the cross correlations are relatively high. The numerals are the periods of the leveling data.

Table 2. Tidal observation data available for use in this study.

Station	Available data		Stations for the oceanographic correction
Mishouko	January 1993–	*1	
Misakiko	April 1976–	*1	
Uwajima	January 1951–	*2	
Tosashimizu	March 1941–	*2	Tosa_kure, Murotomisaki, Kochi, Komatsushima, Kainan, Takamatsu
Ōita	April 1967–	*3	Kure, Tokuyama, Uwajima, Matsuyama, Hiroshima

*1) collected in this study from the Ehime prefectural government. *2) from “Tidal observations” by Japan Meteorological Agency. *3) by Japan Oceanographic Data Center.



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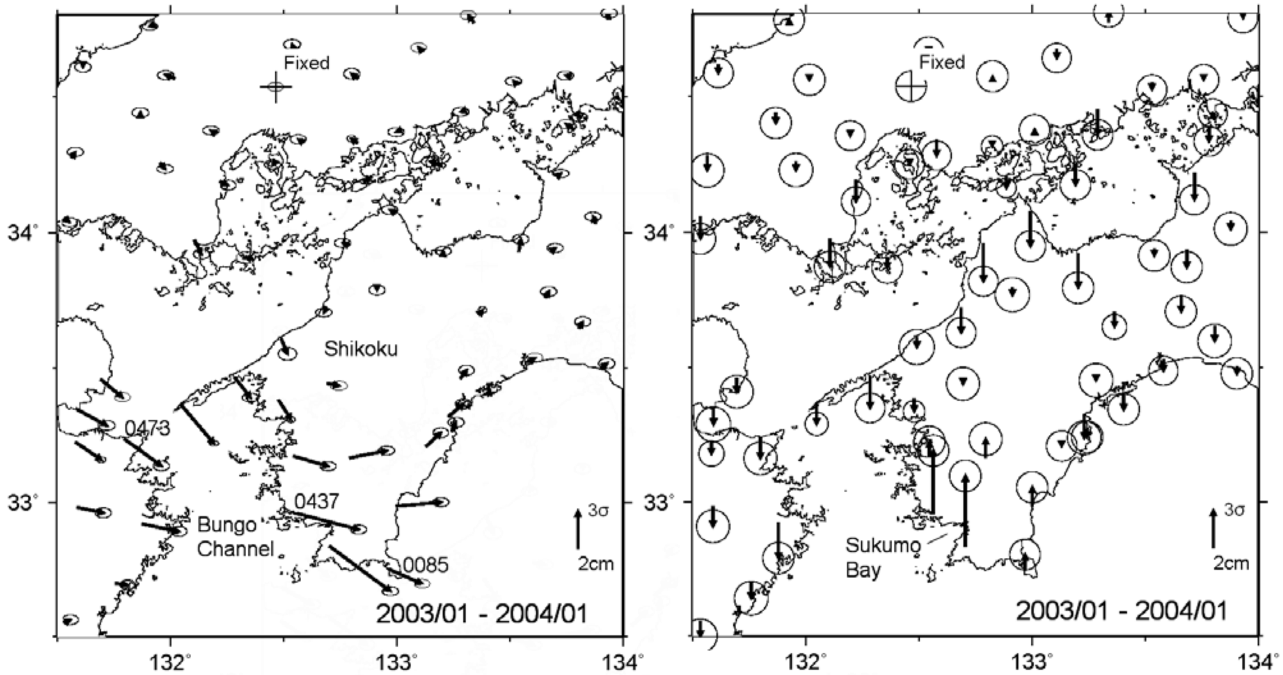

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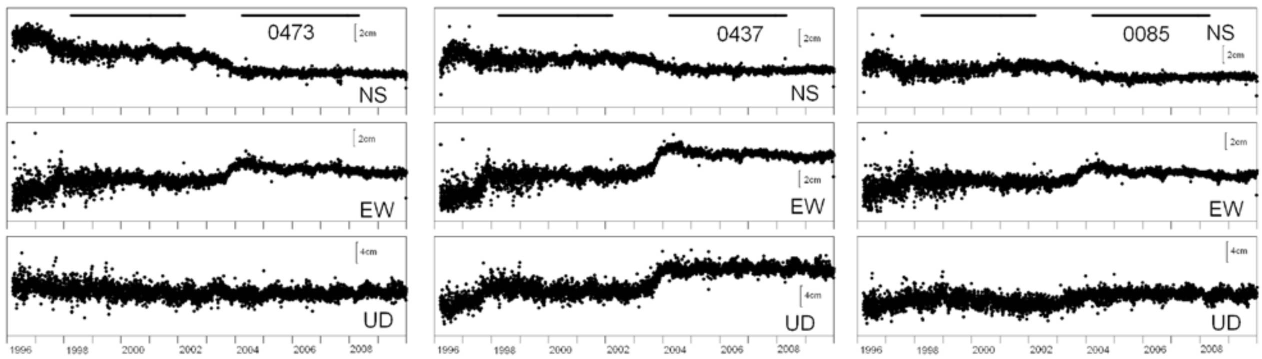

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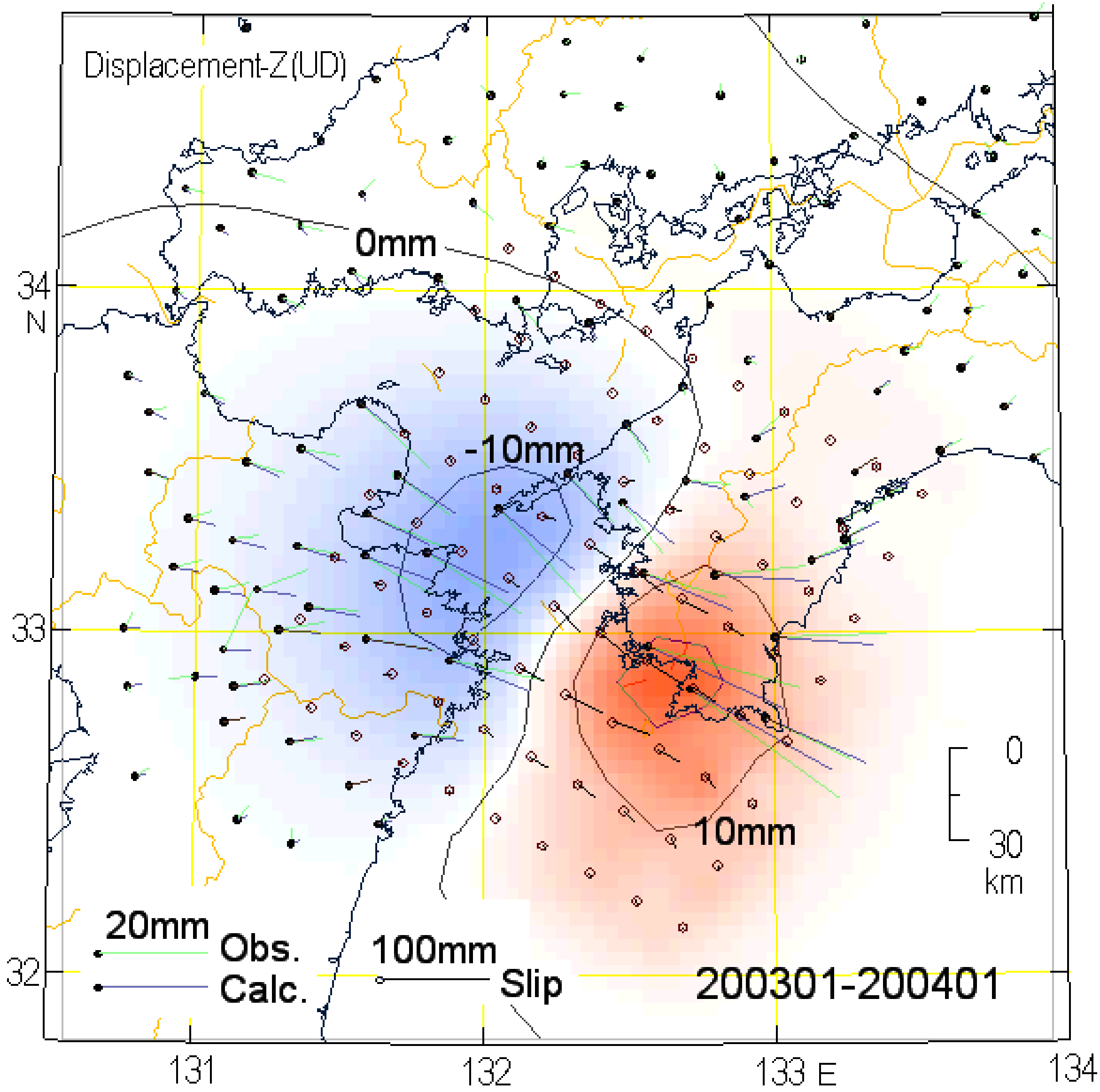

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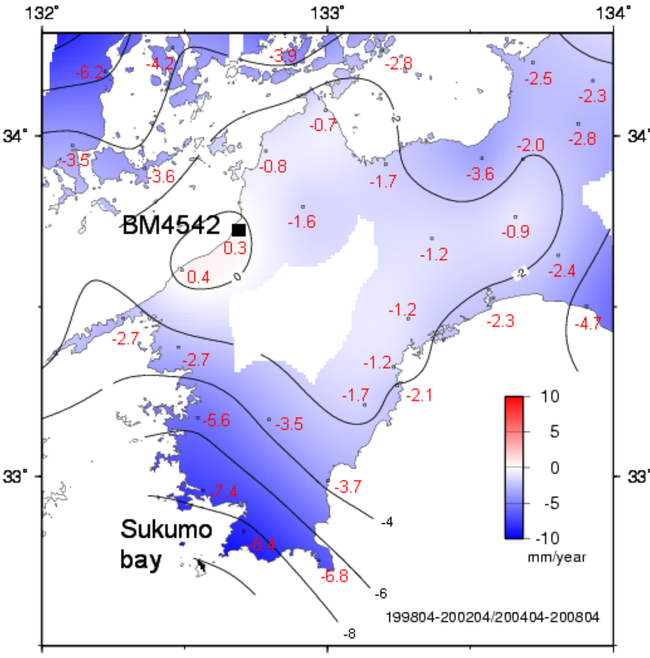

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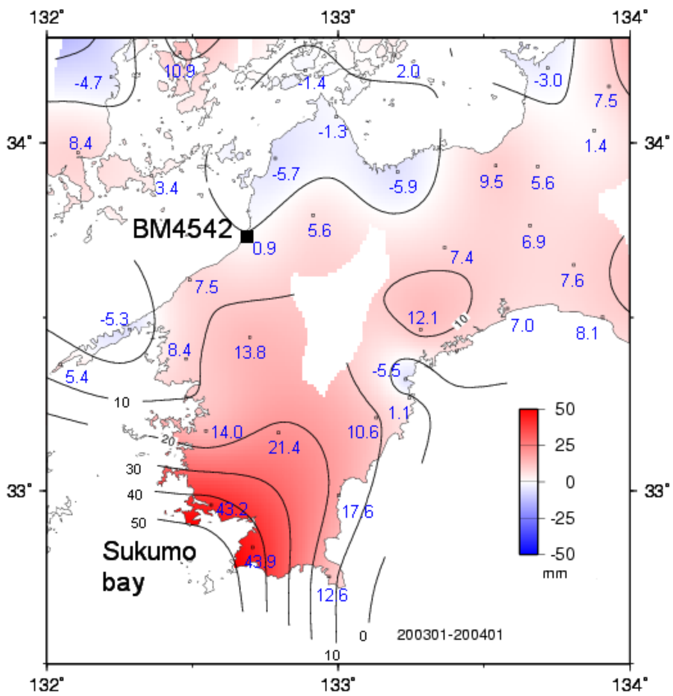

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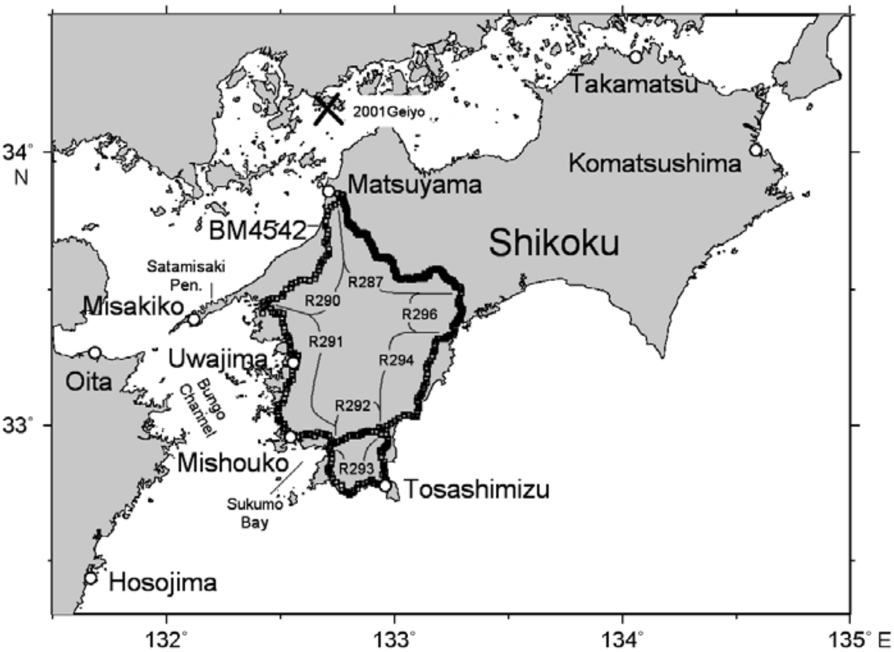

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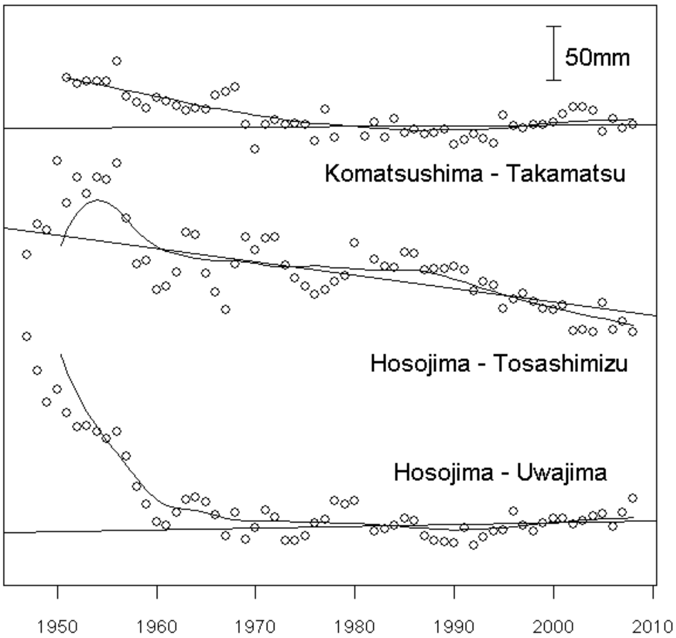

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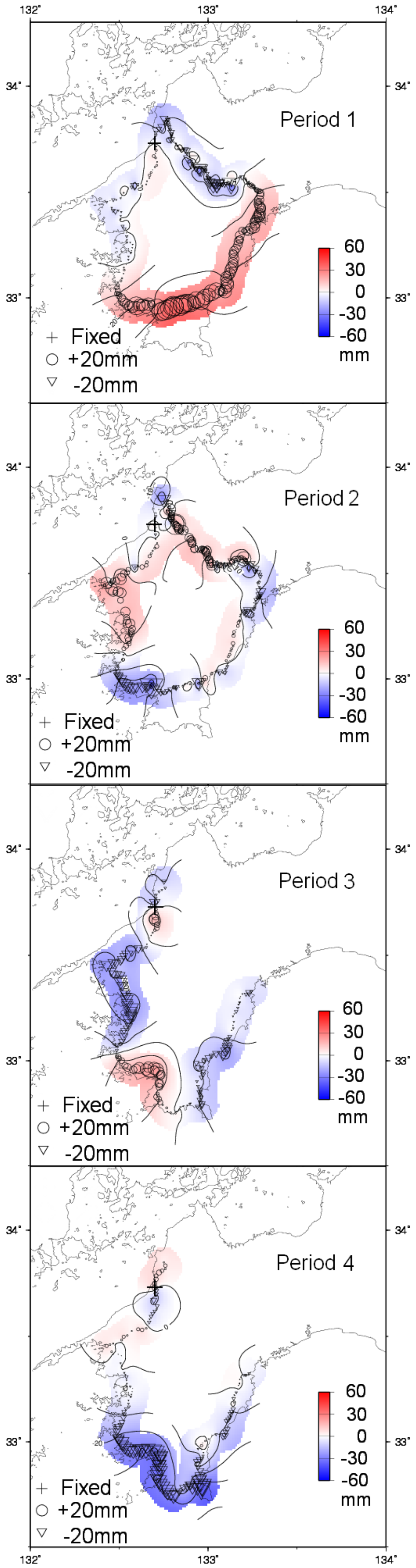

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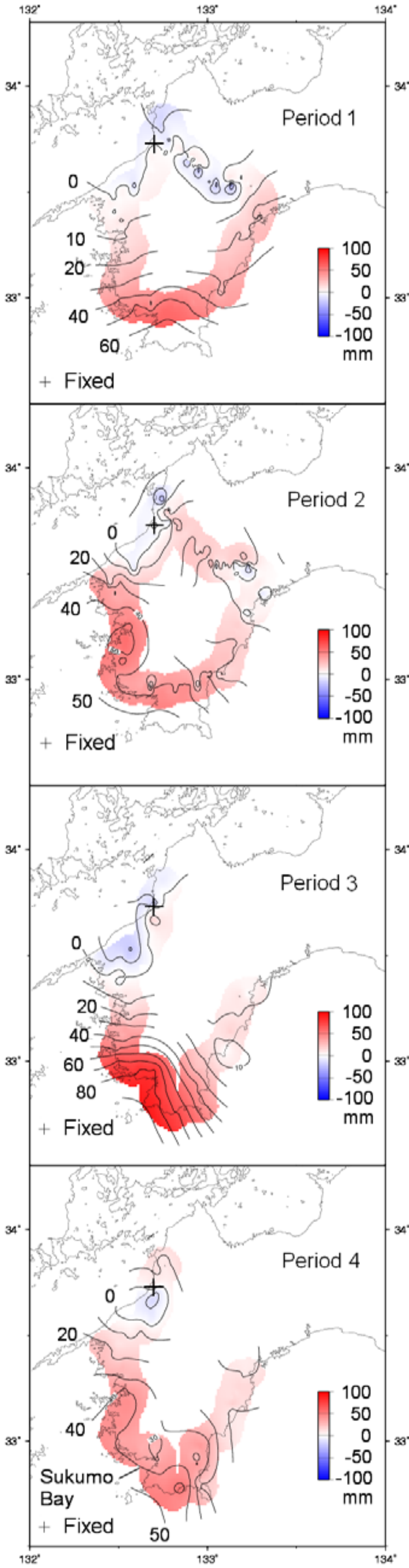

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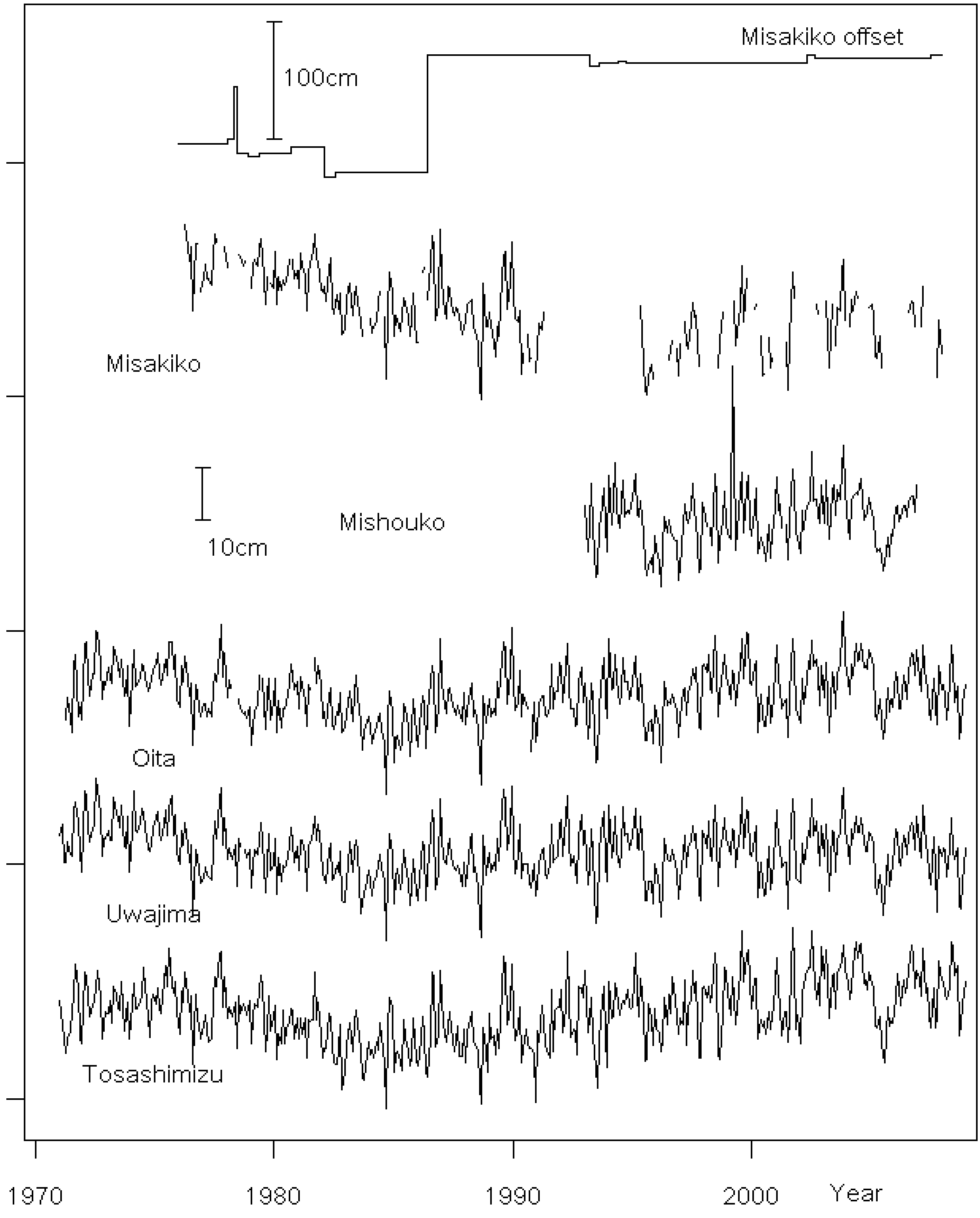

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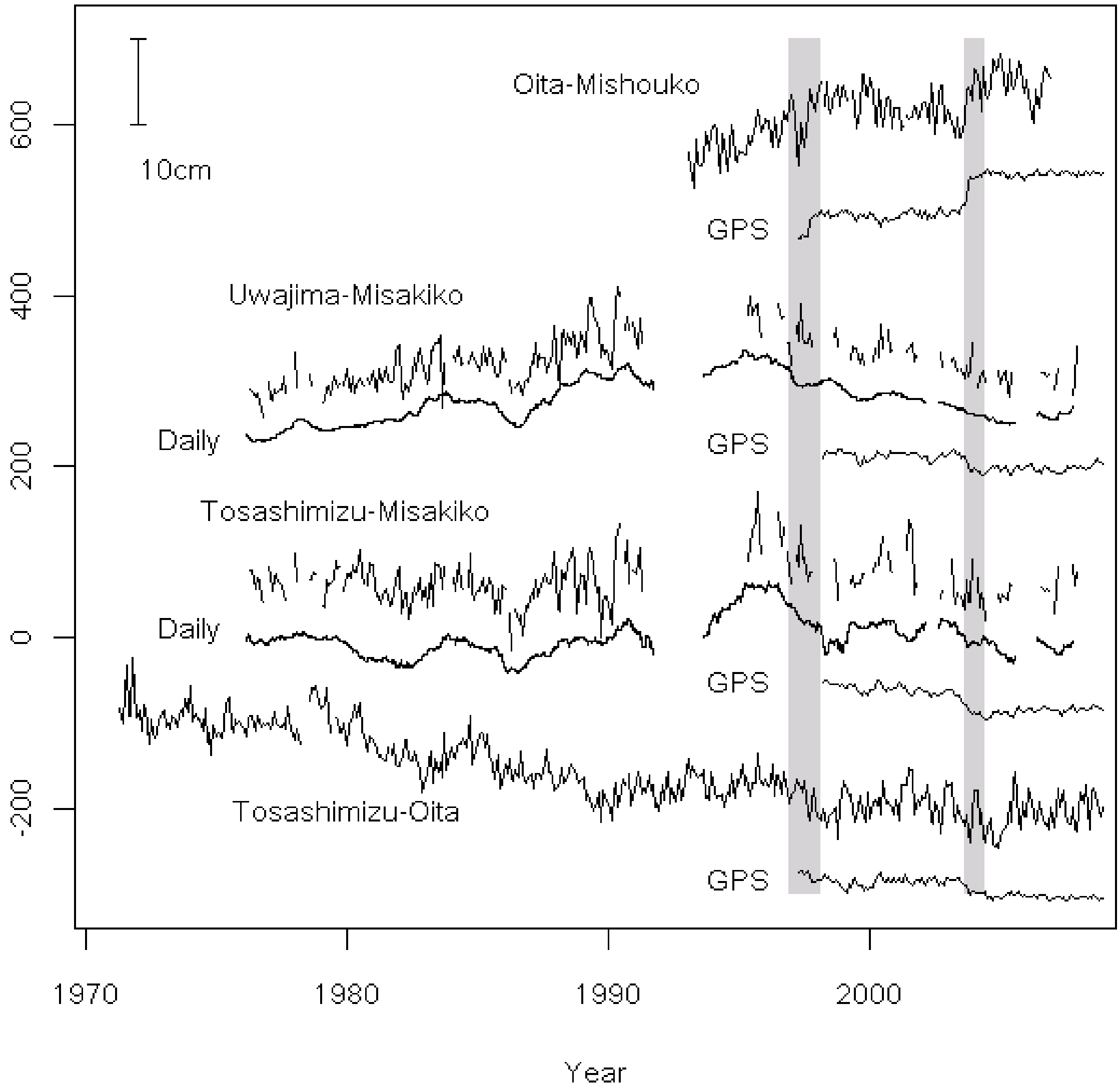

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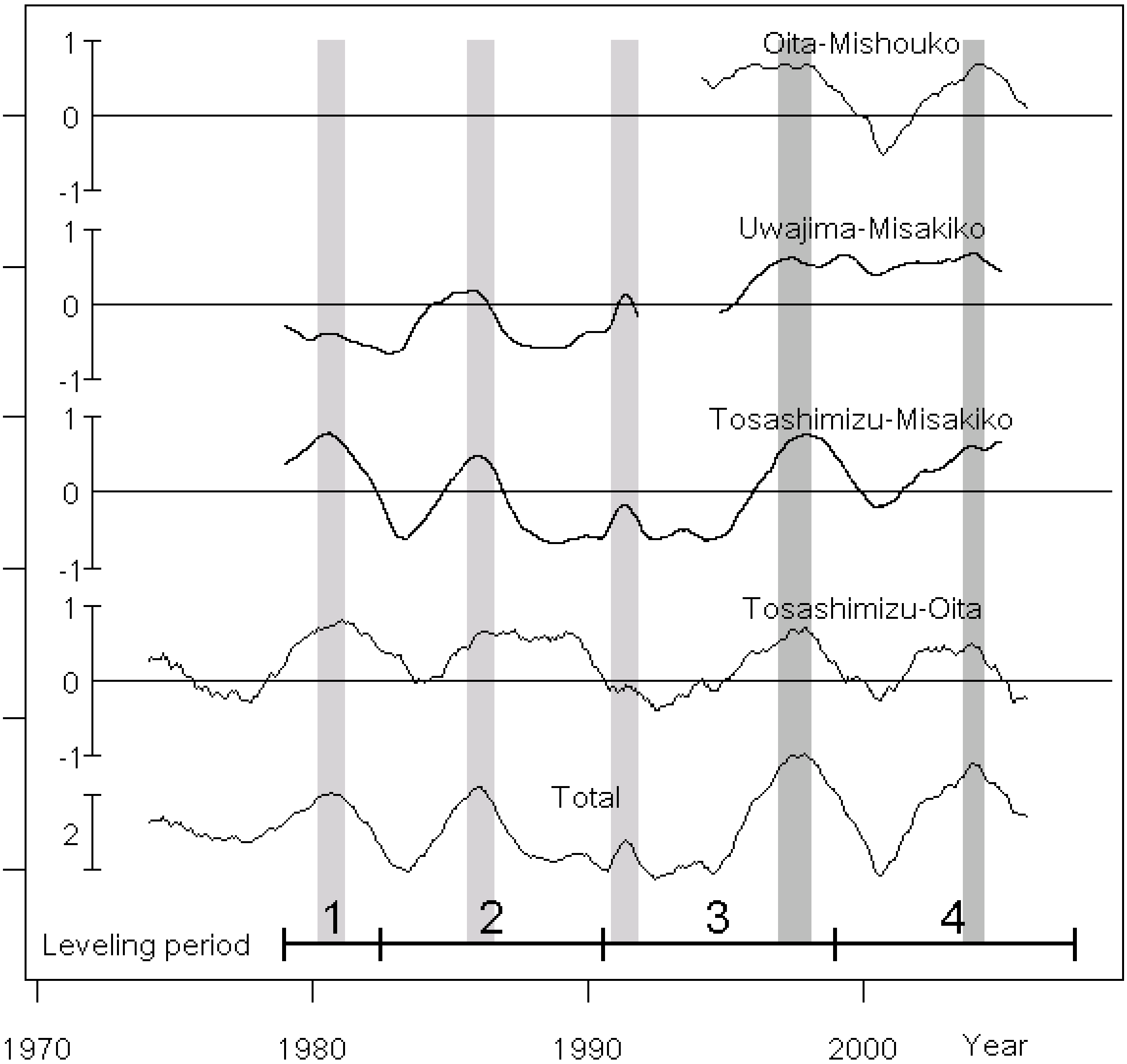

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