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Secular Crustal Deformation Characteristics Prior to the 2011 Tohoku-Oki Earthquake of Mw 9.1 Detected from IGS Array, 2002-2011

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Abstract

In order to reveal the secular deformation evolution and strain accumulation progress along subduction zone, we focus on high-precision Global Positioning System (GPS) data processing, GPS time series analysis and regional spatiotemporal filtering. The GPS position time series is modeled as a combination of the long-term plate movements, short-term noise and the frequency-dependent variations and tectonic deformation information. Common Mode Errors (CME) is removed and the deformation signals is then extracted from the residual time series by Principal Component Analysis (PCA). Combing the filtered displacement array and the dynamic regional strain array derived from GPS baseline, a spatiotemporal tectonic evolution map is exhibited obviously. We process IGS time series over the 2002-2011 period in Japan island and reveal the dynamic evolution of crustal deformation along subduction zone. The results show that the regional reference frame transformation by constraining one site location and one stable

GPS baseline direction can further improve the Signal-to-Noise Ratio (SNR) of GPS observations. A integrated analysis combining the baseline length with azimuth change can show the crustal motion feature more comprehensively. The observed behaviors agree well with the simulation experiment results of the rock rupture in the laboratory. We divide the pre-seismic deformation into four stages, the stable linear strain accumulation stage, the formation stage of the local locked area, local decoupling stage, and strain release stage. We also give an appropriate dynamical model for the interplate coupling to explain the observed deformation characteristics. Research result provides some of the observational new evidence for inter-seismic deformation anomaly detection and the medium- to longer-term seismic hazard assessments.

Keywords: GPS observations; Crustal deformation; Spatiotemporal Filtering; Region strain; Tohoku-Oki earthquake of M_w 9.1

1. Introduction

Japanese islands are located in the convergence of the Pacific plate, the north American plate, the Philippine plate and the Eurasian plate, where plate tectonic activities is strong, volcanoes and earthquakes is frequent. Different from intra-continental plate earthquakes, the Pacific plate is under the Japan trench ([Fig.1](#)). The Pacific plate is subducting westwards beneath the Eurasian plate at a rate of about 80-90mm/yr and the Philippine Sea Plate is subducting beneath

47 southwest Japan at about 65 mm/yr ([Heki et al., 1999](#)). The long-term plate
48 convergence between the Pacific and Okhotsk(or north American) plates forms
49 an EW compressional stress field constraining the tectonic activity of the
50 region([Ohzono et al., 2013](#)). Both shallow and deep source strong earthquakes in
51 this subduction zone are very active. The seismic slip rate in this area and along the
52 adjacent subduction zone to the south is about 1/4 of the plate convergence rate,
53 which has an important implication for the long-term seismic hazard in this
54 area([Kanamori et al., 2006](#)). Contemporary Global Positioning System (GPS)
55 measurements have revealed a significant strain concentration zone in Tohoku
56 region in northeastern Japan([Miura et al., 2004](#)). According to the historical
57 earthquake catalog from Global Centroid Moment Tensors(GCMT), a total of 6
58 earthquakes of over M_w 6.9 have frequently occurred in the region during
59 2002-2012, including the M_w 7.0 in May 2003, the M_w 7.2 in August 2005, the M_w 6.9
60 in June 2008 and the M_w 9.1 in March 2011. The M_w 9.1 earthquake is the largest
61 earthquake in recorded history and it happened in the subduction zone at the
62 boundary between the Pacific plate and the North American plate(or Okhotsk
63 plate), which is characterize by a thrust mechanism, with the strike 202° , dip 10° ,
64 and rake 90° ([Lay et al., 2011](#)). The co-seismic displacements of the seafloor
65 benchmarks associated with the Tohoku-Oki earthquake estimated by the Japan
66 Coast Guard are 22 m eastward and 10 m southward([Sato et al., 2011](#)). Intense
67 co-seismic dislocation happened on the seafloor caused a huge tsunami ([Shao et al.,](#)
68 [2011](#)), resulting in nearly 20,000 dead or missing. A large number of studies have

69 reported the anomalous earthquake activities in the source area preceding the
70 Tohoku-Oki earthquake([Hasegawa and Yoshida, 2015](#); [Mavrommatis et al., 2014](#);
71 [Miyazaki et al., 2011](#); [Ozawa et al., 2012](#); [Uchida and Matsuzawa, 2013](#)). A transient
72 slow deformation, which occurred over 7 days in November 2008, was measured
73 using ocean-bottom pressure gauges and an on-shore volumetric strain meter
74 simultaneously. This deformation has been interpreted as a M_w 6.8 slow-slip
75 event(SSE) with a slip magnitude of 0.4 m at most. The other was observed in
76 mid-February 2011, just before the 2011 Tohoku-Oki earthquake of M_w 9.1([Ito et al.,](#)
77 [2013](#)). These achievements greatly improve our understanding of the nucleation
78 and mitigation processes of earthquakes in subduction zones. However, the
79 earthquake preparation is a long-term process, it is particularly important to know
80 the details of what occurred overall in the source area in a long time prior to this
81 great megathrust earthquake, and reveal the ongoing secular deformations and
82 strain accumulation progress, and improve the medium to longer-term seismic
83 hazard assessments.

Fig.1. Tectonic settings of the Japanese islands. The study area is depicted in the inset map. EUR, PHS, PAC, and OKH denote Eurasian, Philippine Sea, Pacific and Okhotsk plate, respectively. Beach balls denote GCMT of the earthquake. White arrows indicate the relative plate motion directions. EUR: Eurasian plate, OKH: Okhotsk plate, PHS: Philippine Sea plate, and PAC: Pacific plate.

With high-precision geodetic technology, GNSS observations which record continuously before the mainshock is providing both opportunities and challenges in detection of inter-seismic or pre-seismic deformation signals (Xu et al., 2020). GNSS networks yield daily estimates of site positions with a high precision of 1-2 mm in the horizontal and 3-4 mm in the vertical component over regional distances. However, GNSS observation is complicated by the presence of spatially and temporally coherent noise, Common Mode Errors (CME), local benchmark motion, un-modeled atmospheric delay, reference frame errors and other effects. Therefore, it is almost certain that more subtle signals, due to smaller magnitude events, exist in many observation series already collected but have gone

99 undetected. Most observations data used in a previous study were limited to the
100 static deformation field or short-time transient deformation with the larger
101 displacement. Considering that there is a relatively perfect IGS (International GPS
102 Service) continuous observation network distributed on the Japanese islands, it is
103 worth studying whether some crustal deformation information related to the
104 preparation process of this great earthquake can be obtained from GNSS
105 observation array. In this paper, we extend long time GPS array in the source area
106 to investigate long variation in the pre-seismic period, and focus on GPS time
107 series analysis and spatiotemporal filtering to improve GPS Signal-to-Noise Ratio
108 (SNR) and reveal its relevance to the 2011 Tohoku-Oki earthquake of M_w 9.1.
109 Long-term GPS array are used to describe the seismicity process of subduction
110 earthquakes, and the tendency transition of deformation curves in the east coast of
111 Japan island before the earthquake is analyzed. We model the GPS position time
112 series as a combination of the long-term plate movements, short-term noise and the
113 frequency-dependent variations and tectonic deformation information. CME is
114 then removed from the residual time series and the deformation signal is extracted
115 by PCA. Combining the filtered GPS displacement time series with the dynamic
116 strain variation array, the ongoing secular deformations and strain accumulation
117 progress is obtained, and the details of what occurred overall in the source area in
118 a long time prior to this great megathrust earthquake is revealed. We give an
119 appropriate model for the interplate coupling to explain the observed deformation
120 evolution finally.

2. Methods

2.1. Modeling GPS Position Time Series

The original GPS observation array show significant fluctuation mainly due to non-tectonic factors such as frame errors and un-modeled GPS processing errors, seasonal effect, periodic change, or CME([Dong et al., 2006](#)). In addition, the coordinate time sequence is usually discontinuous or has large errors because of bad observation environment or instrument obstacle. For these purposes, it has essential importance to preprocess the data of GPS coordinate time sequence for extracting tectonic deformation signals, such as eliminating the outfield value, recovering the missing data in the sequence, and improving SNR by spatiotemporal filtering. In this paper, the missing data is firstly interpolated by cubic splines function, the time series with abnormally large residuals over 2 root mean square (RMS) (>2.5, >2.5, and >6.5 mm in north, east, and up directions, respectively) are regarded as outliers. The time series is modeled for removing the trends and seasonal effects. CME is then removed and the deformation signal is extracted from the residual time series by Principal Component Analysis (PCA).

The time series of daily GPS site coordinate are fitted as a combination of the annual and semi-annual periodic terms, the initial position and a long-term trend term and the step terms to obtain the residual. The daily time series of the i -th coordinate component of the n -th GPS station can be modeled as,

$$y_n^i(t) = a_n^i + b_n^i t + c_n^i \sin(2\pi t) + d_n^i \cos(2\pi t) + e_n^i \sin(4\pi t) + f_n^i \cos(4\pi t) + \sum_{k=1}^m g_{n,k}^i H(t - t_n^k) + \varepsilon_n^i \quad (1)$$

where, i denotes East, North, and Up components, t denotes observed epoch(day).
 a , b are the initial position and long-term trend of GPS station, respectively. c and d
are the sine and cosine amplitudes at annual period, e and f are the sine and cosine
amplitudes at semi-annual period, respectively. H is the Heaviside step function,
 $g_{n,k}^i$ is a magnitude of the k -th step which occurred at t_n^k due to the earthquakes
or replace receiver antenna of subsequent epoch position overall migration. ε_n^i is
the corresponding noise in the position time series.

A time series of daily solution will constitute a lot equations of type (1), so the
model coefficients can be estimated by the least-squares criterion. After removing
the trend change, seasonal effect and periodic variations, etc., we obtain the
residual time series of GPS position.

2.2. Spatiotemporal Filtering and Signal Extraction

PCA approach is known as the empirical orthogonal function analysis, which
has been widely applied in geodesy, both to filter common mode noise in GPS
networks([Dong et al., 2006](#)) and to detect weak regional tectonic deformation
signals by improve SNR in GPS coordinate time series([Ji and Herring, 2013](#);
[Kositsky and Avouac, 2010](#); [Xu et al., 2015](#)). For GPS residual time series with n
stations and m days, the matrix $X(m \times n)$ is constructed, and each column denotes
the residual value for N,E,U components for each station at all epochs, each rows
denotes N,E,U components of all stations at a given epoch. The elements at i -th
row, j -th column of the covariance matrix B is defined as,

$$b_{i,j} = \frac{1}{m-1} \sum_{k=1}^m x_{k,i} x_{k,j} \quad (2)$$

where $x_{k,i}, x_{k,j}$ are the elements of X , $i=1,2,L m$, $j=1,2,L n$.

$B (n \times n)$ is a symmetric matrix, which can be decompose as,

$$B = V \Lambda V^T \quad (3)$$

where Λ is diagonal matrix with n nonzero eigenvalues. V is orthonormal matrix with n eigenvectors. X can expressed as,

$$X = AV^T, x_{i,j} = \sum_{k=1}^n a_{k,i} v_{k,j} \quad (4)$$

where $a_{k,i}$ is defined as,

$$a_{k,i} = \sum_{j=1}^n x_{i,j} v_{k,j} \quad (5)$$

where a_k, v_k is the temporal variations and spatial response of k -th principal component of X , respectively. The first few PCs usually represent the biggest contributors to the variance of the network residual time series, related to the common source time function. Therefore, CME can be expressed as,

$$CME = \sum_{k=1}^p a_{k,i} v_{k,j} \quad (6)$$

where p is the first p PCs.

2.3. Dynamic Strain Array Calculation

Strain rate tensor is independent of CME and the reference frame, and have the unique advantage for the detection of the crustal deformation. We calculate the strain time series based on the high-precision GPS baseline vectors (see [Fig.6](#)).

Suppose that the plane baseline vector before deformation is $(\Delta x, \Delta y)$ and the length is S , the baseline length after deformation is S' . The infinitesimal element along side length S and S' is dS and dS' , respectively. According to the elastic mechanics theory (Eringen, 1980), the strain tensors of a small element are related with change of a baseline length as ,

$$dS'^2 - dS^2 = 2E_{kl}(x, t)dx_k dy_l \quad (7)$$

where E_{kl} is the Lagrange strain tensor. Regarding E_{kl} as a constant, we integrate two sides of the equation (7) along the side length respectively and yields the following equation.

$$S'^2 - S^2 = 2E_{kl}\Delta x_k \Delta x_l \quad (8)$$

where E_{kl} is a symmetry tensor. Thus, (9) can be extended as follows:

$$S'^2 - S^2 = 2\Delta x^2 E_{11} + 2\Delta y^2 E_{22} + 4\Delta x \Delta y E_{12} \quad (9)$$

where E_{11}, E_{12}, E_{22} represent three plane strain tensors. Because the change of baseline length is much less than baseline length, that is,

$$S' - S = \Delta S \ll S, S' + S \approx 2S \quad (10)$$

Combining (9) and (10) yields

$$\Delta S / S = \cos^2 \alpha E_{11} + \cos^2 \beta E_{22} + 2 \cos \alpha \cos \beta E_{12} \quad (11)$$

where $\Delta S / S$ represents the linear strain, α, β represent the direction cosine of baseline, $\cos \alpha = \Delta x / S, \cos \beta = \Delta y / S$. Replacing direction cosine α, β with coordinate azimuth φ , (11) can thus be written as,

$$\Delta S / S = \sin^2 \varphi E_{11} + \cos^2 \varphi E_{22} + \sin \varphi \cos \varphi E_{12} \quad (12)$$

The linear strain of three baseline of a triangle will construct three observation equations of type (12). The strain tensors E_{11}, E_{12}, E_{22} will be estimated uniquely. The maximum, minimum principal strain E_1, E_2 and the azimuth φ of the maximum principal strain (defined as clockwise rotation from North direction) can then be obtained as follows,

$$E_{1,2} = \frac{e_{11} + e_{22}}{2} \pm \sqrt{\left(\frac{e_{11} - e_{22}}{2}\right)^2 + (e_{12})^2} \quad (13)$$

$$\varphi = \frac{1}{2} \arctg \frac{2E_{12}}{E_{22} - E_{11}} \quad (14)$$

The maximum surface dilatation I , the maximum shear strain T and the first shear strain T_1 can be expressed as,

$$I = E_1 + E_2, \quad T = \frac{1}{2}(E_1 - E_2), \quad T_1 = E_{11} - E_{22} \quad (15)$$

3. Results

3.1. GPS Data Processing Results

This earthquake is recorded by a available modern GPS observation network (<http://geodesy.unr.edu/gsrn.php>), unfortunately, most sites whose available time less than 3 years prior to the earthquake in source area. The time scale is extremely lack relative to the earthquake preparation scale, thus not enough to investigate the pre-seismic crustal motion and evolution. Therefore, GPS observation data used in this study are mainly from IGS network with 7 continuous stations observed from 2002 to 2015. GAMIT/GLOBK 10.4 and QOCA software are used to estimate the station positions and baselines ([Herring, 2002](#); [King and Bock, 1999](#)). GPS

observations from global IGS stations are combined to solve for precise satellite orbits. Dual-frequency phase data are used to compute double-difference ionosphere-free residuals, which are then inverted through a least squares procedure for solving the unknown parameters including single-day positions, satellite orbital elements, phase ambiguity integer numbers, tropospheric delay residuals, etc. Uncertainty of 10 mm for the carrier beat phase data, 30 s of sampling intervals, relax mode for the satellite orbit, the IERS2003 model for earth gravity field, solid tide and pole tide, the FES2004 mode for the global ocean tide, the GMF for troposphere mapping functions, and the parameter of zenith delay is estimated every 2h.

[Fig.2](#) displays the daily position time series IGS permanent sites for North, East, Up (N,E,U) components. Obviously, with the difference of the distance from the seismic source, the influence degree of every site from coseismic effect is different completely. AIRA, the furthest site from the epicenter with about 1300 km, the coseismic displacement is close to zero, with less influence from the earthquake, whereas the stations MIZU and KSMV, about 140km and 280km from the epicenter, have more significant coseismic effect, with -1.25m, 2.35m, -0.11m and 0.06m, 0.71m, -0.26m in N,E,U direction, respectively. Comparing with MIZU, the vertical displacement of KSMV is more significant than the horizontal displacement.

Fig.2. Raw time series of variations in daily site coordinates for the period from 2002 to 2014. The North component, East component and Up components are shown from left to right.

For the sake of better visualization of the pre-seismic deformation features for the earthquake, we extract the period from Jan. 2002 to Mar. 2011 of GPS coordinate time series analysis in this study, as shown in Fig.3. The southward motion of all stations are more significant than the eastward and upward motion in ITRF2008 reference frame. The several recent earthquakes of over M_w 6.9 (e.g., the M_w 7.0 in May 2003, the M_w 7.2 in August 2005, the M_w 6.9 in June 2008) all occurred near the station MIZU, far from other sites. Except for MIZU, the co-seismic and post-seismic effects on other stations are negligible. In addition, AIRA is far from the epicenter of the 2011 Tohoku-Oki earthquake of M_w 9.1. Therefore, we exclude the sites of MIZU and AIRA in following analysis.

Fig.3. Pre-seismic GPS displacement time series over the period of Feb. 12th, 2002-Mar. 10th, 2011 in N,E,U component from left to right

We compare the N,E,U coordinate time series derived from double difference model of GAMIT with those obtained by the precise point positioning strategy of GIPSY/OASIS-II software([Webb and Zumberge, 1993](#)), hereafter referred to as PPP, as shown in [Fig.4](#). Two solutions from the different algorithms show an overall consistency, indicating the correctness and reliability of the calculated GNSS coordinate array, which can be used for subsequent tectonic deformation extraction and analysis.

Fig.4. The comparison between the time series of daily site coordinates at KSMV station calculated by GAMIT10.4 and GIPSY/OASIS-II.

For the clarity of the internal deformation, we transform the station coordinates from ITRF frame into local reference frame by similarity transformation described by [Xu et al. \(2019\)](#). Because the movement trends of TSKB and KSMV are extremely similar, with the displacements discrepancies of less than 10 mm for both N and E component over 9 years, we consider TSKB and TSKB-KSMV as the reference point and reference direction, respectively, and perform the similarity transformation for daily solution array of the whole GPS

observation network. The result shows that the SNR of the time series have been greatly improved and the movement details is displayed more obvious(Fig.5). In particular, the E displacement time series show a significant arc-like deformation anomaly since 2008, while a stable linear change between 2002-2008.

Fig.5. Displacement time series in E component(a) and N component(b) by similarity transformation.

We also constitute GPS baseline network with connecting each site sequentially in near source area. The length and azimuth change time series of all baselines are calculated, as shown in Fig.6. Four baselines reduce linearly between 2002 and 2008, and the longest baseline KSMV-USUD, with the length of 208 km, has the largest contraction rate with about 5 mm/y. The compression is mainly due to the westward extrusion from of north American plate in NE direction and the Pacific plate in E direction. Obviously, since 2008, all the baseline length variations deviate from the initial linear trends and the compression motion start to slow down and turn to the extension. The baseline azimuth show an abnormal increase process like arc-shaped about during 2005-2008. The anomaly variation of the azimuth

291 indicates the shear tectonic movement, which probably play the important role in
 292 the crustal deformation.

Fig.6. Time series of variations in daily GPS baseline length(a) and azimuth (b) prior to the earthquake.

[Fig.7](#) displays the model fitting result for 4 stations in N,E,U component. The position time series of each station is decomposed into the linear inter-seismic deformation, an annual and an semi-annual cycle periods, and residual time series after removing modeled terms. Obviously, the jumps, discontinuities and the linear trend term have been removed in the residual time series.

3.2. Model Fitting Results of GPS Position Time Series

Fig.7. Daily GPS Site Coordinate time series at representative stations, corrected for the secular velocities, seasonal variation and outfield value. The North component, East component and Up components are shown from left to right.

The secular displacement rate is mainly caused by plate movement. In order to illustrate the internal tectonic movement feature of this region, we calculate the

velocity vectors with respect to the stable Eurasian plate based on the Euler parameters ($55.25^\circ\text{N}, 98.3^\circ\text{W}, 0.256^\circ/\text{Ma}$) from [Xu and Wu \(2014\)](#), as shown in [Fig.8](#). The Japanese Islands show a dominated westward motion in the region with a average velocity of 20mm/yr , due to the subduction of Pacific plate and Philippine Sea plate. Comparing with the horizontal motion, the vertical motion is not significant, with about 1mm/yr .

Fig.8. GPS velocity of 5 sites with respect to Eurasian plate. Each velocity arrow originates at the location of the site and points to its motion direction. Error ellipses represent 95% confidence level.

3.3. Filtering Results of the Residual Time Series

The residual time series in [Fig.7](#) still show a significant spatial correlation errors among different stations, so the SNR of the GPS residual time series need to be further improved by PCA spatiotemporal filtering. [Fig.9](#) shows the first 5 eigenvalues normalized by the highest one in N, E, U components. The first mode

317 have significant eigenvalue and other modes are less than 50% of that of the mode
 318 1 signal for the N, E, U components.

Fig.9. First 5 eigenvalues normalized by the highest one in N, E, U components

321 Temporal and spatial responses of the first PCs for the east, north, and vertical
 322 components by first principle component (PC1) are displayed in [Fig.10](#), [Fig.11](#) and
 323 [Fig.12](#), respectively. For all three components, their PC1 in [Fig.10](#), [Fig.11](#) and
 324 [Fig.12](#).left show significant responses with spatially uniform distribution, whereas
 325 other PCs have no obviously uniform pattern in space or spatial coherence.
 326 Although there is no generally accepted consensus on calculation CME at a large
 327 scale, for a small GPS network with a spatial scale of $5^\circ \times 5^\circ$, the mode is considered
 328 as CME where most sites (more than 50%) stations have significant normalized
 329 responses with larger than 25% and the corresponding eigenvalues exceed 1% of
 330 the summation of all eigenvalues ([Dong et al., 2006](#)). According to this criterion, we
 331 regard the PC1 is regarded as CME, and focus on other modes PCs for tectonic
 332 deformation analysis.

333 The temporal variations and spatial response of other modes PC2,3 in the E, N
334 and U component are shown in [Fig.10](#), [Fig.11](#) and [Fig.12](#).right. For all three
335 components, their temporal variations show the a long-period turning motion
336 process, from westward to eastward, from northward to southward, from upward
337 to downward, respectively. The spatial distribution have the opposite sign in the
338 east and west sides of network. The station KSMV has the most significant spatial
339 responses in three components, which are explained that the station is located on
340 the boundary of ocean-continent, where has the strong impact from subduction.
341 An examination of the third mode's spatiotemporal responses in vertical time
342 series show the similarity to those of the second mode in east and north
343 components. The other mode's temporal variations exhibit the high-frequency
344 irregular fluctuations and the spatial eigenvectors indicates that only a small
345 portion of the stations have modest amplitudes with some significance. Therefore,
346 the PCs of these modes cannot be identified as the potential geophysical processes.
347 They are probably the mixture of unmodeled signals, local effects and noise. The
348 filtered results show a significant temporal variations of turning motion, indicating
349 the motion transition process from compression to tension. The spatial responses
350 denote the spatial distribution features of strain accumulation during the pregnant
351 period of strong earthquake. The western Japan island may still keep stable
352 westward extrusion without gradient change with the region while the east coast
353 of Japan island has strong impact from subduction zone. The opposite spatial
354 distribution in the east and west sides of Japan island probably be explained that

355 the strain accumulation will release and turn to move in a oppose direction when
 356 the deformation reaches the limit.

Fig.10. East component of PCA solution. (left) (top) First scaled PC and (bottom) its normalized spatial eigenvectors. The arrows represent the element values of the normalized eigenvectors (not the displacement directions). The upward and downward arrows represent positive and negative responses to the scaled PC, respectively. (right) (top) Second scaled PC and (bottom) its normalized spatial eigenvectors. Solid green curve represent the fit to the data by Gaussian smooth filter.

Fig.11. North component of PCA solution. (left) (top) First scaled PC and (bottom) its normalized spatial eigenvectors. (right) (top) Second scaled PC and (bottom) its normalized spatial eigenvectors. The arrows and solid green curve are defined as in Fig.10.

Fig.12. Vertical component of PCA solution. (left) (top) First scaled PC and (bottom) its normalized spatial eigenvectors. (right) (top) Third scaled PC and (bottom) its normalized spatial eigenvectors. The arrows and solid green curve are defined as in Fig.10.

3.4. Regional Strain Time Series

[Fig.13](#) displays the maximal shear strain, dilatation strain and the first shear strain time series of two areas composed of triangles USUD-KGNI-TSKB and KGNI-KSMV-TSKB (see [Fig.8](#)). The dilatation strain time series of all two areas show a strong compression movement as a whole at the average compression rate of 67 and 22 nanostrain/yr(10^{-9} /yr), respectively. This is mainly related to eastward compression resulted from the subduction of Pacific plate and Philippine Sea plate. Comparing with USUD-KGNI-TSKB, the compression of KGNI-KSMV-TSKB show a significant anomalous change process from stably linear strain accumulation to slow down. It probably is because the area of KGNI-KSMV-TSKB is much closer to the subduction belt along Japan trench. The maximal shear strain and the first shear strain in both areas show a transition process from a stable linear change

status during 2002-2007 to a acceleration increase during 2008-2011. The maximal shear strain have increased significantly from 3 to 26 nanostrain/yr, from 9 to 50 nanostrain/yr for KGNI-KSMV-TSKB and USUD-KGNI-TSKB, respectively. The first shear strain describes the shear deformation of N45°W and N45°E strike accurately, and the positive value with NE strike denotes the left-lateral shear, therefore, it is inferred that the deformation in the region is mainly characterized by expression and the right-lateral shear motion.

Fig.13. Dilatation strain(a), maximum shear strain(b),and first shear strain array(c) of two regions TSKB-KSMV-MIZU and USUD-TSKB-MIZU drawn in Fig.8.

4. Discussion

All the similarity transformation results, baselines array, the filtered displacement time series and the dynamic strain array show a significant pre-seismic deformation anomalies. The dilatation strain time series show a significant change anomaly from stable linear accumulation to slow down. The maximal shear strain and the first shear strain time series show a transition process from a stable linear change status during 2002-2007 to a acceleration change in 2008-2011. The filtered displacement array show a significant evolution process

from the originally stable linear change to the locked status and the reverse motion finally. According to the theory of rock mechanics and deformation, the whole observed behaviors are described as stable linear motion and instable nonlinear motion. In first stage, the deformation show a trend of linear increase, referred to as a elastic deformation. The deformation will restore quickly, once the external force is unloaded. In the second stage, the deformation starts to deviate the linear movement trend, both of the elastic and inelastic deformation coexist. Contrary to the first stage, the deformation will not restore completely if the external force is unloaded. In the stage, the strain of different section on subduciton zone begin to appear the features of the differentiation change. The displacement and the dilation strain rate of part of areas decrease gradually, close to the locked status. After a short period of locking, the part locked areas will decouple and appear the reverse motion trend. Meantime, the shear strain transfer to the remaining locked region and become more and more concentrated, resulting in its acceleration accumulation on the whole region, until the occurrence of the earthquake. Our findings are consistent with the simulation experiment results of the rock rupture in the laboratory ([Ma, 2016](#)).

According to the above spatio-temporal evolution process of crustal motion we have observed and the previous research([Chen et al., 2013](#); [Hoshiba, 2006](#)), we give an model for the interplate coupling to explain the present three-dimensional deformation, as shown in [Fig.14](#). The evolution process is divided into the following four stages.

Fig.14. Seismogenic model in plate subduction region.(a) the stable linear strain accumulation stage.(b) the formation stage of the local locked area. (c) local decoupling stage. (d)great rupture and strain release stage(occurrence of great earthquake)

(1) The stable linear strain accumulation stage([Fig.14.a](#)). The preliminary linear movement can be explained as the relatively stable motion between two plates in the subduction process of the ocean-continental plate at the beginning of the earthquake preparation. Because the subducting ocean plate is getting stuck, the overriding continental plate will be squeezed and dominated by compression deformation, the leading edges is dragged down, while the hinterland areas in near-field surface is bulged upward. As a result, the strain near the boundary of the plate starts to accumulate, and the seismogenic region is formed initially.

(2) The formation stage of the local locked area ([Fig.14.b](#)). With the continuing of the relative motion between plates in far-field, the frictional stress level gradually increases due to the heterogeneity of the ocean-continental subduction belt contact surface. The ability to resist the deformation gradually reduces, in this case, the deformation deviates from the originally linear trend. The local seismogenesis region presents a deformation characteristic of gradual attenuation from deep to shallow. The westward and upward displacement of the region gradually slows down and reaches the locked state, whereas the remaining regions still keep on relative movement under the action of tectonic stress, so the stress begins to transfer gradually to the locked area and become more and more concentrated.

(3) The local decoupling stage ([Fig.14.c](#)). The strain accumulation and the stress level in the locked region continually increases and reaches the limit finally. The seismological element is decoupled to become the slip area, the part strain energy begins to release slowly, and the surface deformation then appears the reverse motion. In this stage, there is usually pre-slip and increased small earthquake activity. However, the shear strain energy still keeps continuing accumulation during locked status. The remaining major locked area gets the further concentration of strain and redistribution of stress, resulting in the accelerated accumulation of the shear strain and increasingly high stress concentration degree.

(4) The great rupture and strain release stage (occurrence of great earthquake) ([Fig.14.d](#)). With more and more concentrated stress and strain accumulation in the remaining locked area, the frictional resistance between plates is overcome

completely. As a result, the widely distributed locked zones become instable and appear the instantaneous mutation and a large strain release, the elastic rebound happen on the leading edge of the jammed overriding plate, where the obduction and upheaval cause the tsunami phenomenon, while the bulge behind the leading edge is collapsed.

In the different stages, the deformation characteristics and the time experienced are different. After four stages of evolution, the whole seismic process is completed.

5. Conclusions

The SNR in coordinate time series for regional GPS networks can be further improved by spatiotemporal filtering from the residual GPS observation array. Integrating filtered displacement time series, regional strain, baseline change and processing of similarity transformation, the significant pre-seismic deformation evolution around a period is detected prior to 2011 Tohoku-Oki earthquake of M_w 9.1. The displacement and the dilation strain rate of part regions decrease gradually, close to the locked status, then reverse motion, instead, the shear strain is more and more concentrated, resulting in the acceleration accumulation. The tectonic evolution for earthquake occurrence along the subduction zone can be described as four stages, the stable linear strain accumulation stage, the formation stage of the locked area, local decoupling stage and great rupture-strain release stage. The surface deformation characteristics of the different stages is also different, the detection of these stages has certain indicative significance for the identification of the surface deformation from destructive earthquakes along the subduction

zone, which are entirely consistent with the simulation experiment results of the rock rupture in the laboratory. An appropriate model is proposed for well interpreting the observed deformation process. Our findings provide a valuable clue for revealing the seismicity mechanism of subduction earthquakes

Abbreviations

IGS: International GNSS Service; GPS: Global positioning system; CME: Common Mode Errors; PCA: Principal Component Analysis; RMS: Root Mean Square; SNR : Signal-to-Noise Ratio; N,E,U: North, East, Up

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Authors' contributions

Keke Xu designed the study, performed the methodology research, and drafted the manuscript. Rong He performed data processing and analysis. Kezhao Li performed the validation and assessment of GPS data. Ankang Ren performed and noises analysis of GPS time series and Siyuan Jiang validate the effectiveness of strain results. All authors read and approved the final manuscript.

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Availability of data and materials

All datasets and methods during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Figures

Figure 1

Tectonic settings of the Japanese islands. The study area is depicted in the inset map. EUR, PHS, PAC, and OKH denote Eurasian, Philippine Sea, Pacific and Okhotsk plate, respectively. Beach balls denote GCMT of the earthquake. White arrows indicate the relative plate motion directions. EUR: Eurasian plate, OKH: Okhotsk plate, PHS: Philippine Sea plate, and PAC: Pacific plate. 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

Raw time series of variations in daily site coordinates for the period from 2002 to 2014. The North component, East component and Up components are shown from left to right.

Figure 3

Pre-seismic GPS displacement time series over the period of Feb. 12th, 2002-Mar. 10th, 2011 in N,E,U component from left to right

Figure 4

The comparison between the time series of daily site coordinates at KSMV station calculated by GAMIT10.4 and GIPSY/OASIS-II.

Figure 5

Displacement time series in E component(a) and N component(b) by similarity transformation.

Figure 6

Time series of variations in daily GPS baseline length(a) and azimuth (b) prior to the earthquake.

Figure 7

Daily GPS Site Coordinate time series at representative stations, corrected for the secular velocities, seasonal variation and outfield value. The North component, East component and Up components are shown from left to right.

Figure 8

GPS velocity of 5 sites with respect to Eurasian plate. Each velocity arrow originates at the location of the site and points to its motion direction. Error ellipses represent 95% confidence level. 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

First 5 eigenvalues normalized by the highest one in N, E, U components

Figure 10

East component of PCA solution. (left) (top) First scaled PC and (bottom) its normalized spatial eigenvectors. The arrows represent the element values of the normalized eigenvectors (not the displacement directions). The upward and downward arrows represent positive and negative responses to the scaled PC, respectively. (right) (top) Second scaled PC and (bottom) its normalized spatial eigenvectors. Solid green curve represent the fit to the data by Gaussian smooth filter.

Figure 11

North component of PCA solution. (left) (top) First scaled PC and (bottom) its normalized spatial eigenvectors. (right) (top) Second scaled PC and (bottom) its normalized spatial eigenvectors. The arrows and solid green curve are defined as in Fig.10

Figure 12

Vertical component of PCA solution. (left) (top) First scaled PC and (bottom) its normalized spatial eigenvectors. (right) (top) Third scaled PC and (bottom) its normalized spatial eigenvectors. The arrows and solid green curve are defined as in Fig.10.

Figure 13

Dilatation strain(a), maximum shear strain(b), and first shear strain array(c) of two regions TSKB-KSMV-MIZU and USUD-TSKB-MIZU drawn in Fig.8.

Figure 14

Seismogenic model in plate subduction region.(a) the stable linear strain accumulation stage.(b) the formation stage of the local locked area. (c) local decoupling stage. (d)great rupture and strain release stage(occurrence of great earthquake)

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