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Statistical Significance of Precursory Gravity Changes Before the 2011 M_w 9.0 Tohoku-Oki Earthquake

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Abstract

It is of paramount importance to independently assess the spatiotemporal uniqueness of a proposed regional precursor initiated a few months before the 2011 M_w 9.0 Tohoku-Oki earthquake. The precursor has been inferred from GRACE-derived gravitational gradient changes and has been interpreted as a large-scale aseismic movement of the subducting plate along the Japan Trench. We design a hypothesis test, which enables the rigorous assessment of the statistical significance of short-term gradient anomalies at any time in any place and the quantitative comparison of the resolved anomalies with the proposed precursory signal. We find that the proposed precursory changes are not statistically unique either in time or in space. Therefore, the precursor cannot be attributed to the proposed dynamic acceleration of the subduction process. Instead, such transient features more likely represent temporally correlated GRACE observation errors or signals associated with other processes.

1 Introduction

The M_w 9.0 Tohoku-Oki earthquake that ruptured the interplate boundary off the eastern shore of northern Honshu on 11 March 2011 is one of the biggest earthquakes recorded in the last 100 years. The well-developed geodetic observation systems over Japan provide abundant information on the temporal and spatial characteristics of the earthquake-related deformation before, during, and after the earthquake (Nishimura et al., 2014; Wang et al., 2018). Onshore coseismic displacements were observed by the GNSS Earth Observation Network (GEONET) (Ozawa et al., 2011). Coseismic displacements on the sea floor were observed by repeated multibeam bathymetric surveys across the Japan trench (Fujiwara et al., 2011) and offshore GPS-Acoustic and ocean bottom pressure sensor observations (Ito et al., 2011; Sato et al., 2011). The seafloor coseismic deformation was also inferred from tsunami waveforms observed by Deep Ocean Tsunami Detection (DART) buoys, ocean bottom pressure sensors, coastal wave gauges, and GPS buoys (Romano et al., 2012). The postseismic deformation, which reflects the viscoelastic relaxation of earthquake-induced stresses in the upper mantle and afterslip on the megathrust, were also observed by using different geodetic techniques, including continuous-operating GPS (Ozawa et al., 2011), offshore GPS-Acoustic surveys (Tomita et al., 2017;

Watanabe et al., 2014), and ocean-bottom pressure gauges (Iinuma et al., 2016).

The Tohoku earthquake was preceded by a propagating foreshock sequence (Kato et al., 2012) and an acceleration of deformation revealed by ocean bottom pressure sensors and a nearshore strainmeter (Ito et al., 2013). These data are consistent with the occurrence of an approximately month-long precursory slow-slip transient just downdip of the mainshock rupture zone (Obara & Kato, 2016; Uchida & Matsuzawa, 2013). Bouchon et al. (2016) suggest that there was also a period of accelerated seismicity within the subducting slab at depths greater than 80 km during this time, which they interpret as a phase of accelerated motion of the slab that triggered failure of the shallow megathrust. However, Delbridge et al. (2017) find that the proposed deep seismicity precursor is not statistically significant.

In addition to the traditional in situ geodetic observations, space-borne gravity measurements by the Gravity Recovery And Climate Experiment (GRACE) mission help quantify and constrain the earthquake cycle deformation of great earthquakes, including the Tohoku rupture. The GRACE mission continuously mapped Earth's gravitational field with temporal resolution of ~30 days and spatial resolution of ~350 km half-wavelength (Tapley et al., 2004). Although GRACE gravity represents an independent observation type, its capability to constrain detailed spatiotemporal characteristics of tectonic deformation is limited by its coarse resolution. GRACE is not able to detect any deformation with temporal scale less than 1 month and spatial scale less than several hundred kilometers. As a consequence, only the coseismic and postseismic deformation of great earthquakes with moment magnitude larger than 8.3 could be detected by GRACE (Chao & Liau, 2019 and references therein).

Based on a space-time analysis of the GRACE gravitational gradients, Panet et al. (2018) infer a large transient in gravitational gradients around the subduction zone of NE Japan, which started a couple of months before the 2011 mainshock and has a large spatial scale exceeding 1,000 km. The detected transient is equivalent to the effect of a M_w 8.4 normal-faulting earthquake at >250-km depth (Panet et al., 2018). Previously, no large-scale deformation transients have been reported by analyses of various geodetic measurements, including GRACE gravity (Han et al., 2011; Matsuo & Heki, 2011; Wang et al., 2012) and high-precision GPS, which allows the measurement of deformation with subcentimeter precision (Yokota & Koketsu, 2015). A local slow-slip event with moment magnitude of 7.1 was revealed by near-field seismicity and pressure-sensor observations (Ito et al., 2013; Kato et al., 2012), but its moment magnitude is too small to explain the large transient in the GRACE observation detected by Panet et al. (2018). They interpret this preseismic transient as an aseismic movement of a > 1,000-km-long section of the descending Pacific slab at ~300-km depth that initiated a few months before the mainshock and consider it as the initial phase of a process that eventually manifested itself in the devastating 2011

M_w 9.0 Tohoku event. These results, if robust, would represent a significant scientific breakthrough, since it would not only revolutionize our understanding of the dynamics of the subduction process, but could also provide important insight for improved short-term seismic hazard forecasting. It is thus critical to independently test and validate these gravity changes preceding the mainshock.

The key questions to answer are the following: (1) whether or not similar changes also occur at any other time and place and (2) if yes, if they are fundamentally different from those found by Panet et al. (2018) around Japan in the 4 months leading up to the 2011 Tohoku earthquake. Here we develop a statistically rigorous method to test the uniqueness of the anomalous changes prior to the event. This method produces uniform measures for the statistical significance of such anomalous changes at any time and place on the globe and thus enables an objective assessment of the proposed anomaly from a statistical perspective.

2 Method and Results

Since transient deformation can be defined as a change of deformation rate, we use a general piecewise linear regression model to describe the transient signals, together with coseismic and postseismic deformations within a time series (supporting information Text S1). Specifically, the deformation is assumed to have an initial constant rate of v_1. At epoch t_1, a transient initiates, and the deformation rate changes by v_2. This transient deformation lasts until epoch t_{eq} when an earthquake occurs, which offsets the time series by an amount of a, that is, the coseismic deformation. After the earthquake epoch t_{eq}, the postseismic deformation is modeled by a fast-deformation phase with a rate of v_3 followed by a slow-deformation phase with a rate of v_4, in order to account for the temporal evolution of postseismic deformation (Panet et al., 2018). The transition occurs at epoch t_2 after the earthquake. Obviously, this simple piecewise linear model does not optimally describe the postseismic deformation involving multiple time-dependent relaxation processes (Hu et al., 2016). By fitting the GNSS position time series of the 2011 Tohoku earthquake, Tobita (2016) suggests a combination of logarithmic and exponential decay functions for modeling the postseismic deformation. However, the purpose of this work is not to study the detailed postseismic development, and the simplified bilinear model for the postseismic deformation does not prevent us from checking the statistical significance of the preseismic signal.

In order to test the statistical significance of the preseismic transient signals proposed by Panet et al. (2018), we analyze the GRACE gravity time series starting from September 2002 (i.e., t_0). The epoch t_1 is chosen as 4 months prior to the mainshock (i.e., November 2010), which is the same as the initiation time of the preseismic transients suggested by Panet et al. (2018). In the supporting information we also consider t_1 of June 2010, following section 2.3.2 in the supplementary information of Panet et al. (2018). The earthquake epoch t_{eq} is March 2011, and the postseismic epoch t_2 is chosen as 1 year after the mainshock (i.e., March 2012), consistent with the fact that the postseismic deformation decayed rapidly during the first year after the mainshock (Tobita, 2016).

By fitting this model to the observation, the statistical significance of the unknown parameters, including a,v_1,v_2,v_3, and v_4, can be tested separately from each other. If the observation noise is Gaussian white noise, and no other processes induce a similar “step” as an earthquake does, the estimated coseismic parameter a is expected to be more significant over the seismically deformed regions compared to areas far away from the epicenter (Figure S1). Here we focus on testing the statistical significance of the preseismic transient parameter v_2. For this purpose, the restricted model is first formulated by introducing the constraint v_2=0 into the full model (Text S1), which is equivalent to a hypothesis that no preseismic transient deformation exists. Hence, based on the F test (Koch, 1999), we statistically test the

$$\textit{null hypothesis} \quad H_0 : v_2 = 0 \quad \text{versus} \quad \textit{alternative hypothesis} \quad H_1 : v_2 \neq 0, \tag{1}$$

and determine the significance level α for rejecting the null hypothesis H_0, and accepting the alternative hypothesis H_1 that the preseismic signal does exist. In other words, the significance of a parameter represents the likelihood that it is nonzero in the model.

The GRACE gravitational gradients have been demonstrated to be able to detect the coseismic deformation of great earthquakes (Wang et al., 2012). Compared with the gradient measurements by the GOCE satellite (Fuchs et al., 2013), the GRACE-derived gradients are sensitive to signals of larger spatial scale. In the study by Panet et al. (2018), the gravitational gradients Vyy' are calculated in a sequence of local coordinate systems, which are defined by azimuthally rotating the local north-east-down (NED) system by different angles θ, sequentially increasing from 20° to 55°, in order to match the strike of the plate boundary. Here the prime symbol indicates the gradient is calculated in a rotated local coordinate system $\{\vec{x}', \vec{y}', \vec{z}'\}$ (Text S2). The average gradients $\overline{V'_{yy}}$ (hereafter simply referred to as “gradients”) over these rotations are calculated. Then, the components of $\overline{V'_{yy}}$ with spatial scales of 1,400 km are deduced from Poisson multipole wavelet analysis.

We first analyze the same GRACE solution as used by Panet et al. (2018), that is, Centre National d'Eutdes Spatiales/Groupe de Recherches de Géodésie Spatiale (CNES/GRGS) Release 03-v1 (RL03-v1) monthly gravity field spherical harmonic coefficients. The same $\overline{V'_{yy}}$ components with spatial scale of 1,400 km are calculated as described by Panet et al. (2018). The annual, semiannual and 161-day (alias period of S2 tide errors (Ray et al., 2003)) sinusoidal terms are fitted using the data spanning 2003–2009 and removed from the time series of the average gradients $\overline{V'_{yy}}$ following Panet et al. (2018). The hypothesis test is then applied to the time series of residuals.

Figure 1a shows the gradient anomalies for 4 months prior to the 2011 Tohoku earthquake with significance level greater than 95%. Over Japan, their locations and geometrical patterns agree well with the "preseismic transient deformation" proposed by Panet et al. (2018, their Figures 1a and S22) based on wavelet analysis, demonstrating the effectiveness of our statistical method. Specifically, to the west of the epicenter, significant positive gradient anomalies are found across the Okhotsk and Eurasian plates, and to the south of the epicenter, significant negative anomalies show up over the Pacific and Philippine Sea plates. However, as shown in Figure 1a, significant differences also exist outside the Japan region. Particularly, to the northwest of Japan, significant negative anomalies reside deep within the interior of the Eurasian plate, and to the southeast of Japan, positive anomalies are found over the Pacific Plate far from the subduction zone. Figure 1b shows the significant coseismic gradient changes for comparison with the preseismic anomalies. Figures 1c and 1d illustrate two time series of GRACE gradient residuals, which show significant coseismic deformation but have opposite hypothesis test results for the existence of preseismic changes. As shown in Figure 1c, the time series of residuals at point $P1$ shows apparent growth starting from epoch t_1 and is better fit by using the full model (Text S1) than the restricted model in which the constraint of $v_2=0$ has been introduced. Here the significance level of accepting $v_2\neq0$ is determined to be 99.8%. In other words, based on the specific hypothesis we posed and the statistics of the data, the probability that the preseismic change does not exist is only 0.2%. In contrast, for the time series at $P2$ not showing anomalous changes between t_1 and t_{eq} (Figure 1d), whether or not to introduce the constraint of $v_2=0$ into the full model does not make a significant difference in fitting the data. Accordingly, the significance level of accepting the existence of preseismic changes at this location is very low, only 12.3%. Figures 1e and 1f show the daily position time series (east and vertical components) from two continuously operating GPS stations, that is, I044 and J923. These two stations are selected such that their locations overlap the regions where both significant preseismic and coseismic gradient changes are detected by GRACE (Figures 1a and 1b). However, as shown in Figures 1e and 1f, while the coseismic displacements are precisely measured by GPS at both stations, no significant preseismic transient displacements are detected, even though GPS displacement measurements are much more precise than GRACE observations.

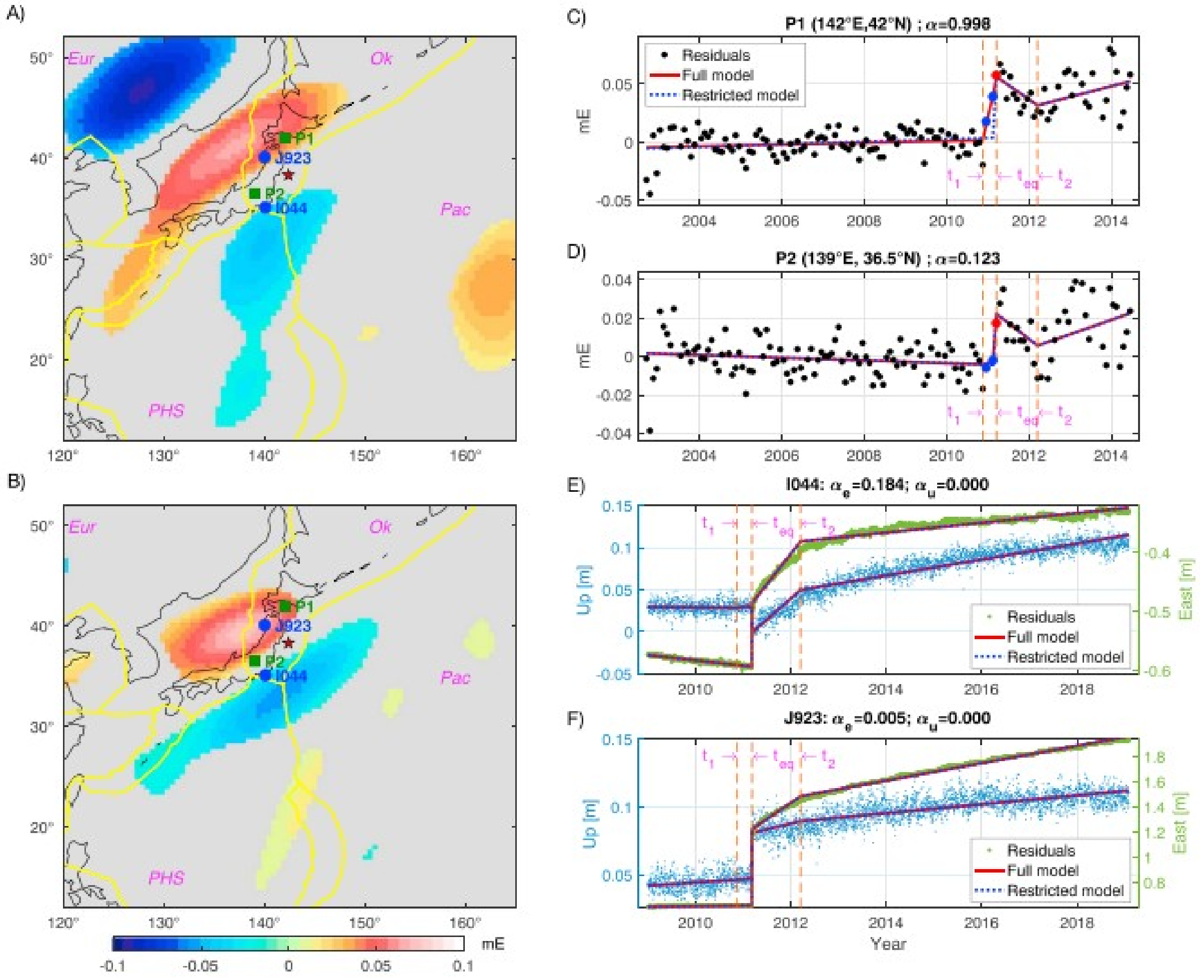

Figure 1. (a) Significant gradient changes ($\overline{V'_{yy}}$ with spatial scale of 1,400 km, calculated based on CNES/GRGS RL03_v1 solution) for 4 months before the 2011 Tohoku earthquake with significance level greater than 95%. The yellow lines denote the boundaries of major tectonic plates, including the Eurasian Plate (*Eur*), Okhotsk Plate (*Ok*), Pacific Plate (*Pac*), and Philippine Sea Plate (*PHS*). (b) Significant coseismic gradient changes. (c and d) Time series of residual gradients $\overline{V'_{yy}}$ with spatial scale of 1,400 km after removing the periodic terms, for two sample locations (see locations of *P*1 and *P*2 on map). The red dot denotes the data for the month of the mainshock (i.e., March 2011), and the blue dots denote the data from 4 months prior to the mainshock (i.e., December 2010 and February 2011). The significance level of accepting the existence of preseismic transient anomalies are 99.8% and 12.3% for the time series shown in (c) and (d), respectively. (e and f) The same hypothesis test is applied to the daily position time series from two GPS stations, I044 and J923. The significance levels for the existence of preseismic transient deformation in east direction are 18.4% and 0.5%, respectively, and all zeros in vertical direction.

Figure 2a shows the significance levels of gradient changes over Japan during 4 months before the 2011 Tohoku earthquake, based on the analysis of the CNES/GRGS RL03_v1 solution. Significant transient gradient changes are confirmed over a broad area around the epicenter. Panet et al. (2018, their Figure 2) show six gradient time series selected from different regions on both sides of the Japan trench, including northern Japan, the Japan Sea, and the Izu-Bonin arc, to support their conclusion. We show the time series from the same locations (Points 1–6) in Figure 3. The time series of the CNES/

GRGS RL03_v1 solution are consistent with those shown by Panet et al. (2018). As shown in Figure 3b, the transient gradient changes prior to the mainshock are statistically significant at all the six sample locations, with significance levels larger than 98%. These significant transient changes can be further justified by checking the statistics of the residuals after removing the fitted restricted model. As shown in Figure 3c, for all the time series, the residuals of the two data points within 4 months before the mainshock are either close or greater than 2 times the root-mean-square scatter of residuals.

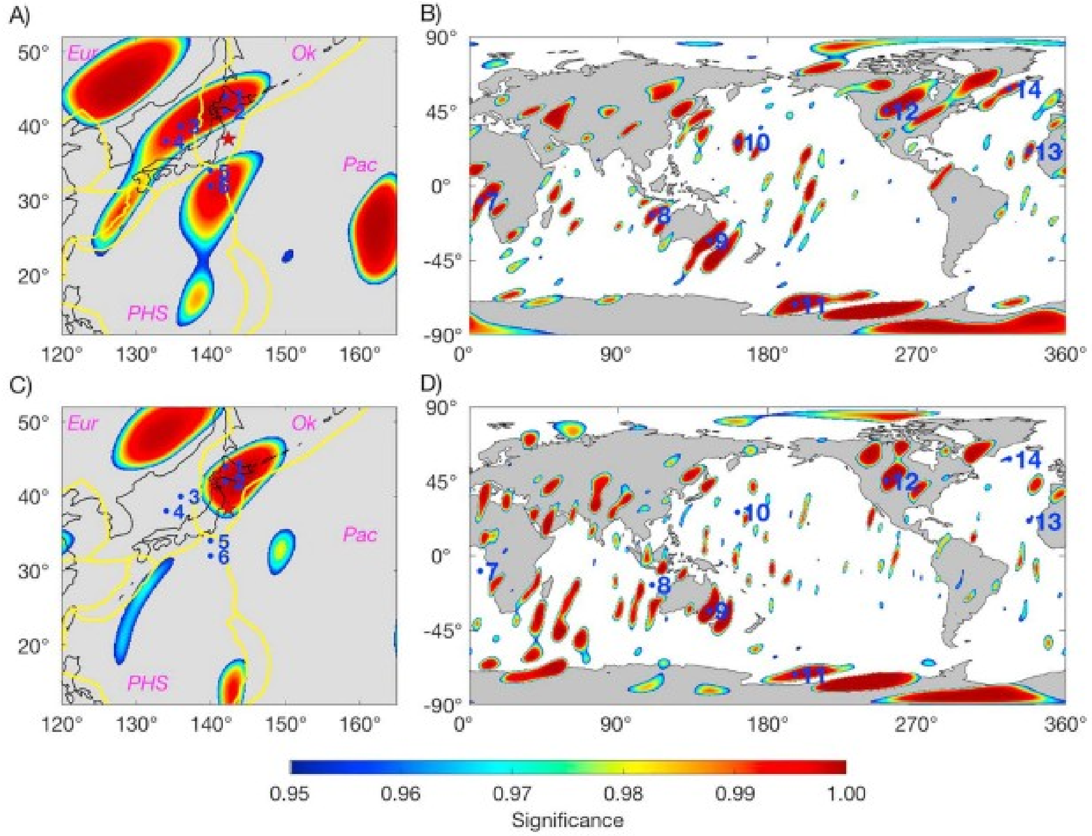

Figure 2. Significance levels of accepting the existence of gradient anomalies within the time series of residuals 4 months prior to March 2011. Only the significance levels larger than 95% are shown. The analyses are based on the monthly GRACE gravity field spherical harmonic coefficients of the CNES/GRGS RL3_v1 solution (a and b), and the CSR RL06 solution (c and d). Panel a (c) is the same as b (d), except it zooms in on the region over Japan. The red star denotes the epicenter of the 2011 M_w 9.0 Tohoku earthquake. Sample time series from different locations, including northern Japan (Points 1 and 2), the Japan Sea (Points 3 and 4), the Izu-Bonin intra-oceanic arc (Points 5 and 6), and regions far away from the epicenter (Points 7–14), are compared in Figure 3.

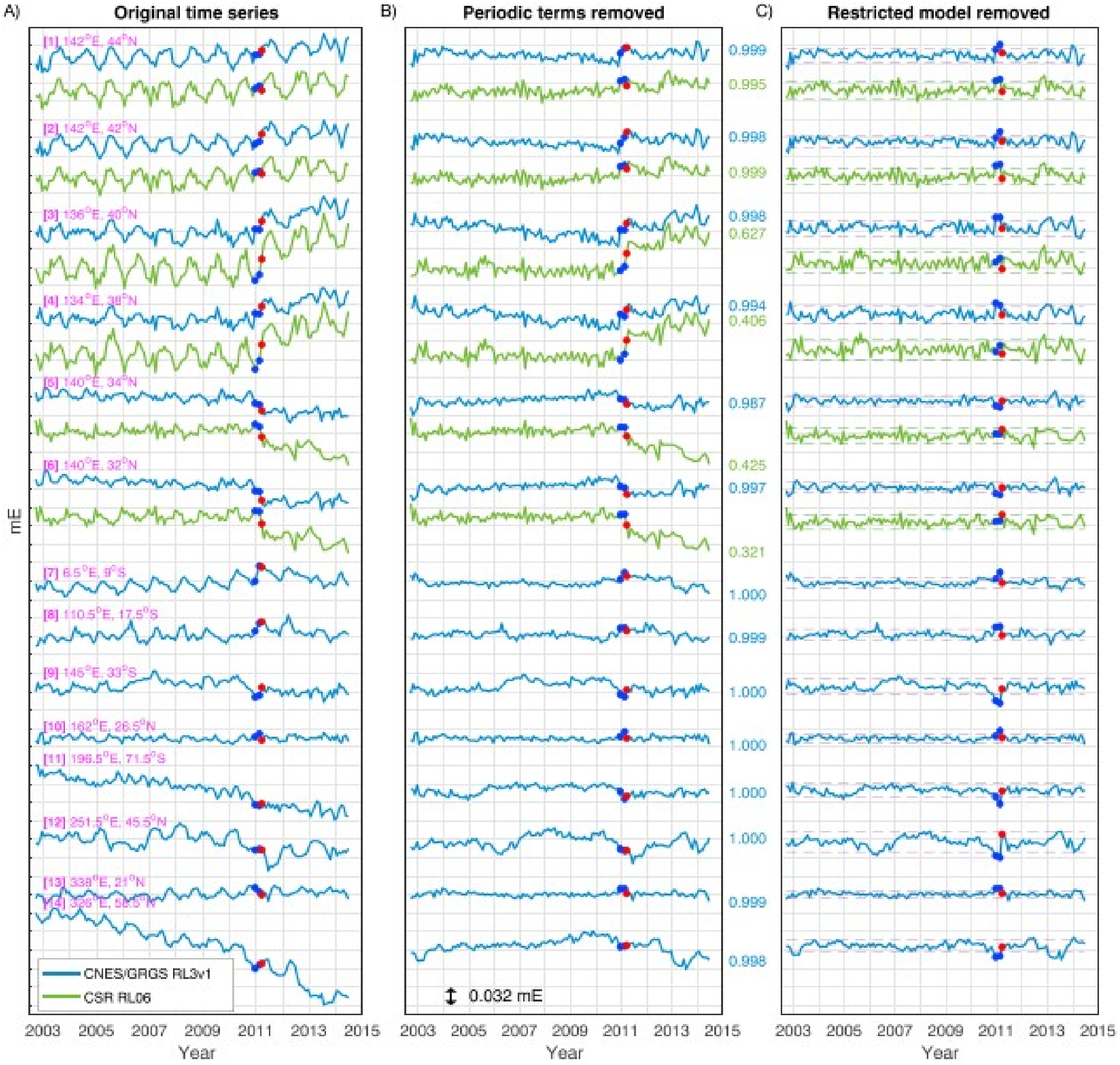

Figure 3. Time series of GRACE gravitational gradients $\overline{V'_{yy}}$ with spatial scale of 1,400 km from the locations near the epicenter, including northern Japan (Points 1 and 2), the Japan sea (Points 3 and 4), the Izu-Bonin arc (Points 5 and 6), and far away from the epicenter (Points 7–14). Their geographic locations are shown in Figure 2 by numbers [1]–[14]. (a) Original time series (blue = CNES/GRGS RL03_v1; green = CSR RL06); (b) annual, semiannual, and 161-day periodic terms are fitted and removed; and (c) the fitted restricted model is further removed. The red dot denotes the data for the month of the mainshock (i.e., March 2011), and the blue dots denote the data from 4 months prior to the mainshock (i.e., December 2010 and February 2011). The dashed lines in (c) denote the range of 2 times root-mean-square scatter of the residuals. The significance levels of the gradient anomaly prior to the mainshock are shown on the *y* axis right side of (b). Grid lines for *y* axes are displayed with an interval of 0.032 mE.

Although we obtain results similar to those reported by Panet et al. (2018) over Japan, anomalous gradient changes prior to the mainshock are found all over the globe by our statistical test, having similar or even greater apparent significance levels when compared with those over the seismic region. As shown in Figure 2b, such significant variations are found both over land and oceans, and do not seem to follow any predictable spatial pattern. Their apparent systematic orientation, particularly over the oceans, may reflect

GRACE systematic errors due to the unidirectional (i.e., along track) sensitivity of the GRACE K-band ranging system. Figure 3 shows the time series selected from different locations (Points 7–14), which are far away from the epicenter and distributed globally (Figure 2). As shown in Figure 3b, although far away from the epicenter, the anomalous gradient variations during 4 months prior to the epoch of the Tohoku earthquake are all statistically significant with $\alpha>99\%$. When the restricted model fits are removed, the residuals are also greater than 2 times the root-mean-square scatter (Figure 3c). Therefore, from a statistical perspective, the gravitational gradient changes over these distant locations 4 months before the Tokohu earthquake show equally significant excursions as those from the regions near the epicenter, which were interpreted as “preseismic signals” by Panet et al. (2018). They could be real geophysical processes but may also reflect observational noise.

In addition, we want to understand whether or not the anomalous gradient changes are unique to the period before the Tohoku event. To do so, the time nodes t_1, t_{eq}, and t_2 in the regression model (Text S1) are shifted sequentially over time with step size of 1 month, and the significance levels for the existence of anomalous gradient changes for the 4-month period between the shifted t_1 and t_{eq} are tested. As shown in Figure 4, anomalous gradient variations that are as significant as those in the months prior to the 2011 Tohoku mainshock also appear randomly over time in varying locations.

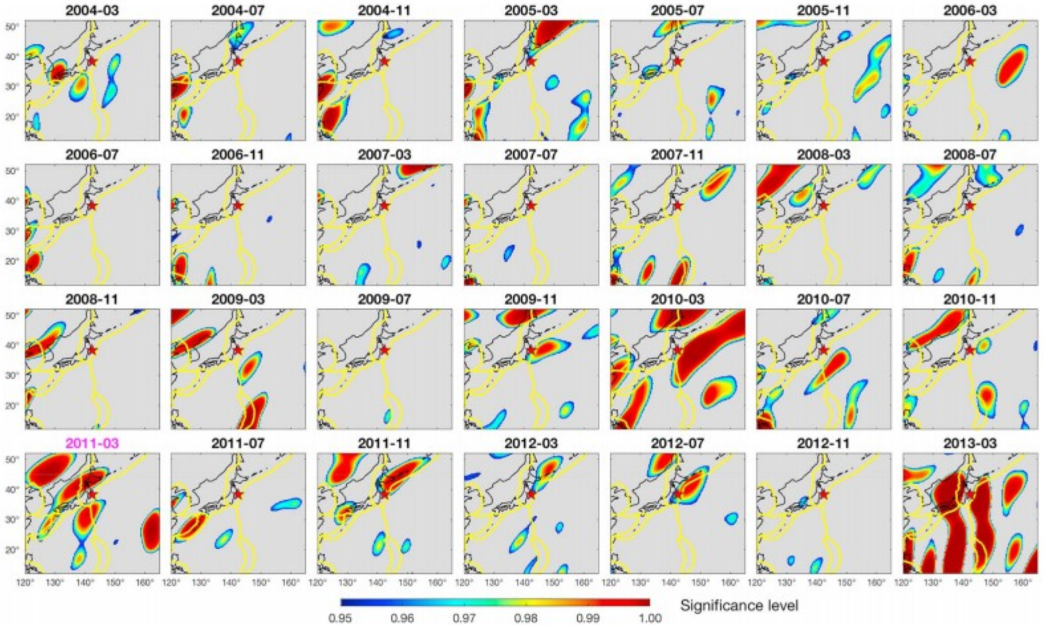

Figure 4. Significance levels for the existence of anomalous gradients $\overline{V'_{yy}}$ with spatial scale of 1,400 km for 4 months before different epochs, which are labeled on top of the plots. The epoch of the 2011 Tohoku earthquake (i.e., March 2011) is labeled in magenta.

In order to better understand whether or not the preseismic changes over Japan are truly associated with geodynamic processes leading up to the

Tohoku earthquake, we also analyze the latest release-06 (RL06) GRACE monthly gravity solution by the Center for Space Research (CSR) at the University of Texas at Austin, which is processed with the latest standards and processing improvements (Bettadpur, 2018). It has been suggested that the CNES/GRGS RL03_v1 solution features erroneous mass signals over the polar regions and overdepressed sectorial terms in the gravity field spherical harmonic coefficients (Lemoine et al., 2015). The hypothesis test is applied in the same way as for the CNES/GRGS RL03_v1 solution. Figure 2 compares the results for these two different solutions. As shown in Figures 2c and 2d, the analysis of the CSR RL06 solution also detects significant gradient anomalies prior to the earthquake. However, their locations are not always the same as those from the CNES/GRGS RL03_v1 analysis (Figures 2a and 2b). Although common features can be found over land, such as west Antarctica and North America, larger differences show up over oceans, including the Indian Ocean, the Pacific, and the Mediterranean. This implies that the different atmosphere and ocean de-aliasing models that have been adopted by CSR and CNES/GRGS for their analyses might play an important role in producing such distinct gradient features over the oceans. Over Japan, the geographic patterns of the significant gradient anomalies from these two solutions are distinct from each other. The analysis of the CSR RL06 solution does not show significant gradient changes over the Japan Sea and Izu-Bonin arc. As shown in Figure 3, in contrast to the analysis of the CNES/GRGS RL03_v1 solution, none of the sample time series of residuals from these two regions (i.e., Points 3 and 4 from the Japan Sea, and Points 5 and 6 from the Izu-Bonin arc) show significant deviations 4 months prior to the mainshock. Significant anomalies are only found over northern Japan. The discrepancies between the two solutions further demonstrate that the detected gradient anomalies may not always be real signals.

3 Discussion

A paradox exists in the study by Panet et al. (2018). On the one hand, they state the preseismic transients are observed from December 2010, but on the other hand, they choose to estimate the transients by setting the initiation time t_1 of the piecewise linear model to an earlier time, that is, June 2010. As Panet et al. (2018) set t_1 to June 2010 and choose to show gradient changes over the 8-month period prior to the Tohoku event (their Figures 1A and 3B), we examine their choice of June 2010 for t_1. As Figure S2 illustrates, the choice of a longer time period for fitting preseismic anomalies results in significant misfits and is thus not justifiable. Indeed, there is no anomalous variation in the data between June 2010 and November 2010 (see Figure S2 of this study, and Figure 2 and Figure S29 of Panet et al., 2018).

One argument used by Panet et al. (2018) to support their conclusion is that the pre-Tohoku signal is significant even by only considering GRACE data up through February 2011 and checking “instantaneous anomalous amplitudes” of the data 4 months prior to the mainshock (see section 2.4 in their supplementary information). However, we find that the same problem we documented above persists. Comparably significant anomalies at the time of the proposed precursor exist within the truncated time series from not only Japan, but other places around the world (see Figure S3).

Panet et al. (2018) detect the proposed preseismic transient gradient change based on a temporal Haar wavelet transformation (Chui, 1992) of the gradient time series. This method is problematic because it only extracts the gradient anomalies that are followed by coseismic offsets, but omits other anomalies despite their comparable or even higher significance levels. In other words, their method matches the preseismic gradient anomalies with coseismic signals, and thus produces preseismic signals that are seemingly unique to both the time and location of the 2011 Tohoku earthquake. Specifically, based on their method, coseismic deformation at epoch t_{eq} can be described by using a Heaviside step function, whose Haar wavelet transform is symmetrical about a peak located at t_{eq} (Figure S2a). Panet et al. (2018) check for the existence of a peak at t_{eq} in the wavelet transform of a given gradient time series, and determine whether or not the time series contains coseismic offset. The peak within the wavelet transformation only exists if the time series contains an offset at a certain epoch. For example, as shown in Figure S2b, if a gradient anomaly occurs at epoch t_1 4 months before the earthquake epoch t_{eq}, but is not followed by a coseismic offset, the wavelet transformation of this anomaly does not have the same symmetric shape (Figure S2b), and thus will not be retained by their method. In contrast, at a location where the gradient anomaly is followed by a coseismic offset, as shown in Figure S2c, its wavelet transform does show a symmetric shape with a peak shifted from t_{eq} to t_1. Panet et al. (2018) searched for this shifted peak and explained it as a preseismic transient signal due to aseismic deformation of the descending Pacific plate slab. However, as shown in Figures 2 and 4, such “anomalies” randomly occur at many times and places, and are statistically no different from the proposed precursory deformation. Whether or not an anomaly would be retained by Panet et al. (2018) depends on if it is followed by a coseismic offset. As a consequence, Panet et al. (2018) only retain those anomalies that by chance overlap the Tohoku coseismic signals, and consequently interpret them as precursory to the mainshock.

An assumption for our hypothesis test procedure is that the GRACE observation noise is Gaussian white noise. However, this assumption does not necessarily hold true for the GRACE gradients time series. As can be seen from Figure 3c, after removing the long-term trend, periodic terms, and coseismic and postseismic deformations, the time series of residuals are apparently correlated in time. Such temporal correlations imply the existence of unmodeled geophysical signals and temporally correlated observation noise, which have been identified based on the stochastic analysis of decade-long GRACE gravity time series (Wang et al., 2016). Therefore, even though the gradient anomalies shown in Figure 2 have been shown to be statistically significant, they do not necessarily reflect real geophysical processes. They are more likely to be temporally correlated observational noise. The identification of the specific causes for the anomalies is beyond the scope of this study.

Panet et al. (2018) consider several first-order models of the proposed mass transfer required to explain the large-scale GRACE signal that should also produce very long-wavelength, centimeter-level surface displacements. However, the GEONET did not capture any clear transients at the invoked spatial (hundreds to thousands of kilometers) and temporal (months) scales (e.g., Yokota & Koketsu, 2015), and intermediate depth slab seismicity did not accelerate during this time (Delbridge et al., 2017).

4 Conclusions

A statistical hypothesis test is applied to assess the uniqueness of an apparent anomaly in GRACE gravitational gradient observations, which initiated 4 months prior to the Tohoku mainshock, and has been interpreted as a precursory aseismic deformation of the descending Pacific plate slab before the mainshock (Panet et al., 2018). The hypothesis test allows quantitive comparison of the statistical significance of the proposed precursory gradient changes over the 2011 Tohoku rupture zone and similar short-term gradient changes that occur at many times and places. Based on our test, the precursory gradient changes proposed by Panet et al. (2018) are not unique either in time or space. In fact, gradient changes with similar or even higher significance levels randomly occur all over the globe, and their geographic patterns change from time to time. These significant gradient changes were omitted by Panet et al. (2018) since their wavelet transform analysis only retains the gradient changes whose locations are linked to the coseismic deformation, and consequently produces “precursory gradient changes” seemingly unique to the Tohoku event. Considering the temporal correlation of the GRACE observation errors, these significant gradient variations in time are unlikely to reflect real geophysical signals. Indeed, based on the analysis of an up-to-date GRACE gravity product (i.e., the CRS RL06 solution), the proposal that there is a precursory signal has little to justify it, as we demonstrate here that it is not unique either in space or time. Although there are still some significant anomalies around Japan in the analysis of the CSR RL06 solution, their geographic extent is substantially different from those found by Panet et al. (2018). Therefore, the gradient changes should not be attributed to the proposed dynamic evolution of the subduction system. Instead, they may just be temporally correlated GRACE observation errors or the signals of other hydrologic, atmospheric, or oceanic processes.

Acknowledgments

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