Total energy of deep low-frequency tremor in the Nankai subduction zone

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Deep low-frequency tremor was first discovered in the Nankai subduction zone of southwest Japan, and is now known to occur in other subduction zones along the Pacific Rim. Because tremor usually occurs simultaneously with short-term slow slip events spatially and temporally, clarifying tremor activity is considered to be an important role to understand the slip process on the megathrust plate interface.

In this study, we estimated the total seismic energy of deep low-frequency tremor in the Nankai subduction zone, southwest Japan, over an 11-year period from 2004 to 2015. For precise estimation of the energy, continuous time sequences of tremor activity were carefully detected using a new procedure designed to minimize false-negative detections. By the result of spatial distribution of accumulated total energy of tremor, we found high-energy area in the western Shikoku region. Tremor activity rate, defined as the yearly average of total tremor energy per unit square, was investigated in each area throughout the Nankai subduction zone. Tremor activity rate averaged in 11 years is very high in near Bungo channel region compared to other regions. In the Bungo channel, the long-term SSE is known to occur at every six or seven years and activate nearby tremor activity. During the analyzing period, the long-term SSE occurred in 2010 and 2014. The tremor activity rate in this region in these two years increases to at least two or three times higher than that of quiescent period without the occurrence of long-term SSEs. This may indicate that external stress perturbations from the source of long-term SSEs in the Bungo Channel increased tremor activity by a factor of two to three. Slip on the plate interface in the tremor source region may be accelerated by nearby long-term SSEs. The relationship between tremor activity and nearby long-term SSEs in the Bungo Channel is consistent with the characteristics of tremor energy. We also note that tremor activity rate in this region is higher than that of other region even in the quiescent period.

In general, the tremor activity rate is high and low in areas west and east of the Kii Channel, where the plate geometry is complicated, respectively. In this comparison, tremor activity rate during quiescent period is used for Bungo channel region. The plate convergence rate shows the same spatial pattern as that for tremor activity. We infer that tremor activity is influenced by accumulated strain due to plate convergence. Strain at the plate boundary may be well accumulated where the plate convergence rate is high; tremor activity begins as a result of accumulated strain. In some areas in eastern Shikoku, the tremor activity rate is extremely low, although the plate convergence rate is relatively high. This may occur because the dip and convergence directions differ. Another possibility is that heterogeneous structures reduce the coupling between subduction rate and strain accumulation. Further investigation of this region is needed to constrain the tremor source mechanism.

Acknowledgement:
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Keywords: tremor, energy, Nankai

Detection of deep low frequency tremor triggered by teleseismic surface wave based on matched filter technique

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Deep low frequency tremor in subduction zone is sometimes triggered by surface waves of teleseismic earthquakes. The triggered tremor can be easily recognized because of its correspondence to each phase of the surface wave whose period is about 30 seconds. The frequency of the triggered tremor is about 1-10 Hz. In Nankai subduction zone in southwestern Japan, triggered tremor was firstly reported for the 26 Sep. 2003 Mw8.3 Tokachi-oki earthquake, and the 26 Dec. 2004 Mw9.0 Sumatra-Andaman earthquake (Miyazawa and Mori, 2005; 2006). Such triggered tremors were observed in subduction zones where ambient deep low frequency tremor occurs associated with short-term slow slip events. However, the triggered tremor is not distributed in all source area of ambient tremor, but is concentrated in several fixed spots. In addition, recent studies have detected triggered tremor in some inland areas within the continental plate away from the subducting plate interface in Hokkaido, Kanto, and Kyusyu area. The triggered tremor and ambient tremor have difference in their activities. In this study, we investigated the relationship between triggered tremor and ambient tremor in detail, using the seismic waveform data.
We first compared the spectrum of tremor triggered by the 11 Apr. 2012 Mw8.6 Sumatra earthquake and that of ambient tremor that occurred at almost the same location in Mie prefecture, Central Japan, by using the waveform data recorded by densely distributed high-sensitivity seismograph network in Japan (Hi-net) operated by National Research Institute for Earth Science and Disaster Prevention. As a result, triggered tremor and ambient tremor showed almost the same spectral property.
Next, we applied the matched filter technique to waveform data with a passband of 2-8 Hz. As template events, we used low frequency events (LFEs) detected by Japan Meteorological Agency in 2014 with the epicentral distance from the triggered tremor of shorter than 30 km. The time length of each template event is five seconds including the arrival of S wave. The cross correlation between 355 template events and three-component waveform data recorded at 10 Hi-net stations including the surface wave of teleseismic earthquake were calculated. Then, we detected similar events to templates by using a threshold for the summed cross correlation coefficients.
We applied the matched filter technique for one hour-length data at 2012 Sumatra earthquake. Although the triggered tremor corresponding to each phase of the surface wave were clearly observed at the beginning part of the arrival of the surface wave from the band-pass filtered seismograms, no event having high cross correlation to the LFE templates was detected. On the other hand, after about 400 seconds from the beginning of triggered tremor, events with high cross correlation were detected. This result may suggest the change in waveform of triggered tremor due to migration during a sequence of triggered tremor.

Keywords: slow earthquake, deep low frequency tremor, triggered tremor, matched filter technique

Estimated the apparent released energy of shallow low-frequency tremor occurred Southeastern Kyusyu through frequency scanning at a single station

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Slow earthquakes, such as tectonic tremors and very-low-frequency earthquake (VLFE), share a common mechanism as shear slip on the plate interface and occur at both ends of updip and downdip of coseismic slip areas. Shallow low-frequency tremors have been observed in the subduction zone off southern Kyusyu [Yamashita et al., 2015].

Yamashita et al. (2015) have detected the shallow low-frequency tremors off southern Kyusyu from ocean-bottom seismometer (OBS) data. Although the seismicity has been documented, the released energy of these tremors has not been calculated. Here we calculate the released energy of tremor sequences off southwestern Kyusyu with applying the frequency scanning analysis [Sit et al., 2012] to OBS data.

Sit et al. (2012) proposed “the frequency scanning analysis” to detect tectonic tremors by calculating ratios of the envelope waveforms through different bandpass filters of broadband data at a single station in the Cascadia margin. We apply this method to the seismic data recorded at 12 short-period OBS stations deployed off southeastern Kyusyu, Japan. Three types of bandpass filters with frequencies of 2-4 Hz, 10-20 Hz, and 0.5-1.0 Hz, corresponding to the predominant frequency band of tectonic tremors, local earthquakes, and ocean noises, respectively, are adopted. When ratio value is over the threshold, we define that the tremor signal is detected in the time window. We estimate the apparent released energy as an approximation that is calculated from the squared amplitude of the median of absolute amplitude within the time window.

We have successfully detected the some sequences with large radiated energy, which correspond to the tremor events reported in Yamashita et al. (2015). In addition, we have also identified other possible sequences of tremors, which have occurred at the further southward that has been reported in Yamashita et al. (2015). The most largest released energy of tremors observed around the southern part of the tremor swarm.

Long-term ocean bottom monitoring of slow earthquakes on the shallow plate interface in the Hyuga-nada region (3)

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The Hyuga-nada region, nearby the western end of the Nankai trough in Japan, is one of the most active areas of shallow slow earthquakes in the world. We have started long-term ocean-bottom monitoring of them in this area from May 2014 using three kinds of sensors: broadband seismometer with pressure gauge (BBOBSP) and short-period seismometer (LTOBS). During the first observation (March 2014 to January 2015), we already reported minor shallow tremor and very-low-frequency earthquakes (VLF) activity and very-low seismicity of ordinary earthquakes within the focal area of shallow earthquakes in the Hyuga-nada. The second observation started from January 2015 using 3 BBOBSPs and 10 LTOBSs, and all sensors were retrieved in January 2016. From the monitoring using land-based seismic observation, many shallow tremors and VLFs occurred just under the OBS network during second observation period, which started from early in May and continued approximately 2 months. We confirmed the existence of these signals in the data recorded by each OBSs. Though the detailed hypocenter determination is still being performed, the observed records strongly suggests that the shallow tremor migrated within the OBS network, which reached at off Cape Ashizuri area where shallow VLFs have been occurred every 6-7 years associated with long-term SSE at Bungo channel. This off Cape Ashizuri’s activity (tremor and VLF) started at the end of May, especially increased activity after the large deep-focused earthquake at Ogasawara region (Mw7.8, 30 May 2015). In the presentation, we will introduce the preliminary result of second observation, in particular focus on the migration of shallow tremor.
Acknowledgements: This study is part of Research project for compound disaster mitigation on the great earthquakes and tsunamis around the Nankai trough region.

Keywords: shallow slow earthquake, Hyuga-nada, Ocean bottom observation

A tentative investigation to detect past activities of deep low-frequency tremor from the paper recording of the Kanto-Tokai observation network for crustal observation

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In the Nankai region, episodes of deep low frequency tremor recur at the intervals of several months. The activity of tremor is detected and monitored by NIED, using Hi-net seismic data. However, other recordings are required to reveal the activity before 2000, as the Hi-net data is available after Oct. 2000. NIED operated the Kanto-Tokai observation network for crustal observation (Okada et al., 2000) from 1979. Seismic stations of this network gradually increased after 1979. Continuous data of vertical component of seismograms has been stored as paper recordings in NIED. At first, we examined whether the recordings are useful to reveal past activities of deep low-frequency tremor. Then, we scanned paper image, and examined the setting to convert the paper recordings, as the paper recordings now causes a trouble in the storing space.
Short-term slow slip events (SSEs) in the Tokai region from 1984 are detected and reported by Kobayashi et al. (2006), using a tiltmeter. We checked the recording around the period of the reported SSEs, and found signals dominant in several Hz with the amplitude of several hundreds of nm/s at some stations (e.g., SMY, KSH, and TOE) in the Tokai region. This is characteristic to the deep low-frequency tremor detected from Hi-net data. For example, the signal is found in SMY, from 13 to 16, Aug., 1984, from 4 to 5, Dec., 1986, and from 8 to 10, May, 1987, while SSEs are reported from 13 to 14, Aug., 1984, from 3 to 4, Dec. 1986, and from 8 to 10, May, 1987, respectively. The several-days difference of the activities between tremor and SSE may be attributed to the spatial migration of tremor and SSE, as the SMY station is about 20 km north from the tiltmeter station.
We examined the digitization of paper recordings. We need to choose appropriate settings (e.g., resolution) in the conversion to image files. Paper feeding speed is 4 mm/s and amplitude of 336 nm/s is scaled to 1 mm on the paper of the recording of SMY. If the resolution is 300dpi, one pixel is about 0.085 mm. This means that temporal resolution is about 47 samples/s, and minimum resolution of velocity is about 28 nm/s. This is sufficient to recognize low frequency tremor. We note that this value is not common in this network, as the settings are different at each station. In terms of color, even the black and white color is sufficient, as the outline of pen is clear.
It takes five minutes to convert images of 1 day. As the observation at SMY started from May 1980, it takes more than 600 hours to convert 20-years data. Much work is required to convert all of paper recordings, as the number of stations is 66 even in 1985, while this data is significant and cannot be replaced.

Keywords: deep low-frequency tremor, paper recording, slow slip event

Detection of shallow very low-frequency earthquake using a grid-based, fixed focal-mechanism method

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Recent observations of shallow very low-frequency earthquake (sVLFE) show the large-scale migration of activity and the simultaneous occurrence with shallow tremor, indicating sVLFE and shallow tremor are induced by background shallow slip event as is the case with the deep slow earthquakes (Asano et al. 2015; Yamashita et al. 2015). Understanding the relationship between the shallow slow earthquakes along the Nankai trough is important in view of occurrence of the future Nankai great earthquake.

In September 2006 a major activity of deep very low-frequency earthquake (dVLFE) and deep tremor occurred in the Bungo Channel and western Shikoku region. This activity is considered to be induced by a small long-term Bungo Channel slow slip event (SSE) because small surface displacements were also observed in GPS records. It is known that large long-term Bungo Channel SSE induces high sVLFE activity in the Hyuganada region (Hirose et al. 2010). Therefore sVLFE activity is expected to be observed also in Sept. 2006.

In this study we applied the grid-based, fixed focal-mechanism method (Suda et al. 2014) to detection of sVLFE in the Hyuganada region. We analyzed the F-net data from 33 stations between August 20 and September 30, 2006. We used only the F-net data because one purpose of this study is to check the feasibility of real-time monitoring of sVLFE using JDXnet data, which include no Hi-net accelerometer data.

We detected over 90 events in the analysis period. The main activity occurred in August 28-31 and only a small number of events occurred in September 7-21 when the activity of dVLFE and deep tremor occurred. This observation is in contrast to that the 2010 sVLFE activity in the Hyuganada region occurred in the acceleration stage of dVLFE and deep tremor activity in the Bungo Channel and western Shikoku region. The present observation suggests that a possible SSE that induced dVLFE and deep tremor in September 2006, if any, was not large enough to induce the high sVLFE activity in the Hyuganada region. The sVLFE activity observed in August might be due to a local shallow SSE.

Keywords: slow earthquake, shallow very low-frequency earthquake, Hyuganada

Distribution of low frequency earthquakes accompanied with very low frequency earthquakes along the Ryukyu Trench

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We investigated the long-term distribution of low frequency earthquakes (LF) which are accompanied with very low frequency earthquakes (VLF) in the Ryukyu Trench. The VLFs occur regularly by the accumulation of short-term burst-type swarms (about 1-4 days) along the Ryukyu Trench. Takahashi et al. (2015) detected the LFs accompanied with the VLFs using ocean bottom seismometers in the southwestern Ryukyu Trench. However, the long-term distribution of the LFs has not been known along the Ryukyu Trench. Then we detected the LFs for long-term and determined the hypocenter distribution in the Yaeyama and Okinawa region.
First we analyzed the long-term appearance of LFs accompanied with the VLFs. We hi-pass-filtered (1 Hz) to the waveforms of F-net (NIED) seismograms. Then we checked manually whether the LFs are found in the seismograms. The results showed that the appearance of the LFs is from 2 (Amami area) to 16% (Yaeyama area) along the Ryukyu Trench from 2004 to 2013. The LFs were successfully detected when the magnitudes of the VLF is over 4.0, whereas they were not found when the magnitude of the VLF is less than 3.7. Small amplitude of LF would be obscured by noise if magnitude of the VLF is small though LF would be always accompanied with VLF.
Next we determined the hypocenter of the LFs. For the hypocenter determination, we used the short-period seismometers by Japan Meteorological Agency (JMA) in the Ryukyu arc. First we selected the swarm of VLFs using the VLFs catalogue by Nakamura and Sunagawa (2015). Then we analyzed the waveform of the JMA seismometers. The surveyed period is from 2004 to 2013. We analyzed the data in the Yaeyama and Okinawa region where is near the cluster of the VLFs (Nakamura and Sunagawa, 2015). We picked the relative arrival time difference among the stations automatically using envelope cross-correlation method (Obara, 2002). We composited the horizontal waveforms and computed the RMS amplitude with 10 s average. We computed the cross-correlation for each network and we determined the hypocenters when the at least 4 stations satisfy the cross-correlation over 0.85. We used the S-wave velocity structure for the hypocenter determination because the phases are dominant with S wave.
The results show that the epicenters are distributed between south of Yonaguni Island and south of Iriomote Island in the Yaeyama area. Almost events are located between the Ryukyu Trench and Ryukyu arc. Since hypocenters are located out of the seismic network and only S phases are used for the calculation, estimation errors for the NS and EW direction are 70 km and 30 km, respectively. However, the distribution of the LF along the trench direction are similar to those of the VLFs which is estimated using semblance method (Nakamura and Tu, 2015). This suggests that the LFs occur in the similar region as VLFs in the Yaeyama. The LFs are found with accompanied with the occurrence of the large VLFs. The occurrence of the isolated LFs is rare. Moreover, the hypocenters of the LF concentrate at the southeast of south Okinawa Island and southeast of Okinoerabu Island in the Okinawa island area.
The hypocenters of the swarm of LF concentrate at the diameter of approximately 40 km in the Okinawa and Yaeyama areas. The migration of the hypocenters of the swarm activity was not found in the Okinawa and Yaeyama areas. This suggests that the distance of the migration of large LF was limited within 40 km if the hypocenters of the LF swarm migrate.

Keywords: very low frequency earthquake, low frequency earthquake, Ryukyu Trench

Swarm of shallow very low frequency earthquakes in the Bungo channel region in 2015 observed by temporal broadband seismic stations in the Shikoku island, southwest Japan

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The Bungo channel region in southwest Japan is one of regions where various types of slow earthquakes are observed at the top surface of subducting Philippine Sea plate. The slow earthquakes includes (i) long-term slow slip events (SSEs) at depths around 30 km and short-term SSEs at deeper depths recorded by geodetic instruments, (ii) shallow/deep low frequency tremor recorded by short-period seismometers at 1-10 Hz, (ii) and shallow/deep very low frequency earthquakes (VLFEs) recorded by broadband seismometers at 10-100 s. Although the coincidence of long-term SSEs and shallow VLFEs indicates relationship between them, there still exists a gap area between their estimated source areas without detection of any slow earthquake at this moment. For further understanding of slip distribution at the plate interface, we installed one Guralp CMG-3T (100 s) broadband seismometer and two Nanometrics Trillium (120 s) broadband seismometers in the southwestern part of the Shikoku island in February 2015 and June 2015, respectively. The observation plan at least continues to 2020.
The preliminary records showed seismic waves from shallow VLFEs activated in early June 2015. The data quality of vertical components was comparable to that of permanent stations of F-net broadband seismograph network operated by National Research Institute for Earth Science and Disaster Prevention at a period range of 20–50 s. We first applied the GRiD MT method (Tsuruoka et al. 2009) to records of 18 F-net stations as well as three new stations on June 8th filtered at a period range of 20–50 s for determining location and focal mechanism of each VLFE. We then applied the matched filter technique (Shelly et al. 2007) to detect similar events for eight months from May to December in 2015 by using a Mw4.1 event as a template event. The total number of detection is 1,476. We also determined the amplitude and location of each event with respective to the template event by grid search and waveform fitting.
The space-time plot of detected events showed two migrationg sequences of shallow VLFEs from southwest to northeast for two times, and several rapid reversal movements in June 2015. The cumulative number plot of time interval between adjacent events shows power-low distribution, which is different from exponential distribution for normal earthquakes and may characterize the swarm-like activity of VLFEs. The cumulative number of amplitude could be explained by both exponential and power-low functions due to limited range of amplitudes. Further discussion about the detection level for small amplitude is needed to conclude which function better explains the obtained distribution.
We also applied various band-pass filters to the waveforms at the time-windows aligned by the origin time of detected events. As a result, we could observe coherent signals between each time-windows at a period range of 10–100 s. Since the data quality was limited especially at periods longer than 50 s, we improved the signal-to-noise ratio by calculating station-averaged waveforms for each event. The averaged waveforms showed constant phase shifts between each time-windows at least at a period range of 20–100 s. This result indicates that the moment release function of each VLFE has a typical duration less than ~20 s.

Keywords: Very low frequency earthquake, Southwest Japan, Broadband seismic observation

Shallow very-low-frequency (VLF) earthquake activities along the Nankai trough in 2015

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In 2015, we observe shallow very-low-frequency (VLF) earthquakes along the Nankai trough by DONET, a permanent ocean-floor observation network. The activity started off the Shiono-misaki in August, which is followed by the activity off the Kii channel in September. In October the activity moved beneath the Kumano fore-arc basin. I investigated their source location and mechanism. Previous VLF activities along the Nankai trough are observed in 2004 (Obara and Ito, 2005), 2009 (Sugioka et al., 2012), and 2011 (To et al., 2015).
I determined the source location and mechanism of the VLF events by a waveform inversion using the SWIFT system (Nakano et al., 2008). Bband-pass filtered waveforms between 20 and 30 s, of which VLF signal is dominant, are used for the inversion.
Obtained CMT solutions show that the VLF sources are concentrated in several clusters located off the Kii channel, off Shiono-misaki, and Kumano fore-arc basin. These clusters well overlaps those reported by Obara and Ito (2005). The sources in the Kumano fore-arc basin can be divided into two clusters, which are located east and west of the previous major activity reported by Sugioka et al. (2012).
The source depth is between 7 and 10 km, corresponding to the base of the accretionary prism. The focal mechanism solutions represent low-angle thrust; one of the nodal planes is almost horizontal and the slip direction is almost perpendicular to the dip of slope of the sedimentary wedge. These results infer that the VLF events are caused by a slip along the plate boundary beneath the accretionary prism. We note that the dip of slope of the sedimentary wedge above the cluster off the Kii channel rotates about 60 degrees eastward due to the subduction of a seamount, but the rake angle of the obtained focal mechanism is very similar to those in the other clusters.
The obtained magnitude is at most about 4. The b-value obtained from the frequency-magnitude distribution is 2.4, inferring low stress level at the source.
I found that the occurrence of each event corresponded to minimal (not always the minimum) of ocean-bottom pressure caused by the ocean tide observed at DONET stations. This feature is evident in the activities off the Kii channel and off the Shiono-misaki. The correspondence to the low pressure was not evident in the activity beneath the Kumano fore-arc basin because of the swarm activity, although several events before the swarm activity corresponded to minimal of ocean-bottom pressure.
Assuming almost horizontal fault plane for the VLF sources, unclamping the fault by the decrease of hydrostatic pressure would promote VLF events. The tidal pressure change is about 10 kPa, comparable to the stress drop estimated for VLF earthquakes (Ito and Obara, 2006), which would be enough to perturb the state of stress at the source. But the truth would not be as simple as this because several of VLF events did not occur at minimum of the pressure. Combined effect of tidal force and external loading, a proposed model for deep non-volcanic tremor (e.g. Nakata et al., 2008; Ide and Tanaka, 2014), would be necessary to model the trigger of VLF earthquakes.

Keywords: DONET, off Kii channel, off Shiono-misaki

Investigating the relationship between slow-slip events and tremor in the Shikoku region, Southwest Japan

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In the subduction zone of Southwest Japan, Obara (2002) discovered nonvolcanic tremor, which is characterized by longer duration than regular earthquakes. After this discovery, other new slip phenomena at the plate boundary, characterized as well by longer durations, have been discovered in subduction zones around the world. These phenomena are collectively known as “slow earthquakes”. Understanding of slow earthquakes is an important issue for understanding the physics of subduction zones and may help the risk assessment of huge earthquakes. Fortunately, by the strengthening in recent years of the observation networks, the routine analysis of slow earthquakes is becoming possible and open observation data are being made available.
In this study we analyze and discuss the characteristics of slow earthquakes by using catalog data which have been newly developed in the recent years in the Shikoku region. This area has a new catalog of SSEs (Nishimura *et al.*, 2013; Nishimura 2014) and tremor (Idehara *et al.*, 2014).
Our results show that in the Shikoku region, almost all of the short-term SSEs (S-SSEs), which were detected by Nishimura (2013, 2014), synchronize with tremor activity. Assuming that tremor activities reflect the destruction of small patches on the SSE fault, we observe a consistent relationship of linear increase in the duration of the activation of tremors with the moment of SSEs. This result is in agreement with the scaling law of SSEs (Ide et al., 2007) and observation case of long-term SSEs (L-SSEs) (e.g., Miyazaki *et al.*, 2006). In addition, the calculation of the magnitude of L-SSE by using the tremor activation period during the periodic L-SSEs at Bungo Channel and the scaling law obtained in this paper is consistent with geodetic observations (Yoshioka *et al.*, 2015).
The obtained results suggest that the space-time pattern of tremor is well explained by SSEs characteristics and that the tremor can be used as a proxy for the detection of SSEs.

Keywords: ETS, tremor, scaling law of SSEs

Relationship between coupling and tremor rate in the region adjacent to the Bungo Channel SSE area

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In the Bungo Channel area, southwestern Japan, repeating long-term slow slip events (SSE) occur every several years. The recent events before 2011 occurred in 1997, 2003 and 2010 in almost the same area. Along the Nankai subduction zone, which contains the Bungo Channel area, deep low-frequency tremor activities occur on the subjecting plate interface. Hirose et al. (Science, 2010) shows the relationship between the tremor and SSE that the tremor in the northern part of the SSE area was activated by the SSE.
Ochi (EPSL, 2015) analyzed daily GNSS coordinates from 1997.0 to 2011.0 and inferred temporal evolution of the interplate coupling and long-term SSE. According to the results, the interplate coupling in the region on the east of the 2010 Bungo Channel SSE area strengthened in synchronization with the SSE. On the other hand, AIST makes the tremor catalog in this area after July 2008 using envelope correlation method (Maeda and Obara, JGR, 2009). According to the tremor catalog, the tremor active rate in this region increased after 2011 when the long-term SSE terminated. The increased active rate continues around mid-2014 and decreased to the level that was almost the same as before 2011. Because the long-term SSE occurred again after mid-2014 (GSI, Report of CCEP, 2015), decrease of the tremor active rate seems to coincide with the long-term SSE in the adjacent area. We will discuss the relationship between coupling rate after 2011 and the tremor active rate in this region.

Keywords: Slow earthquake, deep low-frequency tremor, interplate coupling

Short-term Slow Slip Events in the Kanto Region, Central Japan Detected Using GNSS Data

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The Kanto region, central Japan is situated under complex tectonics where the Philippine Sea and the Pacific plates subduct from the Sagami Trough and the Japan Trench, respectively. Several large earthquakes including the 1923 M7.9 Kanto earthquake historically damaged the Kanto region. Shallow short-term slow slip events (SSEs) were observed by continuous GNSS east off the Boso Peninsula in 1996, 2002, 2007, 2011, and 2014 [e.g., Ozawa *et al.*, 2014]. These Boso SSEs with M_w ~6.6 occurred on the Philippine Sea plate in a depth of 10-20 km. Some studies reported that SSEs occurred on the Pacific plate. However, spatiotemporal distribution of SSEs remains unclear in the Kanto region. In this study, we accomplish systematic searches for SSEs along both the Sagami Trough and the Japan Trench using GNSS data.

An operation of a continuous GNSS network was started in 1994 in the Kanto region. We estimate daily coordinates at all available stations operated by the Geospatial Information Authority of Japan and the Japan Coast Guard using GIPSY 6.2 software. We apply the method of Nishimura *et al.* (2013) and Nishimura (2014) to detect a jump associated with short-term SSEs in GNSS time-series and estimate their fault models from observed displacements. A rectangular fault on the Philippine Sea or the Pacific plates is assumed for each SSE. The stacking of GNSS time-series based on the displacement predicted by the fault model [Miyaoka and Yokota, 2012] enable us to estimate duration of SSEs. For SSEs on the Philippine Sea plate, five Boso SSEs are detected with duration of 9-13 days. Although the largest SSE with M_w6.7 is detected far east off the Boso Peninsula, no apparent seismicity is observed. The duration of the SSE is estimated to be 23 days, which is longer than the Boso SSEs. The longer duration may be a cause of no seismicity related with the SSE. For SSEs on the Pacific plate, we found 24 SSEs. Their moment magnitude ranges between 6.0 and 6.4. Many SSEs are clustered near the eastern rim of the overriding Philippine Sea plate. This may reflect on a difference of interplate coupling controlled by geology of the overriding plate [Uchida *et al.*, 2009]. It is also suggested that the SSE cluster corresponds to a subducted seamount induced from a bathymetry.

Keywords: Slow Slip Event, GNSS, Kanto region

Long-term slow slip events beneath the Kyushu Island

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A transient deformation in the Kyushu Island from January to April 2014 was detected by GNSS observation network in Japan. We estimated slip distributions at the plate boundary between the subducting Philippine Sea Plate and the continental plate from that GNSS data. Two slipped areas were estimated beneath the Kyushu Island. The south slip area corresponds to the Hyuga-nada SSE area. The north slip area corresponds to the gap area between the Bungo-channel SSE and the Hyuga-nada SSE, that has not been reported long-term SSE previously. We also found that long-term SSEs occur in the gap area repeatedly before the 2014 event.

Keywords: long-term SSE, Bungo-channel, Hyuga-nada

Comparison of the spatio-temporal evolution of slow slip events in the Yaeyama Islands, southwestern Japan

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Along the Ryukyu Trench, the most southwestern part of Japan, no historical records of large thrust type earthquakes (Mw > 8.0) exist for the last 300 years (Ando et al. 2009) and therefore it is assumed that subduction zone in this region are aseismic. However, a tsunamigenic normal fault type earthquake occurred in 1771 around the Yaeyama Islands and its source region was estimated in the shallower part of the Ryukyu Trench from the tsunami heights (Nakamura 2009a). Recently, very low frequency earthquakes (VLFEs) were detected from a broadband seismic network along the trench (Ando et al. 2012). On the other hand, Heki and Kataoka (2008) reported that slow slip events (SSEs) had repeatedly occurred with a recurrence interval of about six months along the southwestern Ryukyu Trench. They estimated simple time-independent fault model for the SSEs assuming a planar rectangular fault with spatially uniform slip around the Iriomote Island by analyzing GNSS data at eight GEONET stations. However, the spatio-temporal evolution of SSEs has not been investigated.
We have developed four GNSS stations in the Yaeyama Islands in 2010 in addition to eight GEONET stations to clarify the characteristics of the subduction zone along the southern part of the Ryukyu Trench. Because no large earthquakes recently occurred in this region, it is expected that the GNSS observations contain signals of SSEs that are not contaminated by earthquakes although some meteorological phenomena such as typhoon may affect the observations. In this study, we apply a geodetic time-dependent inversion scheme to these GNSS data to clarify the spatio-temporal evolution of the SSEs and its relation to VLFEs.
Data period used in this study is between March 2010 and July 2013. GNSS data from the 12 stations are processed with the GIPSY-OASIS II software. As a result, 5 SSEs were detected during the period. First of all, we remove the trend from each time-series. Then we conduct a geodetic time-dependent inversion using the detrended time-series to infer the spatio-temporal evolution of slip during each event. For this purpose, we employ a modified Network Inversion Filter (NIF) which is based on the Monte Carlo mixture Kalman Filter (MCMKF, Fukuda et al. 2004, 2008). This method is an improved version of the standard NIF (Segall & Matthews, 1998) and is able to extract slow slip signals without oversmoothing or undersmoothing of estimated slip.
The estimated temporal evolution of moment rate suggests that the first event initiated around 10 August 2010 and lasted for about 40 days and the moment magnitude is estimated as about 6.75. The main slip region locates at the northwestern part of the Iriomote Island and the maximum magnitude of slip is about 10 cm, which is consistent with Heki & Kataoka (2008). The resolution of slip below the Iriomote Island is improved by adding the four new observations, and hence no slip is inferred at the southeastern part of the Iriomote Island at depths of about 30 km where some amount slip is inferred without the four new stations. We find that the passage of a typhoon in the summer of 2010 affected the GNSS position estimates. We thus removed the data during that period to avoid the estimated slip to be affected by the typhoon. In the presentation, we will also show the results for the four other SSEs between 2010 and 2013 and compare the spatio-temporal evolution among the five SSEs.

Keywords: slow slip event, Ryukyu Trench, time-dependent inversion, GNSS

Automated detection of slow slip events from tilt and strain data

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In subduction zones such as Nankai and Cascadia, various types of slow earthquakes have been detected using dense geodetic and seismic observation networks. Kimura et al. [2011] developed an automated detection method for the identification and location of short-term slow slip events (SSEs) within the Nankai region using continuous tilt data observed at NIED Hi-net stations. Recently, AIST has constructed a borehole strainmeter network around the Shikoku and Kii peninsula regions, and these strainmeters are generally more sensitive to short-term SSEs than the Hi-net tiltmeters [Itaba, et al. 2010]. In this study, we apply the automated detection method of SSEs not only to the tiltmeter data but also to the strainmeter data in order to enhance the detection capability and improve the accuracy in the SSE model.
We evaluated the capability of detecting short-term SSEs in Shikoku using the strength of the white and random-walk noises estimated for each geodetic time-series data [Kimura et al. 2011]. The comparison between the capability using tiltmeter data and that using both the tiltmeter and strainmeter data indicated that the addition of the strainmeters enhances the detection limit by 0.1-0.2 in the magnitude of SSEs in the Bungo channel and western and central Shikoku regions. On the other hand, in the eastern Shikoku region, the detection capability does not change significantly because strainmeter stations are relatively far from short-term SSE source area.

Keywords: Slow slip event, strainmeter, tiltmeter

Magneto-telluric monitoring for probing changes in crustal resistivity associated with slow earthquakes

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In southwest Japan, various slow earthquakes such as deep low-frequency tremor, deep very-low-frequency earthquake, and short-term slow slip events occur at the subducting plate interface (e.g. Obara, 2002, Scinence; Ito *et al*., 2007, Science; Hirose and Obara, 2005, EPS). To understand their mechanisms by probing the associated structural changes around the plate interface, we have been carrying out continuous magneto-telluric (MT) observations in western Shikoku, Japan since 2008. MT survey along the dip direction of subducting Philippine Sea plate revealed an existence of low-resistivity structure in the lower crust in this region (Yamashita and Obara, 2009, AGU). Two observational sites KBN and SGW were installed on the survey line. The observation at SGW terminated and representative observation at IKT, which is about 10 km away from the survey line, has started in 2010. Qualities of the data recorded at these sites are relatively fine. However, to further improve the quality, we are applying a data processing method same as Honkura *et al*. (2013, Nat. commun.); we use only data whose coherency between electric and magnetic field is higher than a threshold. Using the high-quality data, we estimate daily MT parameters, apparent resistivities and phases at nine frequencies from 0.00055Hz to 0.141Hz. As a result of the careful data analysis, we found some temporal changes in MT parameters. They should not be originated from a noise but the structural change in crust, because amounts of the changes in apparent resistivity and phase over nine frequencies are consistent with the theoretical relation in MT method. In addition, those temporal changes are common among two observational sites. We further found that the changes in the MT parameters looked correlated with the activity of the deep low-frequency tremor beneath the observational sites. Based on the surveyed resistivity structure, we will further investigate amount and location of the resistivity changes.

Keywords: Slow earthquake, Crustal resistivity, Magneto-telluric monitoring

Continuous measurements of S-wave splitting parameters for monitoring of seismic anisotropy

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In this study, we approach an unsolved question with respect to mechanisms of triggering and synchronization among members of a family of slow earthquakes using seismic anisotropy. The study area is the Nankai trough subduction zone, southwest Japan. In this presentation, we mainly focus on a tremor activity from 2015/12/26 to 2016/01/05 beneath eastern Shikoku.
Features of seismic anisotropy are attributed to characteristics of stress state, structure, and physical properties of the medium. A study of seismic anisotropy using slow earthquakes can, therefore, provide physicochemical, geometrical and mineralogical information in their source regions and along the ray paths. In our previous study, we focused on one of a slow earthquake, deep low frequency earthquakes (DLFEs), reported by JMA. Ishise & Nishida (2015 JpGU) investigated S-wave polarization anisotropy using DFLEs and tried to detect temporal variation of seismic anisotropy in the source region of DLFEs in the Nankai trough subduction zone: S-wave splitting analysis (Ando et al., 1983 JGR) was applied to S-phases of DFLEs picked by JMA. However, the seismicity of DLFEs was too low to show the temporal variation of anisotropy. Ishise & Nishida (2015 SSJ), then, applied S-wave splitting analysis continuously to continuous waveform data including DLFEs analyzed in our previous study and continuously measured S-wave splitting parameters in order to detect temporal variations of seismic anisotropy during the tremor activities. Since tremor signals are inferred to be composed of S-waves primarily, we can obtain S-wave anisotropy during the tremor activity. A similar analysis provided crustal anisotropy beneath northern Cascadia (Bostock and Christensen, 2012 JGR).
In this study, we applied the S-wave splitting analysis to filtered seismograms (2-8 Hz) and determined the polarization direction of fast S-wave and the delay time between fast and slow S-waves. The time window and time step of the continuous analysis were 60 and 30 seconds, respectively. Together with the anisotropy monitoring, we performed polarization analysis to estimate the incoming wave. Following Bostock and Christensen (2012 JGR), assuming S-wave incidence, we estimate back azimuths and incident angles.
The continuous measurements of splitting parameters showed the relatively smaller variability of the parameters and high reliability of the estimated anisotropic parameters when strong tremors were recorded. In a similar manner to splitting analysis, polarization analysis provides reliable estimation when strong tremors are recorded because it assumes S-wave incident during the polarization analysis. Actually, we found a number of clear temporal variations of back azimuth of the incoming waves that were synchronized between more than one stations. Judging from the intensity of the tremor signals, the temporal variations suggest processes of tremor migration.
As for characteristics of anisotropy, we found that polarization directions of fast S-wave tend to fluctuate around the strike directions of geological lineaments (from SW–NE to NW–SE). It suggests that the surface anisotropy would prevent from detection of deeper anisotropy. At the same time, we observed clear temporal variations of anisotropic parameters at stations near the center of tremor activities. The temporal variations of anisotropy tended to synchronize with those of parameters of incoming waves. The temporal variation of anisotropic parameters can, therefore, be explained by spatial variations of seismic anisotropy. In order to achieve our purpose to detect temporal variation of seismic anisotropy in tremor source region, we need more case studies through retrospective analyses.

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Keywords: monitoring of seismic anisotropy, deep low frequency tremor

Laboratory-observed slow frictional slip instabilities in Tohoku plate boundary fault zone samples

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The plate boundary megathrust at the Japan Trench has exhibited remarkable slip behavior that has drastically changed our understanding of fault slip behavior. The 2011 Tohoku-Oki earthquake produced an extraordinarily large amount of coseismic slip (several 10’s of meters) up to the seafloor, on a portion of the megathrust previously thought to be aseismic. Additionally, this region is also known to generate slow earthquakes. One of these slow earthquakes occurred with the rupture area of the 2011 Tohoku earthquake; this event was observed one month before the 2011 earthquake and was likely ongoing during the earthquake. This shows that the Japan Trench megathrust does not exhibit strictly stable slip and thus failure can occur in a variety of styles. During Integrated Ocean Drilling Program Expedition 343, the Japan Trench Fast Drilling Project (JFAST), samples of the plate boundary fault zone in the Tohoku region were recovered ~7 km from the Japan Trench axis, within the region of largest coseismic slip during the 2011 Tohoku earthquake. We sheared these samples in laboratory friction experiments utilizing a slip velocity of 2.7 nm/s, equal to the convergence rate between the Pacific and North American plates (85 mm/yr). One key observation is that infrequent strength perturbations occurred which are interpreted to be laboratory-generated slow slip events (SSE). For intact samples, these events have stress drops of ~50-120 kPa that occurs over several hours. The stress drop matches the estimated stress drop of the SSE that occurred prior to the 2011 Tohoku earthquake. Peak slip velocities of the laboratory SSE reach 10-25 cm/yr, comparable to observations in natural subduction zone SSEs worldwide. Displacement records indicate a slip deficit accumulation prior to the laboratory SSEs which is recovered during the subsequent stress drop. The laboratory SSEs tended to occur more frequently in intact samples rather than powdered samples, suggesting that the intense scaly fabric is favorable for the SSEs. Velocity-stepping tests also reveal velocity-weakening frictional behavior, suggesting that the laboratory SSEs are slip instabilities or quasi-instabilities. This is supported the observation that in powdered samples, very large SSEs appear at 16 MPa effective normal stress whereas they are mostly absent at 7 MPa. This is consistent with critical stiffness theory, in which increased effective normal stress is associated with an increased likelihood of slip instability.

Keywords: Slow slip, rock experiment, The 2011 Tohoku-Oki Earthquake

