# Water depth dependence of correlations in nontidal variations of ocean bottom pressure measurements and ensuing development of methods to detect slow slip events from the seafloor deformation signal

（海底圧力記録中の非潮汐成分における相関の水深依存性と
それに基づくスロースリップイベント検出手法の開発）

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## 1. Introduction

Since the 1990s, slow earthquakes have been found in many subduction zones worldwide and have been recognized as a common phenomenon found in subduction zones (Hirose et al., 1999; Ito et al., 2007; Linde et al., 1996; Obara, 2002; Ozawa et al., 2004). Slow slip events (SSEs) are a type of slow earthquake observed on geodetic time scales of several days to several years. Some SSEs have been detected in the northern Hikurangi subduction zone with relatively large signals, predominantly in both offshore and onshore geodetic time series (Wallace et al., 2016; Woods et al., 2020, 2022). Offshore and onshore geodetic observations revealed that the SSE that occurred off the coast of Gisborne in September 2014 extended to a depth of approximately 2 km from the seafloor to the plate boundary and that the slip amount of the SSE was relatively small around the seamounts (Wallace et al., 2016). In general, the use of seafloor geodetic measurements enhances the details of slip distributions of SSEs occurring in shallow subduction zones.

Techniques for seafloor geodetic measurements, such as acoustic ranging including direct-path ranging and GNSS-acoustic (GNSS-A), tiltmeters, and ocean bottom pressure gauges, are useful tools for observing shallow SSEs in subduction zones. In this thesis, we focus on ocean bottom pressure gauges (OBP) that can observe seafloor crustal deformation due to SSEs as changes in the seafloor pressure. The OBPs also observe oceanographic components, including short-period tides of fewer than 2 days, long-period tides of more than 2 days, and nontidal components driven by wind and surface air pressure fluctuations. As the period and amplitude of the observed nontidal components are similar in the duration and amplitude of pressure changes due to SSEs, the nontidal components of the observed pressure data should be removed before calculating a slip model of SSEs from OBP data (Muramoto et al., 2019).

To date, several methods have been proposed for the removal of nontidal components. These methods can be divided into two categories: subtracting an oceanographic model from sites on the landward slope of the trench (e.g., Muramoto et al., 2019) and taking differences in pressures between sites (e.g., Wallace et al., 2016; Fredrickson et al., 2019; He et al., 2020). In most previous studies considering differenced pressures, the nontidal spatial variations have been considered to change depending on the inter-site distance. After processing for nontidal variations by assuming the dependency on inter-site distance, the processed time series in the previous study still showed fluctuating signals due to nontidal variations.

The origin of the nontidal variations observed in the OBP data is still an open question. To understand the origin of nontidal variations, we investigated the spatiotemporal characteristics of nontidal variations using seafloor pressure data installed in subduction zones. Furthermore, we evaluated several methods for the removal of nontidal variations in seafloor pressure data, using the detectability of SSEs in each method.

## 2. Data acquisition and primary processing

We used self-popup OBPs installed in the Hikurangi subduction zone of New Zealand and those connected to cable seafloor observatories installed in the Nankai subduction zone of Japan. In the Hikurangi subduction zone, we used 15 ocean bottom pressure gauges from an international collaborative research project, the Hikurangi Ocean Bottom Investigation of Tremor and Slow Slip (HOBITSS). In the Nankai subduction zone, we used 29 OBPs on the Dense Ocean floor Network System for Earthquakes and Tsunamis (DONET2) installed off the coastline of the Kii Peninsula and off the coastline of Muroto.

As the fundamental principle for measuring pressure, the pressure sensor counts the oscillation frequency changes in high-precision quartz. The oscillation frequency of the quartz oscillator varied with externally applied pressure and temperature. Therefore, the pressure on the seafloor can be measured by recording the oscillation frequency at constant time intervals, calibrating it with water temperature, and converting it to pressure using equations (Paroscientific, 2014).

Raw OBP data with a sampling rate of 100 Hz and 0.5 Hz were averaged to the hourly data, and the average of an entire time series was subtracted from the time series equivalent to subtracting the pressure according to the installation depth. To remove short-period tides, we used the 48-hours tide killer filter (Hanawa & Mitsudera, 1985) as a low-pass filter. The primary processing of the OBP installed in the Nankai Trough is the same as that of the Hikurangi subduction zone, except for the processing of missing data. The hourly pressure data were averaged from raw data with 10 Hz sampling. The processed pressure time series were used as data on pressure changes due to instrumental drift, nontidal variations, long-period tides, and SSEs in this thesis.

## 3. Water depth dependence of long-range correlation in nontidal variations in seafloor pressure

We evaluated the characteristics of nontidal components in seafloor pressure in terms of the dependence on the installed depth difference between sites and the dependence on the distance between sites. To evaluate the similarity between all pairs of OBP data in the HOBITSS experiment and DONET2, we adopted two statistical quantities: (i) the standard deviation of the residual pressure between a pair of sites and (ii) correlation coefficient between a pair of sites. To investigate the characteristics of nontidal variations, we focused on time windows that did not include the signals of SSEs.

As a result, the nontidal components observed on the OBPs in the HOBITSS network showed strong similarities between site pairs at similar water depths (e.g., within 500–1,000 m of each other). In contrast, very little dependence of the SD on the horizontal distance between site pairs (maximum distance between sites ~75 km) was noted, as no significant increase in the SD as a function of the inter-site distance was observed. As in the Hikurangi subduction zone, nontidal components in the OBPs in DONET2 showed strong similarities between site pairs at similar water depths. However, very little dependence of SD on the horizontal distance between almost all site pairs (maximum distance between sites is ~160 km) was noted.

We discuss a potential mechanism causing the similarity of nontidal variations along the observed isodepths. In the Hikurangi and Nankai subduction zones, a difference between the observed and theoretical propagation directions was noted, considering the topographic Rossby waves. Meanwhile, the phase velocities observed could be sufficiently explained by the topographic Rossby waves. The spatial pattern of the seasonal pressure variability can be explained by the topographic Rossby wave pathway. The pathway is a function of the parameter $f/h$, which is the Coriolis parameter $f$, over the water depth $h$ (Chen et al., 2022). The spatial pattern of seasonal pressure variability in the Pacific is in line with the pathway of topographic Rossby waves (Chen et al. 2022). Therefore, the topographic Rossby wave is likely an appropriate factor for the features observed in the nontidal variations in subduction zones rather than the Kelvin wave.

## 4. Advantages of using relative displacements between sites through detectability analysis

We have evaluated a suitable pre-processing technique for OBP time series in Hikurangi in terms of detectability for transients from short-term SSEs to optimize a pre-processing technique for detecting SSEs. We defined pre-processing as the processing of a time series prior to estimating displacements and a geodetic inversion for a slip model.

We applied a geodetic matched filter (e.g., Rousset et al. (2017); Okada et al. (2022)) for the synthetic and observed time series. The synthetic time series was composed of simulated nontidal components (Inazu et al., 2012), simulated long-period tides (Takanezawa et al., 2001), and an instrumental drift estimated from the observations. The observed time series were selected from the data period observed in the HOBITSS experiment, except for the obvious SSE transients observed at the onshore GNSS sites.

After applying the tidal killer filter to the raw observed time series (Chapter 2) and adding the transient due to an SSE with a specific duration of 14 days and date into the synthetic and observed time series, respectively, five pre-processing techniques applied to the time series are as follows: 1) no pre-processing with only the detided time series; 2) subtracting the ocean model from sites on the landward slope of the trench (e.g., Inazu et al., 2012; Muramoto et al., 2019); 3) taking the difference between the paired sites on the landward and seaward slopes of the trench (e.g., Wallace et al., 2016); 4) taking the difference between sites with a depth difference within 1000 m following the methods of Fredrickson et al. (2019), and 5) taking the difference between all the paired sites, which is equivalent to detecting the relative pressure change, that is, the relative displacements. The pre-processing technique 5) is based on our suggestion, as shown in Chapter 3.

The highest detectability of SSEs was obtained using the pre-processing technique 5), when using the synthetic time series. In pre-processing technique 5), the median of the detection limit had the smallest magnitude of ~Mw 6.1 in the five pre-processing techniques, indicating the highest performance of the detectability. This also suggests that the use of all paired sites in the pre-processing technique 5) can capture smaller SSEs. As in the case of observed time series, the results in the case of technique 5) pre-processing showed the highest performance in the detectability (~Mw 6.1) in averaged magnitude overall timings, as the synthetic time series. Consequently, the pre-processing technique 5) was found to be the optimal method in terms of detectability of SSEs. The two reasons, which are the low noise at paired sites with similar depth and the large number of data points, could have contributed to the most successful results for detectability in pre-processing technique 5).

We applied the proposed pre-processing 5) to the entire observed time series of OBP in the Hikurangi subduction zone to confirm the performance of detecting SSEs. As a result, we confirmed the detection of SSEs in September 2014, November 2016, and March 2019, which has been reported in previous studies (Wallace et al., 2016; Wallace et al., 2017; Woods et al., 2022). We also detected other potential transients that had not yet been reported in previous studies. The detection of possible transients around days 320–340 in early December 2014, for instance, coincided with the activity of the earthquake swarm occurring in the Raukumara Peninsula on Day 341. This suggests that the transients detected from the OBP data may have originated from another SSE that has not yet been reported.

**5. General discussion**

Residuals from OBP data in Cascadia have been estimated to be less than 1 hPa RMS (e.g., <1 cm) when taking the difference between sites at similar depths within a range that varies with depth (e.g., within 10 m for sites on shallower locations (100–250 m) and within 1,000 m for those on the abyssal plain (>1,400 m)) even for sites spaced far apart (<326 km) (Fredrickson et al., 2019). These results are comparable to those of the Hikurangi and Nankai subduction zones. Our observations in the Hikurangi and Nankai subduction zones have reinforced the idea proposed by Fredrickson et al. (2019) that the most effective way of using reference sites is to have those sites in similar water depths as the other sites in the areas of interest. Additional analyses in other subduction zones off the Pacific coast of Tohoku and offshore of Chile may highlight the universal feature of the water depth dependence of the correlation in nontidal variations in seafloor pressure among subduction zones.

In the Cascadia and Alaska subduction zones, the detectability of SSEs was also investigated using OBPs. The lower detection limit of the previous study (Cascadia: Mw 5.9) is comparable to this thesis in the use of 5) pre-processing (Hikurangi: ~Mw 6.1). We have shown that the estimated slip distribution is highly resolved with a low slip error, especially in the shallow portion (~0.5–2 km depth) when considering the difference in displacements between sites in the Hikurangi subduction zone. This suggests that it is optimal to consider the difference between sites and calculate the pressure step as relative displacements between sites when accurate detection of an SSE and an estimation of the slip model with high resolution are needed.

We additionally investigated the detectability of the designed network of OBPs in the case of placing new sites outside the deforming zone due to SSEs to maximize the detectability of SSEs in the Hikurangi subduction zone. Consequently, placing the OBP site outside the deformation zone from the SSE is likely to substantially improve the detection capability of the SSEs in the shallow part of the subduction zone. We evaluated the time-dependent detectability based on the time series in the Hikurangi subduction zone in Chapter 4, in which we pointed out that the spatial and temporal variation in the detectability of the SSE was attributed to the fluctuating time series after the pre-processing technique. This time-dependent detectability analysis can be a highly useful indicator for constructing future OBP networks. Therefore, when OBP sites are deployed in subsequent observations, the time-dependent detectability of SSEs with OBP and GNSS should be considered in order to achieve the removal of nontidal variations and the detection of SSEs.

## 6. General conclusion

Using data from the 2014-2015 OBP experiment offshore of New Zealand and the OBP data 2016-2017 in the Nankai Trough, we developed a method to detect SSEs occurring in a shallow portion of subduction zones. We propose that the best method of OBP time series is taking the difference between the sites of all pairs through time-dependent detectability. When the geodetic matched filter was applied to the observed time series utilizing the best pre-processing, we could detect transients due to the SSEs reported by previous studies that occurred in September 2014, November 2016, and March 2019 in the Hikurangi subduction zone. We also detected an unreported potential SSE in December 2014, coinciding with the occurrence of the earthquake swarm. In addition, to eliminate nontidal variations more effectively in seafloor pressure to detect

SSEs, at least, in the Hikurangi subduction zone, we found that it is necessary to place new OBP sites outside the expected source region of the SSEs with a similar installed depth to sites above the source through time-dependent detectability. This result also indicates that our proposed idea of time-dependent detectability of SSEs is an important indicator in designing a future OBP network to avoid contamination of nontidal variations in seafloor pressure data to detect small SSEs.