Extraction of crustal deformations and oceanic fluctuations from ocean bottom pressures

Importance of integral studies combining seismology, ocean physics and tsunami engineering technology

Keisuke Ariyoshi, Hiroyuki Matsumoto, and Takeshi Iinuma
Research and Development Center for Earthquake and Tsunami (CEAT)
Japan Agency for Marine-Earth Science and Technology (JAMSTEC) Yokohama Institute for Earth Sciences
Yokohama, JAPAN

Akira Nagano and Takuya Hasegawa
Research and Development Center for Global Change
Japan Agency for Marine-Earth Science and Technology (JAMSTEC) Yokosuka Headquarter
Yokosuka, JAPAN

Motoyuki Kido
International Research Institute of Disaster Science (IRIDeS)
Tohoku University
Sendai, JAPAN

Naoki Uchida
Research Center for Prediction of Earthquakes and Volcanic Eruptions (RCPEV)
Tohoku University
Sendai, JAPAN

Toshihiro Igarashi
Earthquake Research Institute (ERI)
The University of Tokyo
Tokyo, JAPAN

Yusuke Yamashita
Miyazaki Observatory of Disaster Prevention Research Institute (DPRI)
Kyoto University
Miyazaki, JAPAN

DONET (Dense Oceanfloor Network system for Earthquakes and Tsunamis) has been developed and installed around Nankai Trough, which is motivated by the 2004 Sumatra-Andaman Earthquake. DONET contains pressure gauges as well as seismometers, which are expected to detect crustal deformations driven by peeling off subduction plate coupling process. From our simulation results, leveling changes are different sense among the DONET points even in the same science node. On the other hand, oceanic fluctuations such as melting ice masses through the global warming have so large scale as to cause ocean bottom pressure change coherently for all of DONET points especially in the same node. This difference suggests the possibility of extracting crustal deformations component from ocean bottom pressure data by differential of stacking data. However, this operation cannot be applied to local-scale fluctuations related to ocean mesoscale eddies and current fluctuations, which affect ocean bottom pressure through water density changes in the water column (from the sea surface to the bottom). Therefore, we need integral analysis by combining seismology, ocean physics and tsunami engineering so as to decompose into crustal deformation, oceanic fluctuations and instrumental drift, which will bring about high precision data enough to find geophysical phenomena.

Keywords— subduction zone; Kuroshio current, Tonankai earthquake, environmental experiment of ocean bottom pressure gauge, climate change

I. Introduction

It has been well known that megathrust earthquakes such as the 2004 Sumatra-Andaman Earthquake (M_w 9.1) and the 2011 Pacific Coast of Tohoku Earthquake (M_w 9.0) had devastated the coastal areas in the western of Indonesia and the north-eastern of Japan, respectively. Some researchers have pointed out that the 2011 Tohoku earthquake may correspond to the recurrence of the 869 Jogan earthquake [1]. These may indicate that megathrust earthquakes like the Nin'na earthquake might occur along the Nankai Trough in the near future [2]. After the 2004 Sumatra-Andaman Earthquake, nearby megathrust earthquakes such as the 2005 Northern Sumatra Earthquake (M_w 8.6 and the 2007 Southern Sumatra Earthquake (M_w 8.5) followed so as to cover the seismic gap. This means that megathrust earthquakes nearby the 2011 Tohoku Earthquake may occur off Ibaraki and/or Iwate prefectures.

978-1-5090-1537-5/16/$31.00 ©2016 IEEE

To mitigate the disaster of those forthcoming megathrust earthquakes such as Tonankai earthquake and Tohoku earthquake, the Japanese government has established seafloor networks of cable-linked observatories around Japan: DONET (Dense Oceanfloor Network system for Earthquakes and Tsunamis along the Nankai Trough) and S-net (Seafloor Observation Network for Earthquakes and Tsunamis along the Japan Trench). The advantage of the cable-linked network is to monitor the propagation process of tsunami and seismic waves as well as seismic activity in real time [3].

So far, we estimate the plate coupling in the shallower part of subduction zones on the basis of Very Low Frequency Earthquake (VLFE) activity detected by seismometers. If the VLFEs can be detected by hydraulic pressure gauges on the seafloor, the reliability of our plate coupling estimation will be more robust. In the next section, we investigate the detectability of shallow VLFEs by the DONET in Tonankai district.

In this study, we try to extract crustal deformations from ocean bottom pressure data in order to detect the process of peeling off subduction plate coupling on the basis of simulation studies [2] and observations [4].

II. Strategy to Extract Crustal Deformations Component from Ocean Bottom Pressure Data

As Ariyoshi et al. [2] suggested, the differential data is useful to detect the local leveling change just in one observation point, if the leveling change averaged in the same node is nearly zero due to different sense of the change. However, the condition that the averaged leveling change due to VLFEs is nearly zero seems to be practically much limited.

Moreover, most of crustal deformation such as Slow Slip Event (SSE) [5] is not so local, which means that the differential data may miss the wide-area deformation. Since the activity of Low Frequency Tremors (LFTs) and VLFEs is thought to be related with SSE [6], the monitoring of VLFE activity should detect both the local and wide-area changes. This means that we have to develop the data analysis of seafloor hydraulic pressure gauge from the differential data.

Since the hydraulic pressure on the seafloor is expressed as integration of weight density dependent on temperature and salinity from the ocean surface to the bottom, the raw data of the pressure gauge is composed of crustal deformation and oceanic current fluctuation in addition to instrumental drift [7].

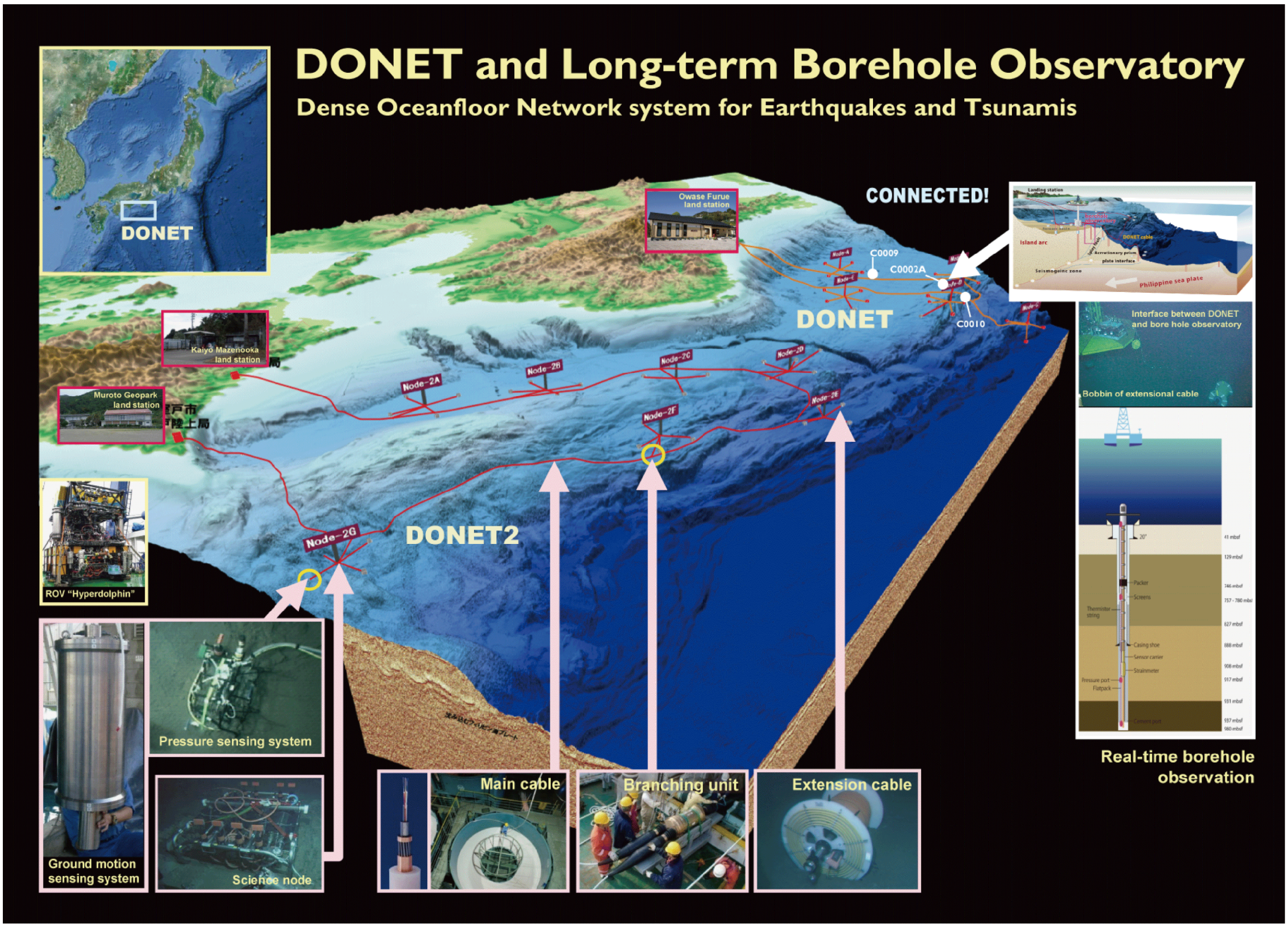

Figure 1. Overview of DONET and Long-term Borehole Observatory [3].

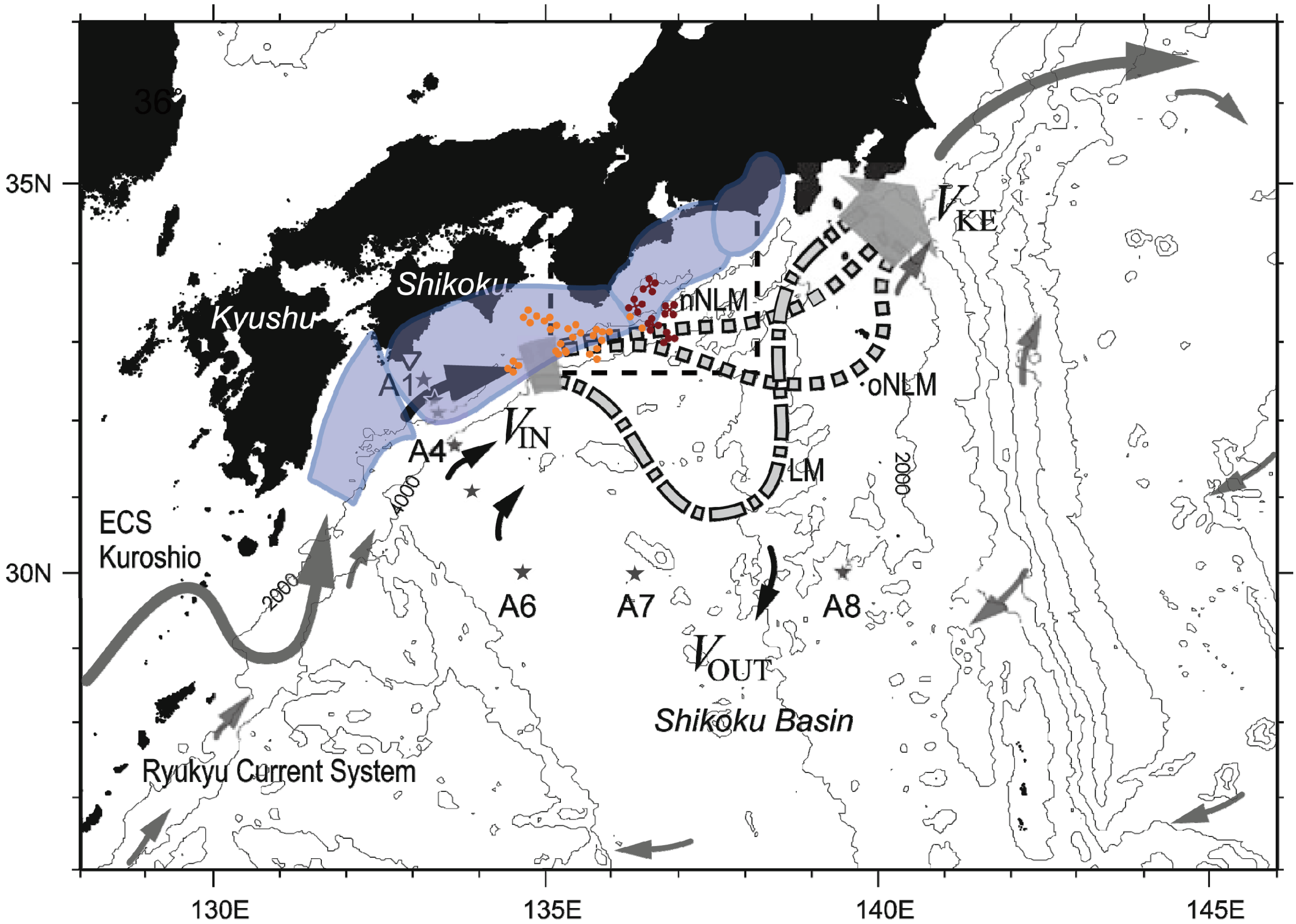

Figure 2. Significant currents are schematically shown by arrows; large-meandering (LM), offshore and nearshore nonlarge-meandering (NLM) paths of the Kuroshio are indicated by dashed and dotted curves, respectively. Locations of IES (inverted echo sounder) sites and Tosa-Shimizu tide gauge station are indicated by black stars and an open inverted triangle, respectively. Four blue regions along the Nankai Trough represent the estimated source regions of (in order from east to west) Tokai, Tonankai, Nankai and Hyuganada earthquakes, respectively. Dusky-red and orange colored closed circles represent DONET-I and DONET-II, respectively. This figure is adapted and modified from Nagano et al. [8].

Fig. 2 shows significant surface currents in the region off the southern coast of Japan. This figure suggests that the change of the hydraulic pressure at DONET is affected by the Kuroshio, because sea surface height and the vertical distributions of temperature and salinity are perturbed by the path variation of the Kuroshio [8]. In addition, because temperature in the Kuroshio region is considered to be more sensitive to long-term climate change than that in Oyashio region [9], we should monitor climate changes such as on El Niño-Souther Oscillation (ENSO) and longer time scales [10].

To estimate the crustal deformation more precisely, we have to evaluate all of the components (crustal deformation, ocean fluctuations, instrumental drift) quantitatively. Since ocean bottom pressure data is affected by weight density in the range from ocean bottom to over the sea surface, we need integral analysis by combining seismology, ocean physics and tsunami engineering. Concretely, seismologists use repeating earthquakes reflecting on plate motion along directions parallel and/or normal to the oceanic trench [11,12], geodesists use Global Navigation Satellite System (GNSS) data to estimate vector of slip driven by megathrust earthquakes [13,14], and ocean physicians estimate the depth profile of salinity and temperature of sea water [8,10].

Compared with seismological and ocean physical phenomena, the spatial and time scales of mesoscale eddies [15] and current variability [16] is largely the same as those of crustal deformations driven by slow-earthquakes [2]. These spatial scales are about 50-100 km, which is detectable by DONET because of spatial interval is about 15-20 km. This means that we have to know the different characteristics of ocean bottom pressure change between the crustal deformations and the oceanic variation.

On the crustal deformation, pressure change is expected to be so local as to be different sense even in the same science node because of short distance from the source region of slow earthquake and the observation point of DONET. From numerical simulation study [2], we can extract the crustal deformations by differential of stacked data in each science node. Because of static displacement on the subduction fault, the crustal deformations basically contains static change component.

On the oceanic variation, ocean current change does not contain the static component because it is basically temporal. In addition, characteristics of bottom pressure variation by current change are not the same as path of slow earthquake migration [5,6,8]. These differences may be a clue to separate crustal deformations and ocean fluctuations.

III. Strategy to Extract Crustal Deformations Component from Ocean Bottom Pressure Data

Fig. 3 shows the concept of our integral study plan from the view of available data. In addition, tsunami engineers try to reduce drift component by operating environmental laboratory experiments under the condition of the installed seafloor [17]. The combination of these evaluations brings about win-win results for all of various researchers and technicians.

Fig. 4 shows overview of our plan to analyze ocean bottom pressure at DONET by integral study of seismology, geodesy, ocean technology and meteorology. Repeating earthquake analysis [11,12] and tilt estimated by accelerometers [6] help us to detect crustal deformation in addition to leveling change at seafloor. In summary, it is important for us to integrate the analysis of hydraulic pressure data by collaborating between seismologist, geologist, meteorologist and tsunami engineer in order to extract crustal deformation as well as oceanic change with removal of the instrumental drift. This collaboration will bring about more robust data for both the two geo-signal components, which reveals the crustal deformation near the trench due to VLFEs and oceanic warming significantly.

Acknowledgment

This study was supported by JSPS KAKENHI Grants-in-Aid for Scientific Research Numbers 15H04228, 15KK0218 and Slow Earthquake Project. Fruitful discussion with JAMSTEC researchers was supported by JAMSTEC innovation award for Exploratory Research.

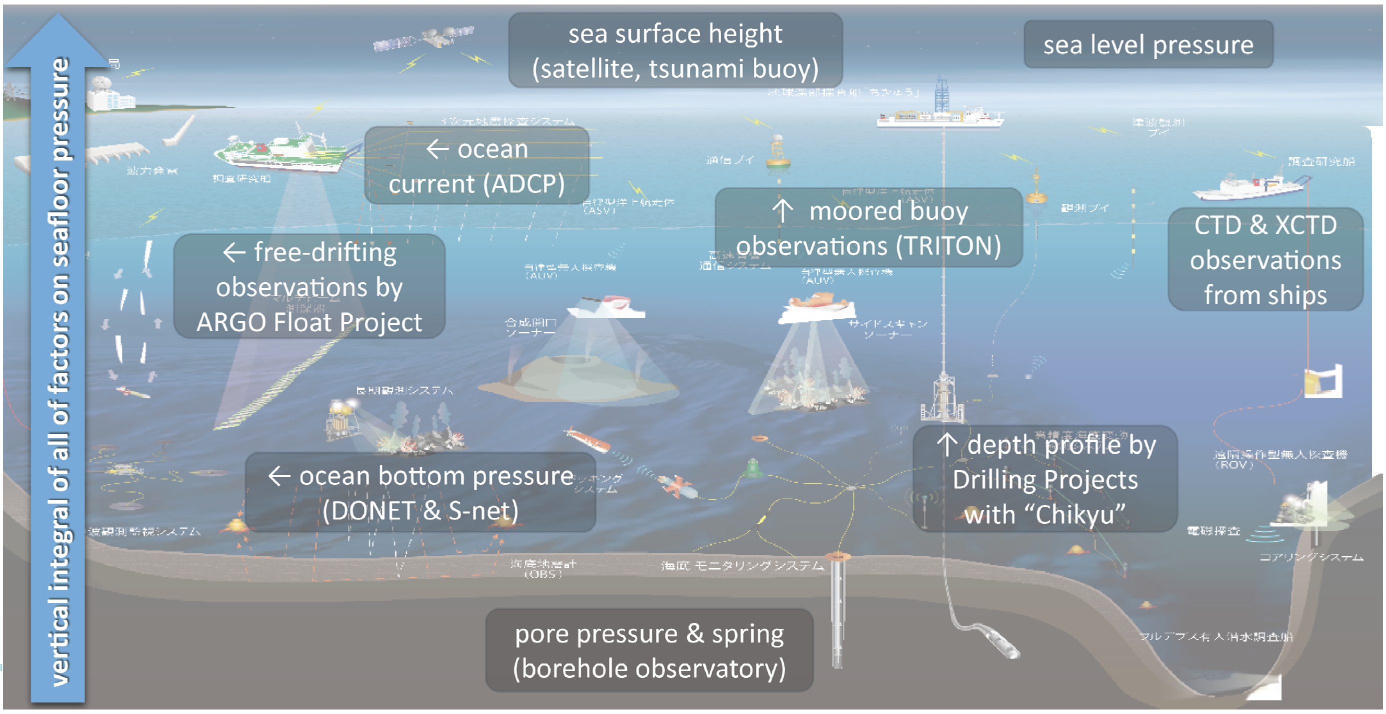

Figure 3. Concept of our integral study plan from the view of available data. ADCP is "Acoustic Doppler Current Profiler". ARGO Float (Project) is "A Global Array for Temperature/Salinity Profiling Floats". TRITON (buoy) is "TRIangle Trans-Ocean buoy". CTD is "Conductivity Temperature Depth profiler". XCTD is "eXpendable CTD".

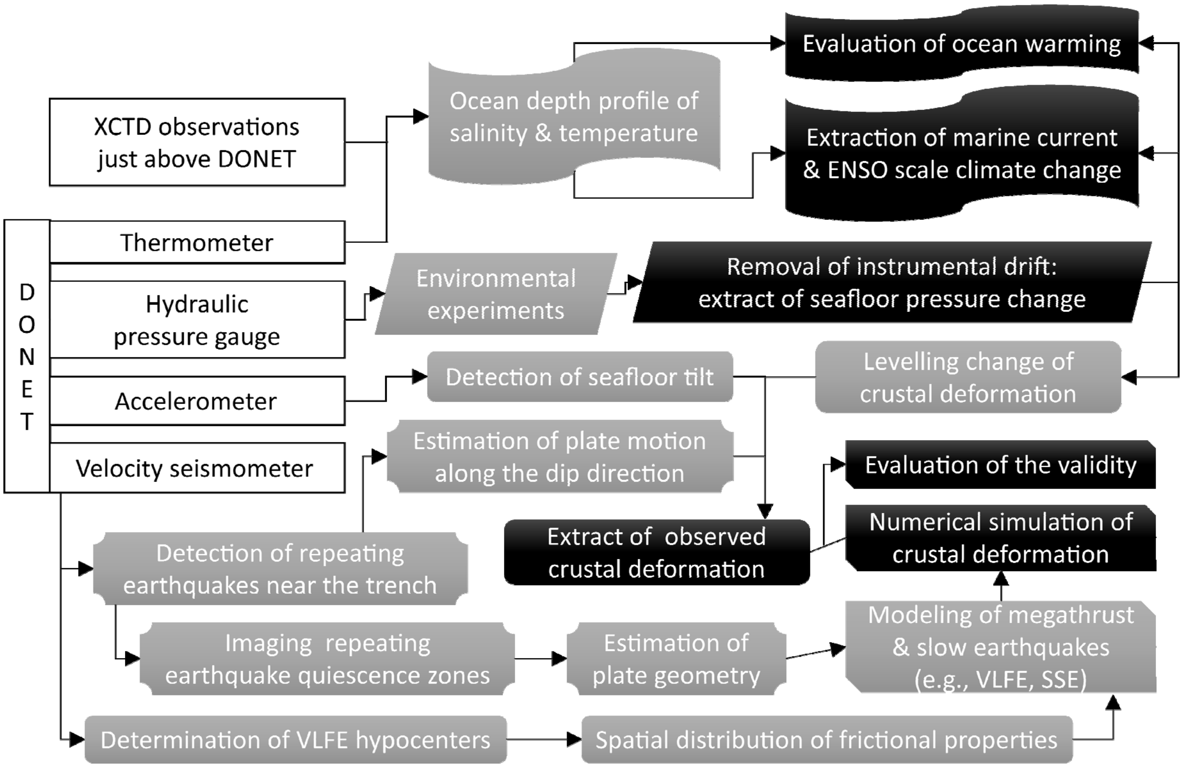

Figure 4. Overview of integral study in order to extract crustal deformation component of hydraulic pressure change

References

[1] S. Ozawa et al., "Coseismic and postseismic slip of the 2011 magnitude-9 Tohoku-Oki earthquake", Nature, vol. 475, No.356, pp. 373-376, doi:10.1038/nature10227, 2011.

[2] K. Ariyoshi et al., "The detectability of shallow slow earthquakes by the Dense Oceanfloor Network system for Earthquakes and Tsunamis (DONET) in Tonankai district, Japan", Marine Geophysical Research, vol. 35, No. 3, pp. 295-310, doi:10.1007/s11001-013-9192-6, 2014.

[3] Y. Kaneda et al., "Advanced Real Time Monitoring System and Simulation Researches for Earthquakes and Tsunamis in Japan", Chapter of Post-Tsunami Hazard, Advances in Natural and Technological Hazards Research, V. Santiago-Fandiño et al. (Eds.), Springer Switzerland, vol. 44, pp. 179-189, doi: 10.1007/978-3-319-10202-3_12, 2015.

[4] Y. Yamashita et al., "Migrating tremor off southern Kyushu as evidence for slow slip of a shallow subduction interface", Science, vol. 348 No. 6235, pp. 676-679, doi:10.1126/science.aaa4242, 2015.

[5] H. Hirose, K. Hirahara, F. Kimata, N. Fujii, and Shin'ichi Miyazaki, "A slow thrust slip event following the two 1996 Hyuganada earthquakes beneath the Bungo Channel, southwest Japan", Geophysical Research Letters vol. 26, No. 21, pp. 3237–3240, doi:10.1029/1999GL010999, 1999.

[6] K. Obara, H. Hirose, F. Yamamizu, and K. Kasahara, "Episodic slow slip events accompanied by non-volcanic tremors in southwest Japan subduction zone", Geophysical Research Letters, vol. 31, No. 23, L23602. doi:10.1029/2004GL020848, 2004.

[7] H. Matsumoto, E. Araki, K. Kawaguchi, S. Nishida, Y. Kaneda "Some characteristics of bottom pressure sensors of DONET", Proceedings of Underwater Technology Symposium (UT) 2013 IEEE International, pp. 1-7, doi:10.1109/UT.2013.6519863, 2013.

[8] A. Nagano et al., "Origin of near-surface high-salinity water observed in the Kuroshio Extension region", Journal of Oceanography, vol. 70, No. 4, pp. 389–403, doi:10.1007/s10872-014-0237-5, 2014.

[9] L. Wu et al. "Enhanced warming over the global subtropical western boundary current", Nature Climate Change, vol. 2, No. 3, pp. 161-166, doi: 10.1038/nclimate1353, 2012.

[10] T. Hasegawa, K. Ando, I. Ueki, K. Mizuno, S. Hosoda, "Upper-ocean salinity variability in the tropical Pacific: Case study for quasi-decadal shift during the 2000s using TRITON buoys and Argo floats", Journal of Climate, vol. 26, pp. 8126-8138, doi:10.1175/JCLI-D-12-00187.1, 2013.

[11] T. Igarashi, "Spatial changes of inter-plate coupling inferred from sequences of small repeating earthquakes in Japan", Geophysical Research Letters, vol. 37, No. 20, L20304, doi:10.1029/2010GL044609, 2010.

[12] N. Uchida, T. Iinuma, R. M. Nadeau, R. Bürgmann, R. Hino, "Periodic slow slip triggers megathrust zone earthquakes in northeastern Japan", Science, vol. 351, No. 6272, pp. 488-492, doi:10.1126/science.aad3108, 2016.

[13] T. Iinuma et al., "Coseismic slip distribution of the 2011 off the Pacific Coast of Tohoku Earthquake (M9.0) refined by means of seafloor geodetic data", Journal of Geophysical Research, vol. 117, No. B7, B07409, doi:10.1029/2012JB009186, 2012.

[14] M. Kido, Y. Osada, H. Fujimoto, R. Hino, Y. Ito, "Trench-normal variation in observed seafloor displacements associated with the 2011 Tohoku-Oki earthquake", Geophysical Research Letters, vol.38, No.24, L24303, doi:10.1029/2011GL050057, 2011.

[15] S. Imawaki, and K. Takano, "Low-Frequency Eddy Kinetic Energy Spectrum in the Deep Western North Pacific", Science, vol. 216, No. 4553, pp. 1407-1408, doi:10.1126/science.216.4553.1407, 1982.

[16] A. Nagano, Y. Michida, M. Odamaki, K. Suzuki, and J. Ogata, "Seiches in Lützow-Holm Bay, Antarctica", Polar Science, vol. 4, No. 1, pp. 34-41, doi:10.1016/j.polar.2010.02.002, 2010.

[17] H. Matsumoto, S. Inoue, T. Ohmachi, "Dynamic Response of Bottom Water Pressure due to the 2011 Tohoku Earthquake", Journal of Disaster Research, vol. 7, No. sp, pp. 468-475, doi:10.20965/jdr.2012.p0468, 2012.