A total station plan combined with "Chikyu" and DONET: simultaneous observation from seafloor to atmosphere

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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. Since "Chikyu" has a plan of operation to connect borehole observations to DONET, we have to discuss the best way to do simultaneous observation from seafloor to atmosphere by taking advantage of this chance.

References [1] S. Ide et al., *Nature* 447, 76-79 (2007). [2] K. Obara & S. Sekine, *Earth Planets Space* 61, 853-862 (2009). [3] S.Y. Schwartz & J.M. Rokosky, *Rev. Geophys*. 45, RC3004 (2007). [4] T. Matsuzawa et al., *Geophys. Res. Lett.,* 42, 4318-4325 (2015). [5] K. Ariyoshi et al., *Earth Planets Space* 66(55) (2014). [6] A. Ruina, *J. Geophys. Res.* 88, 10359-10370 (1983). [7] K. Ariyoshi et al. *Mar Geophys. Res.*, 35(3), 295-310 (2014).

Keywords: subduction zone, megathrust earthquake, ocean current

Intensive XBT measurement reveals short-period gravitational internal wave in the sea: its impact on GNSS/acoustic seafloor geodetic survey

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GNSS/acoustic measurement, consisting kinematic-GNSS monitoring of a sea-surface platform and acoustic ranging to seafloor transponders, is significantly affected by temporal variation of sound speed structure in seawater. In most cases, it can be well approximated with a time-varying laterally stratified structure. Therefore, we usually assume this condition in the GNSS/acoustic analysis. Any violation of this assumption results in apparent fluctuation of horizontal position of transponders. The fluctuation generally shows unstable long-timescale feature (several hours to a day), but sometimes shows clear periodic feature (0.5-1 hour). Such a short-timescale periodic feature can be interpreted by gravitational internal wave. Its quantitative contribution to the GNSS/acoustic analysis highly relies on local horizontal gradient of the field, which is the product of vertical gradient of sound speed, wave amplitude, and inverse wavelength of the internal wave. However, no direct observational evidence of this hypothesis has been available so far.

Then we conducted intensive XBT profiling of water column concurrently with GNSS/acoustic point survey in Kumano-nada, Nankai trough in 2016. Total 12 XBT-based temperature profiles with an interval of 10 minutes (lasting 2 hours), and a single XCTD-based density profile at the end were obtained, which provide fundamental information on the wave period. In the temperature profiles, we clearly identify up to 20 m of vertical oscillation of the water column shallower than 600 m. In the next step, we will estimate horizontal wavelength of this observed internal wave and calculate the local horizontal gradient of the net sound speed structure in order to be compared with apparent horizontal fluctuation observed in the concurrent GNSS/acoustic survey. These fundamental data in the water column will also contribute to understand small fluctuation in pressure at ocean bottom.

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Keywords: acoustic ranging, GNSS/acoustic, internal gravitational wave, sound speed, seafloor geodesy

Bottom pressure variation associated with 2004-2005 Kuroshio large meander south of Japan

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Off the southern coast of Japan, a Kuroshio large meander occurred in late July 2004 and continued to exist until about August 2005. Before the formation of the large-meander (LM) path, a Kuroshio path disturbance, called a small meander, occurred to the southeast of Kyushu. The propagation and development of the small meander were observed by bottom pressure sensors installed on inverted echo sounders (PIES) off Ashizuri-misaki and a seismic observing system off Muroto-misaki. The variations in bottom pressure, sea surface height (SSH), and the PIES-derived geopotential distance were examined focusing on the formation of the LM path. The bottom pressure was found to be depressed presumably due to a deep cyclonic eddy associated with the small meander, and this depression led the SSH depression by up to about two months. The phase shift between the surface and deep layers was significantly greater than those of other small meanders that did not develop into large meanders. This is evidence that baroclinic instability is an important process for the development to the large meander. After the formation of the LM path, the bottom pressure beneath the Kuroshio increased with a lag of about two months behind the SSH elevation. The high bottom pressure continued until about February 2005 when the LM path began to decay. The bottom pressure increase suggests that due to the stronger near-bottom current in the LM period than the non-LM period, the topographic steering is effective in the LM period and stabilizes the path. This is consistent with the fact that no small meanders occurred in the early LM period from late July 2004 to early February 2005.

Keywords: Kuroshio, Large meander, Bottom pressure, Inverted Echo Sounder, Seismic observing system

Microscale ocean disturbance that affects the GPS-A seafloor geodesy

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Seafloor geodetic observations accomplished several monumental works in the fields of seismology and geodesy. Many seafloor geodetic works were performed using the GPS-Acoustic ranging combination technique (GPS-A) [e.g., Gagnon et al., 2005, Nature; Sato et al., 2011, Science; Kido et al., 2011, GRL; Yokota et al., 2016, Nature]. In this technique, we observe using vessels (or buoys) on the sea around the seafloor acoustic mirror-type transponders set within the range of 1 - 3 km. Seafloor absolute positions were determined using this acoustic data, the attitude data and the GPS data on the vessels. Although the GPS-A technique achieved establishment of the stable and sophisticated seafloor observation network, an observation precision (1 σ = 2 - 3 cm: horizontal) remains lower than other geodetic observation techniques.
The observation precision is affected by ocean disturbances strongly. We have reduced this effect using analytical approaches in this decade (Figure). In that process, spatial and temporal changes of undersea sound speed structures (SSS) were approximated as fields modelled using high-order temporal functions [Fujita et al., 2006, EPS]. In the recent study, we found out a possibility that spatial biases of the SSS were also able to be modelled by using the similar method. These methods could make contributions to upgrade the precision of the GPS-A data. In this presentation, we’d like to review our current analysis flow and discuss effects of these analytical approaches.
Additionally, we remark the SSS modelled in our analysis. Although it was just noise for us, it is able to be considered as an important parameter visualizing an ocean event. The obtained SSS has very small spatial and temporal scales, a km-scale and an hour-scale, and is difficult to be acquired in other observations. Therefore the GPS-A may have possibility to open a new window to see a microscale ocean event.

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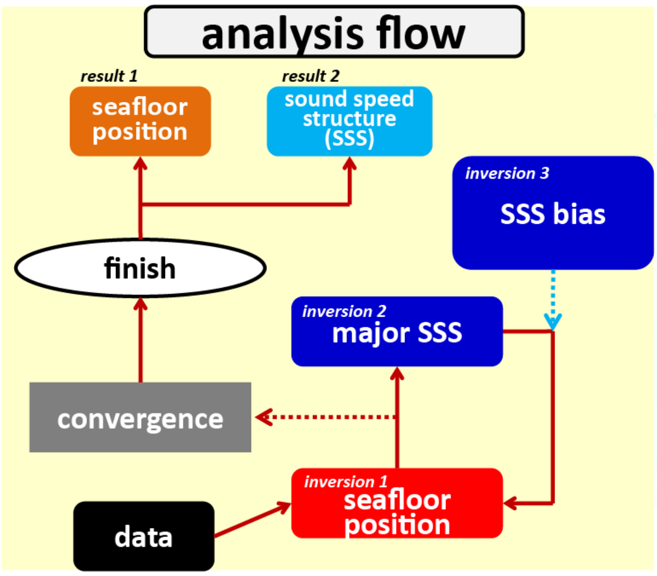
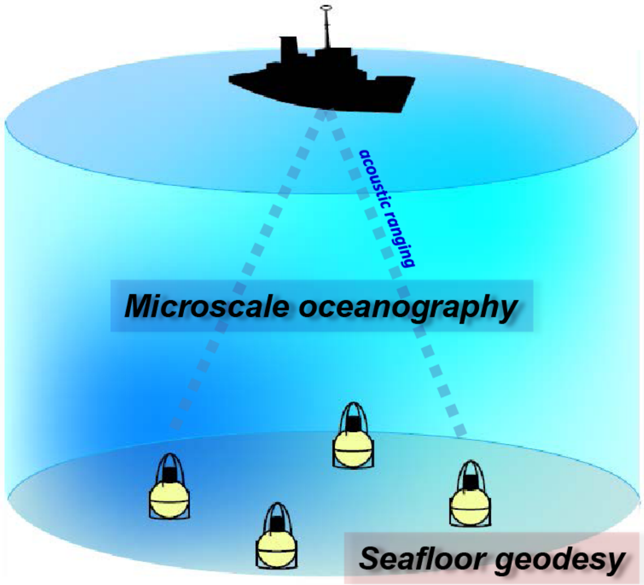
Keywords: Microscale oceanography, GPS-Acoustic ranging combination technique, Seafloor geodetic observation


analysis flow
result 1
seafloor position
result 2
sound speed structure (SSS)
inversion 3
SSS bias
finish
inversion 2
major SSS
convergence
inversion 1
seafloor position
data


acoustic ranging
Microscale oceanography
Seafloor geodesy

Ocean Current Prediction for Deep-Sea Scientific Drilling Vessel CHIKYU

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We conducted predictions of the ocean currents during 3 cruises of the Deep-Sea Scientific Drilling Vessel CHIKYU in 2016. In this presentation, we discuss the ocean situations during the cruises, potentials of the CHIKYU as an observation platform, and the current skills and future developments of the ocean current predictions.

Keywords: ocean current prediction, Chikyu, Kuroshio

Impact of explosive cyclones on the deep ocean in the North Pacific: Simulations and observations

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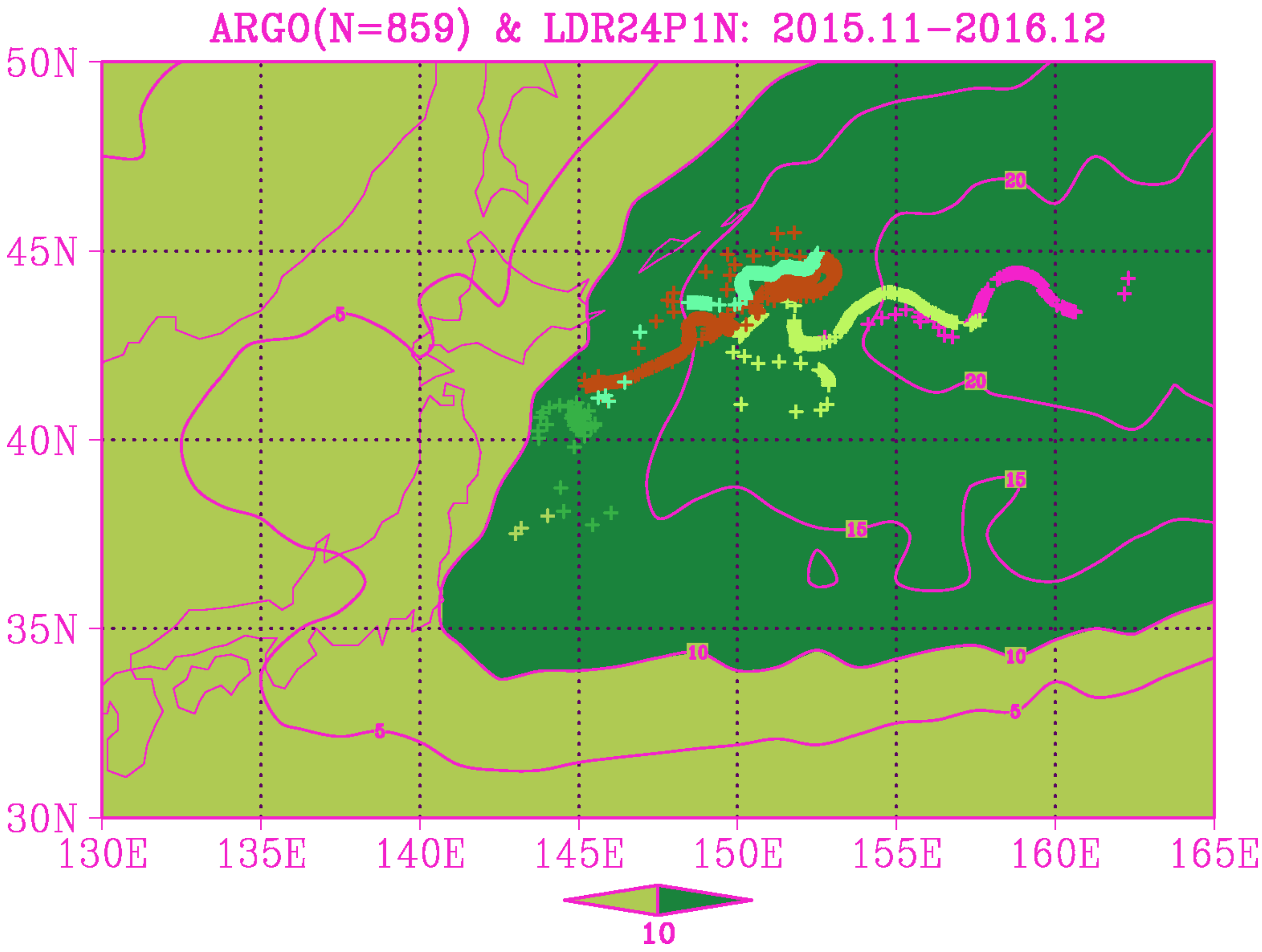
The Northwestern Pacific Ocean is the deepest ocean above which explosive cyclones frequently develop in winter. Composite analysis using eddy-resolving 34 year hindcast simulation of quasi-global ocean by OFES shows that explosive cyclones induce large horizontal divergence within the surface-mixed layer and upward flow that reaches 2000 m depth. In addition, interannual variability of explosive cyclone activity affects the amplitude of vertical motion and the daily-scale temperature variations in the deep ocean. However, normal observations of ocean cannot capture the oceanic response to explosive cyclones. Sea-surface temperature observations from satellite are not sensitive to explosive cyclones because of deep mixed layer in winter. The time interval of ARGO floats, usually 10 days, is too long to observe rapid change associated with explosive cyclones within 1 day. To observe the oceanic response, high-frequency observations using ARGO floats has been conducted in two winters in 2015/2016 and 2016/2017 in the Northwestern Pacific. The ARGO floats used for the special observations allow real-time change of observation mission including time interval and depth of profile observation through satellite communication. The mission change was operated based on medium-range ensemble forecast data by Japan Meteorological Agency. When an explosive cyclone was predicted with high probability by the forecast, 6-hourly observations with 650 m depth were conducted. Otherwise daily observations with 2000 m depth were conducted between November and March in each winter. 859 profiles were observed until December 2016 under the region where explosive cyclones were active.

References: Kuwano-Yoshida, A., H. Sasaki, and Y. Sasai, *Geophys. Res. Lett*, 44, 320-329 (2017).

Keywords: explosive cyclone, ARGO float, OGCM


ARGO(N=859) & LDR24P1N: 2015.11-2016.12
50N
45N
40N
35N
30N
130E
135E
140E
145E
150E
155E
160E
165E
5
10
15
20
10

Relationship between Ocean Bottom Pressure Variations and Baroclinic Eddy off Kushiro-Tokachi

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The scope of this study is to explore relationships between ocean bottom pressure variations and oceanic climate changes. We analyzed ocean bottom pressure data at stations PG1 and PG2 obtained from the Long-Term Deep Sea Floor Observatory off Kushiro-Tokachi by JAMSTEC, satellite- observed sea surface height (SSH) data provided by AVISO, and conductivity-temperature-depth (CTD; i.e., temperature and salinity vertical profile) data at a repeated observation line (A-line) from 2004 to 2013. The result shows that ocean bottom pressure variations at PG1 and PG2 are almost in phase in most of the analysis period, but from the early 2006 to the end of 2007, are quit discrepant. Expecting a peculiar hydrographic feature at the occasion, CTD data along the A-line in January 2007 are analyzed. A lenticular eddy was found to exist in a layer between 1500 and 3000 dbar. Probably due to the baroclinic eddy feature, ocean bottom pressure at PG2 is not in phase with the SSH, in contrast to PG1. The present results imply that oceanic temperature and salinity observations like CTD, in addition to SSH, are required to understand the mechanism of ocean bottom pressure changes.

Keywords: ocean bottom pressure variation, oceanic eddy

Comparison between temporal variation of sound velocity derived from GPS/acoustic and CTD measurements

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The GPS/acoustic (GPS/A) technique enables us to detect the seafloor crustal deformation by combining Global Positioning System and acoustic ranging. In the GPS/A technique, horizontal displacement of a seafloor transponder array, which composed of at least three instruments, can be estimated for each of single ranging shot (e.g., Spiess, 1985; Kido et al., 2006). The traveltime residual in the estimate is related to sound speed variation when it is normalized to nadir total delay (NTD), which is equivalent to zenith total delay (ZTD) in GNSS analysis. The equivalent quantity can be also obtained from in-situ measurements of sound speed profiles by integrating its slowness throughout the profile. Kido et al. (2008) compared the two quantities and found that they are in good agreement at least for the semidiurnal variation. In this study, we investigate two subjects as applications of Kido et al. (2008).
First, we investigated whether the shorter (~1 hour) timescale variation of NTD obtained through GPS/A analysis also reflect the sound speed variations. For this purpose, we conducted intensive XBT casts every six minutes for one hour and calculated corresponding NTD. After adapting proper correction for sensor bias of each XBT cast, we confirmed that the GPS/A analysis well resolves the sound speed variation even in a short timescale.
Second, we investigated the potential accuracy to resolve vertical crustal displacements using precise sound speed profile obtained by CTD measurements. In the GPS/A analysis, absolute NTD intrinsically contains uncertainty of the transponder depth. However, this NTD must be unchanged through campaigns; therefore, relative change between campaigns may indicate vertical movement of the transponders. For this context, we evaluated the potential accuracy by comparing the discrepancy between up and down CTD casts relative to GPS/A estimates of NTD for several observation sites. Considering CTD errors both in temperature and time axes (because each CTD cast takes finite time), we found the detectable level of the vertical movement is about 15 cm.

Keywords: seafloor geodesy, GPS/acoustic observation, sound velocity, CTD measurements

Evaluation of the sound speed equations for seawater proposed by Chen-and-Millero and Del-Grosso using GPS/Acoustic observation data

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There are two widely accepted equations for the computation of the speed of sound in seawater: the Chen and Millero's (CM) equation (*Chen and Millero*, 1977), which is also known as the UNESCO equation, and the Del Grosso's (DG) equation (*Del Grosso*, 1974). They are polynomial functions of pressure, temperature, and salinity defined by 42 and 19 coefficients for the CM and DG equations, respectively. For typical ocean temperatures and salinities, the DG equation generally gives smaller values than the CM equation. Though the difference is small near the sea-surface, it becomes larger as the pressure (or depth) increases and reaches as much as 0.6 m/s at depths greater than 3000 m. The two equations are empirically deduced from laboratory measurements and then have been examined by actual measurements in the ocean (*Spiesberger and Metzger*, 1991a; 1991b; *Dushaw et al.*, 1993; *Meinen and Watts*, 1997). These studies reached the same conclusion that the DG equation is more accurate than the CM equation, though the accuracy of the DG was evaluated variously. In this study, we evaluated the two equations using GPS/Acoustic observation data that have been collected for the detection of seafloor crustal movements off the Tohoku region since 2012. Advantages of this study are a large number of traveltime data collected during repeated surveys and great water depths of the observation sites (mostly deeper than 3000 m), which is a preferable condition to distinguish differences between the CM and DG equations.

The data were collected during a total of 120 observation campaigns conducted at the 20 sites from 2012 to 2016. There is a triangle or square array in each site, which consists of 3–6 transponders settled on the seafloor. Two-way traveltimes between a transducer on a ship and the seafloor transponders were measured to an accuracy of 10 microseconds. The pulse transmission was executed at an interval of 30–60 seconds typically for ~15 hours during one campaign. The analysis was performed for each site, and the data of 3–8 campaigns which was devoted to one site were used together for an inversion procedure. Assuming that the array geometry is rigid among the campaigns, we determined the position of each transponder at the time of the first campaign and displacements of the array at the time of subsequent campaigns. In terms of the sound of speed, we first prepared a reference vertical profile for each campaign based on XBT, CTD, or XCTD measurements conducted in the campaign and converted either with the CM or DG equations. Then, assuming that the sound speed does not change in horizontal directions, time-variation of the sound-speed profile was modeled to vary at the same scale factor over all depths. Consequently, time-variations of the scale factor during each campaign were simultaneously obtained in the inversion as well as the array positions. The results with the CM equation showed that scale factors for the sound speed were significantly smaller than 1.0: time-averaged scale factors for all the campaigns have a mean of 0.9994 and a standard deviation of 0.0001, which corresponds to a correction for the reference sound-speed profiles as much as -0.9 ± 0.2 m/s over all depths. With the DG equation, the mean scale factor of 0.9997 ± 0.0001 was obtained, which corresponds to a correction of -0.5 ± 0.2 m/s. It is closer to 1.0 than that with the CM equation, though it is still smaller than 1.0. Our result that smaller corrections were needed with the DG equation than the CM equation agrees with the results in the previous works, but the amounts of correction are larger than their estimates. Moreover,

when the DG equation was used the resulting scale factor had clear correlation with the depth of the sites: scale factors approach closer to 1.0 for campaigns conducted in deeper sites. This may indicate that errors in the DG equation occur in shallow parts rather than in deep parts.
* All references are in *J. Acoust. Soc. Am.*

Keywords: sound speed in seawater, GPS/Acoustic observation

Sea-level records analysis with empirical mode decomposition and its variations: Boundary effect improvement and mode reconstruction method

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Sea-level records analysis with empirical mode decomposition and its variations: Boundary effect improvement and mode reconstruction method

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A common goal of most time-series analysis is to separate deterministic periodic oscillations in the data from random and aperiodic fluctuations associated with unresolved background noise (unwanted geophysical variability) or with instrument error. For many applications, the sea level records are treated as linear combinations of periodic or quasi-periodic components that are superimposed on a long-term trend and random high-frequency noise. The periodic components are assumed to have fixed or slowly varying amplitudes and phases over the length of the record. Fourier analysis is one of the most commonly used methods for identifying periodic components in near-stationary sea-level data. If the sea-level data are strongly non-stationary, then more localized transforms like Wavelet transform can be used. However, the sea-level is a naturally non-linear process and data with the non-linear interactions among the physical processes with different time scales causing sea-level changes.
Empirical Mode Decomposition (EMD) is an adaptive (data-driven) method to analyse non-stationary signals stemming from non-linear systems (Huang et al., 1998). It produces a local and fully data-driven separation of a signal in high and low frequency oscillations, called intrinsic mode functions (IMFs), and a monotonic trend (residual). Detailed information on EMD and EEMD are referred to Huang *et al.* (1998) and Wu and Huang (2009). The CEEMDAN is an important improvement of EEMD (Torres et al., 2011), achieving a negligible reconstruction error and solving the problem of different number of modes for different ensemble numbers with signal plus noise. The improved CEEMDAN is a further improvement of CEEMDAN for solving the problem of residual noise in modes and spurious modes (Colominas et al., 2014). For the sake of paper length, readers refer to the relevant literature above for detailed algorithms of EMD and its variations. For applications of EEMD, refer to Lee *et al.* (2012).
In this study, we illustrate two improvements in the signal decomposing and analysis process of EMD; the boundary effect and reconstruction method for decomposed intrinsic mode functions (IMFs). We use the mirror method for boundary effect and statistical significance test for reconstruction of IMFs to improve the statistical significance of each modes. The artificial signal test show that the proposed mirror method for boundary effect and the statistical significance test for reconstruction of IMFs improve the decomposing results dramatically compared to the original artificial signal components.

Keywords: empirical mode decomposition, boundary effect, mode reconstruction method, sea-level records

