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Deep-sea bottom-water environment change caused by sediment resuspension on the continental slope off Sanriku, Japan, before and after the 2011 Tohoku Earthquake

Masahide Wakita[1*], Shuichi Watanabe[1], Jun Yoshino[2], Kazumasa Oguri[3,4], Hidetaka Nomaki[5], Shinsuke Kawagucci[3], Keisuke Ariyoshi[6], Akira Nagano[7] and Katsunori Fujikura[3]

Abstract: The 2011 off the Pacific coast of Tohoku Earthquake occurred off southern Sanriku, Japan, on March 11 and generated strong shaking and huge tsunami along the entire eastern coast of Tohoku. The mainshock and numerous large aftershocks caused mass-wasting sedimentation events on the continental shelf, slope, and trench bottom. To investigate the impacts of the 2011 Tohoku Earthquake on the deep-sea bottom-water environment off Sanriku, we conducted shipboard surveys up to ~ 2000 dbar during 2011–2018 and long-term monitoring of the seafloor on the continental slope using a deep-sea station (~ 1000 dbar) off Otsuchi Bay during 2012–2018. The high turbidity (maximum ~ 6%) was observed for the bottom water deeper than 500 dbar on the continental slope of the entire area off Sanriku during 2012–2018. This high turbidity was caused by sporadic sediment resuspension induced by frequent large aftershocks. Furthermore, dissolved oxygen concentrations in the bottom layer from 1000 to 1500 dbar dropped significantly by about 10% after the earthquake, while nutrients and dissolved inorganic carbon showed no significant changes but exhibited wide variations. The high turbidity was associated with the increase in the concentrations of phosphate, dissolved inorganic carbon, and methane, as well as the decrease in those of dissolved oxygen and nitrate. This suggests that remineralization of suspended organic matter resulting from the respiration and denitrification of microbial communities after the earthquake caused the chemical properties of the deep-sea bottom-water. The deep-sea bottom-water environment change was maintained by sporadic sediment resuspension due to continued large aftershocks and was likely caused by variations in dissolved inorganic carbon and phosphate. There are two peaks in the concentration and carbon isotope ratio of methane on the deeper slope from 1000 to 2000 dbar near the hypocenter, which were advected along isopycnal surfaces of 27.38σ_θ (1000 dbar) and 27.56σ_θ (1500 dbar). The source of the shallower peak of chemical input is considered to be the sediment resuspension from the shallow sediment on the continental slope induced by the mainshock and large aftershocks.

Keywords: The 2011 off the Pacific coast of Tohoku Earthquake, Deep-sea bottom-water environment, Continental slope, Turbidity, Sediment resuspension, Dissolved oxygen, Dissolved inorganic carbon, Methane

*Correspondence: mwakita@jamstec.go.jp

[1] Mutsu Institute for Oceanography (MIO), Research Institute for Global Change (RIGC), Japan Agency for Marine-Earth Science and Technology, 690 Kitasekine, Sekine, Mutsu, Aomori 035-0022, Japan
Full list of author information is available at the end of the article

1 Introduction

The 2011 off the Pacific coast of Tohoku Earthquake with a moment magnitude (M_w) of 9.0 (hereafter "the 2011 Tohoku Earthquake") occurred on March 11, 2011, and generated strong shaking and huge tsunami along the entire eastern coast of the Tohoku area (e.g., Hirose et al. 2011). On this same date, many large aftershocks occurred (Fig. 1a), including a M_w 7.5 event off Sanriku and a M_w 7.7 event off Ibaraki Prefecture (e.g., Hirose et al. 2011). Aftershocks have been active around the source region of the mainshock since its occurrence, and the two largest aftershocks ($M_w \geq 7$) define the northern and southern limits of the aftershock region (Fig. 1a) (e.g., Uchida and Bürgmann 2021). The annual mean earthquake frequency since the 2011 Tohoku Earthquake ($M_w \geq 5$) has been higher than that during 2001–2010 within the aftershock area of Tohoku (Japan Meteorological Agency (JMA) 2022).

The mainshock together with the numerous large aftershocks triggered mass-wasting sedimentation events associated with dense turbidity on the continental shelf, slope, and trench bottom off Sanriku (e.g., Kawagucci et al. 2012; Noguchi et al. 2012; Arai et al. 2013; Oguri et al. 2013, 2016; Nomaki et al. 2016). This mass-wasting sedimentation events associated with dense turbidity impacted deep-sea bottom-water environment. For example, a disturbance in the deep-sea bottom-water environment below 2000 dbar depth has been detected in the form of turbulent diffusion of sediments and anomalous increases in the concentrations of manganese, methane, and helium-3, and increases in planktonic microbial communities near the hypocenter 36 days after the mainshock (Kawagucci et al. 2012; Sano et al. 2014). In other regions, just after large earthquakes, dense turbidity and high manganese concentration anomaly were also observed in the bottom water of the Sagami Bay (Kasaya et al. 2009; Gamo et al. 2007), off Tokachi (Mikada et al. 2006), and off Kii Peninsula (Ashi et al. 2014). Moreover, large aftershocks of the 2011 Tohoku Earthquake on December 7, 2012, and February 17, 2015, increased turbidity through sediment resuspension in the bottom water at ~ 1000 m depth, though this did not affect benthic habitats (e.g., ophiuroids, sea cucumbers, gastropods, deep-sea eels, and rockfish *Sebastolobus macrochir*), as observed during 2012–2016 at the deep-sea station (~ 1000 m) off Otsuchi Bay (Oguri et al. 2016, 2018). These results indicate deep-sea bottom-water environments in some areas changed as a result of the 2011 Tohoku Earthquake and aftershocks. However, these observed changes have not been fully compared with pre-earthquake bottom-water conditions and variability because of the lack of pre-earthquake data, and such a comparison is required to properly assess the impact of the 2011 earthquake and aftershocks on the deep-sea bottom-water environment.

Before the 2011 Tohoku Earthquake, the Japan Meteorological Agency (JMA) and Japan Agency for Marine-Earth Science and Technology (JAMSTEC) collected physical and biogeochemical data over the entire continental slope area off Sanriku and the abyssal plain ocean floor of the western North Pacific Ocean (Fig. 1). After the 2011 Tohoku Earthquake, to examine the impacts of the earthquake and aftershocks on deep-sea bottom-water environment change, we conducted surveys onboard research vessels over the continental slope area off Sanriku during 2012–2018 under the Tohoku Ecosystems-Associated Marine Sciences (TEAMS) Project. Using these two sets of data and long-term monitoring data at the deep-sea station off Otsuchi Bay, we compared the deep-sea bottom water before and after the 2011 Tohoku Earthquake and aftershocks.

2 Data and method

2.1 Observations off the Pacific coast of Sanriku

After the 2011 Tohoku Earthquake, we performed ship-based hydrographic observations in the entire continental slope area off Sanriku onboard the research vessels *Mirai*, *Shinsei-Maru*, and *Hakuho-Maru* of JAMSTEC and the training ships *Oshoro-Maru* of Hokkaido University and *Bosei-Maru* of Tokai University (Fig. 1 and Table 1). We conducted vertical hydrocasts using a conductivity–temperature–depth (CTD) profiler with a carousel multiple sampling system (CTD–CMS) from the sea surface to just 10 m above the seafloor (up to 2000 dbar depth). The CTD–CMS system consisted of a CTD SBE 911plus (Sea-Bird Scientific), a light transmissometer (C-star 25 cm light-path type, WET Lab), and Niskin-X bottles (12 L type, General Oceanics). Light transmission anomaly (LTA) values were calculated from the difference between the in situ light transmission value and the maximum value of the transparent layer in deep water during each cruise and were interpreted as representing deep-sea water turbidity (Kawagucci et al. 2012). We collected water samples in Niskin bottles for measurements of dissolved oxygen (DO), nutrients, salinity, dissolved inorganic carbon (DIC), and methane. During 2011–2018, we performed observations at a total of 166 stations on 14 cruises (Table 1). These data will be publicly available from the JAMSTEC Web site, Tohoku Ecosystem-Associated Marine Sciences (TEAMS) Data Catalog (https://www.jamstec.go.jp/j/about/informations/notification_2021_maintenance.html?lang=en).

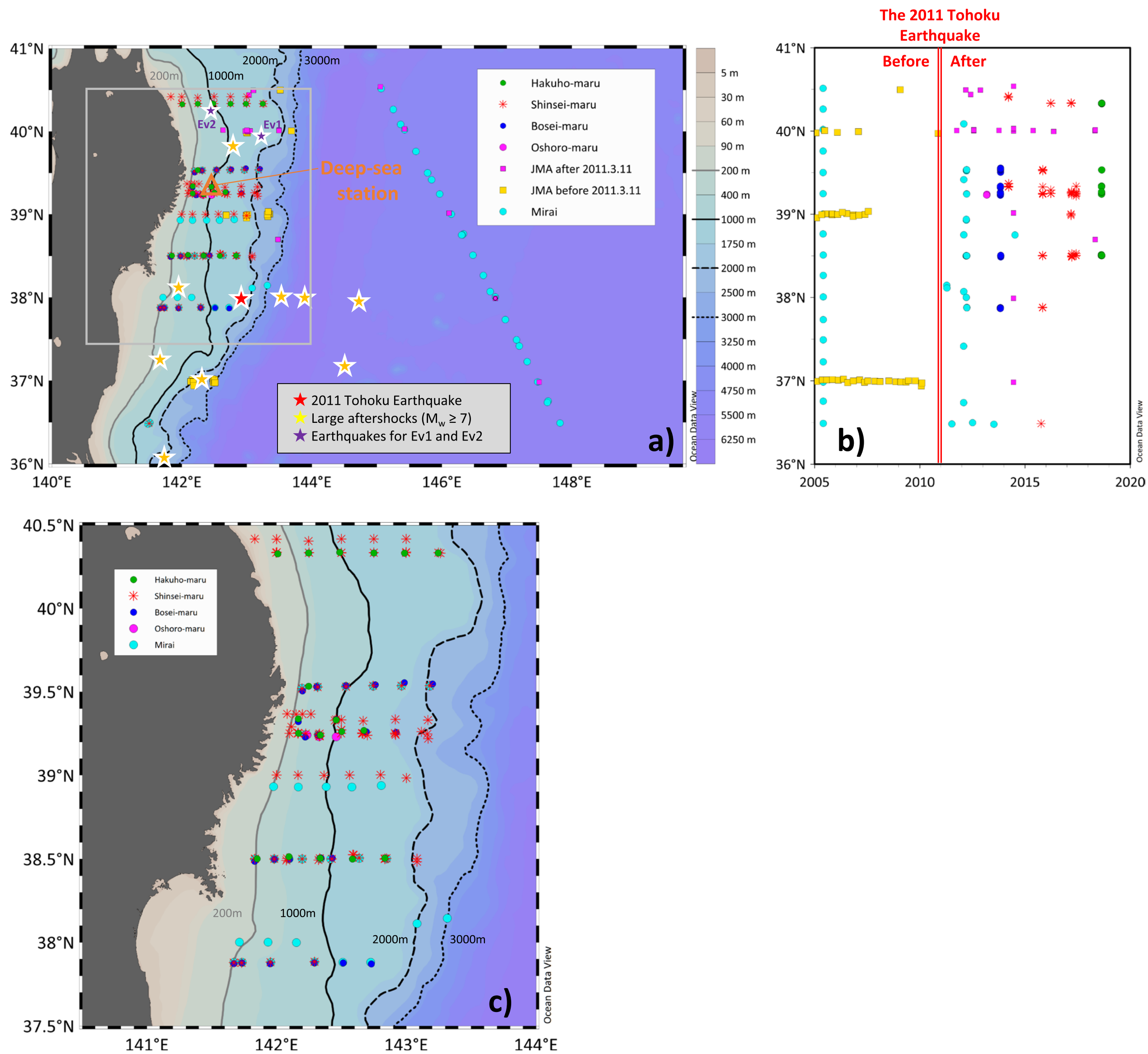

Fig. 1 Location map and bathymetry (**a**), and time series as a function of latitude of location (**b**) of sampling stations in this study. (**c**) Location map of our sampling stations (Table 1) encircled by the square in panel (**a**). The hypocenter of the 2011 Tohoku Earthquake is shown by the red star, and the hypocenters of large aftershocks ($M_w \geq 7$) until 2019 in the northern and southern limits of the aftershock region and the earthquakes for the Ev1 and Ev2 are shown by yellow and purple stars, respectively. Ship-based hydrographic observations were performed onboard research vessels [*Mirai* (aqua-blue circles), *Shinsei-Maru* (red asterisks), and *Hakuho-Maru* (green circles) of JAMSTEC] and Japanese training ships [*Oshoro-Maru* (pink circles) of Hokkaido University and *Bosei-Maru* (blue circles) of Tokai University], and by the JMA before (yellow squares) and after (pink squares) the 2011 Tohoku Earthquake. The open orange triangle denotes the deep-sea station (~ 1000 m depth) used for long-term monitoring of the seafloor on the continental slope (Oguri et al. 2016, 2018). Bathymetric contours show 200 m depth (solid gray line), 1000 m depth (solid black line), 2000 m depth (dashed black line), and 3000 m depth (dotted black line). The color bar shows the depth of bathymetry

DO was measured with automatic photometric titrators (DOT-01X, Kimoto Electric, during the *Mirai* and *Bosei-Maru* cruises; and DOT-05, Kimoto Electric, during the *Shinsei-Maru* cruise). According to results for replicate samples, the precision of DO measurements was less than ± 0.2 μmol kg^{-1}. Apparent oxygen utilization (AOU) was determined by subtracting the observed DO concentration from the saturated concentration calculated from temperature and salinity using the formula by Weiss (1970). Nutrients (nitrate (NO_3), phosphate (PO_4), and silicate) and salinity were measured with a continuous-flow analyzer (QuAAtro, BL TEC K.K.) and a salinometer (Model 8400B AUTOSAL, Guildline Instruments), respectively. Values of nutrients were calibrated against the certified reference material (RM) provided by KANSO TECHNOS, and those of salinity against the International Association for the Physical Sciences of the Ocean (IAPSO) standard seawater provided by Ocean Scientific International. The precisions for NO_3, PO_4, silicate, and salinity were within ± 0.1 μmol kg^{-1}, ± 0.01 μmol kg^{-1}, ± 0.2 μmol kg^{-1}, and ± 0.001 based on replicate sample determinations, respectively. We measured DIC with coulometers (CM5012, UIC; MODEL 3000A, Nippon ANS) (Wakita et al. 2021). DIC values were calibrated against CO_2 in seawater RM produced by KANSO TECHNOS. This RM value was determined by measuring DIC relative to the certified RM provided by Prof. A. G. Dickson (Scripps Institution of Oceanography, University of California San Diego). The precision of DIC measurements was within ± 0.8 μmol kg^{-1}, based on replicate sample determinations. Concentrations and carbon isotope ratios of methane were determined simultaneously with a combination of purge and trap techniques and continuous-flow isotope ratio mass spectrometry (Kawagucci et al. 2018). We present the stable carbon isotope ratio in delta notation on a per mil scale with respect to Vienna Pee Dee Belemnite (VPDB). To perform isopycnal analysis, we linearly interpolated the values of LTA, DO, nutrients, DIC, and methane onto two selected isopycnal surfaces ($27.38\sigma_\theta$ and $27.56\sigma_\theta$).

In addition, to understand the variation in seafloor environment following aftershocks, we analyzed CTD and DO data for the period 2012–2018 from the deep-sea station deployed at ~ 1000 m depth for long-term monitoring on the continental slope off Otsuchi Bay in the Sanriku region (Oguri et al. 2016, 2018) (Fig. 1). CTD and DO data were obtained from CTD and DO sensors (RDCP 600 with 4050, 4019B, 3830, and 4017D; Xylem) and calibrated against salinity and DO data measured onboard for seawater samples obtained in Niskin bottles at 1000 m depth during cruises BO13-20, KS-15-15, KS-16-2, and KS-17-J08C (Oguri et al. 2016).

To compare the deep-sea bottom-water environment before and after the 2011 Tohoku Earthquake over the entire area off Sanriku, we used data for CTD, DO, nutrients, and DIC collected during 2005–2018 off the Pacific coast of Sanriku and along the international repeat hydrography program P10 section in the abyssal plain of the Pacific plate by the JMA (http://www.data.jma.go.jp/gmd/kaiyou/db/vessel_obs/data-report/html/ship/ship_e.php) (yellow and pink squares in Fig. 1) and during the 2005, 2012, and 2014 *Mirai* cruises (https://www.ncei.noaa.gov/access/ocean-carbon-data-system/oceans/RepeatSections/clivar_p10.html).

2.2 Remineralization of organic matter near the seafloor on the continental slope

To investigate the impacts of disturbances of sediments caused by the 2011 Tohoku Earthquake and aftershocks on the deep-sea bottom-water environment, we estimated the remineralization of organic matter by oxygen respiration and denitrification of microbial communities near the seafloor on the continental slope. When a water mass on the slope moves along an isopycnal surface, the concentrations of DIC, nutrients, and AOU increase, and DO decreases owing to the remineralization of organic matter by respiration, and NO_3 is consumed by denitrification in the anaerobic sediments. Denitrification

Table 1 Our ship-based hydrographic observations and water sample measurements conducted after the 2011 Tohoku Earthquake

Cruise	Ship	Period	CTD	LTA	DO	Nutrients	DIC	CH_4	$\Delta^{13}CH_4$
MR11-03	Mirai	Apr. 2011	✓	✓	✓				
MR11-05	Mirai	Jul. 2011	✓	✓	✓	✓	✓		
MR12-E02	Mirai	Mar. 2012	✓	✓	✓	✓	✓		
MR12-02	Mirai	Jul. 2012	✓	✓	✓	✓	✓		
OS252	Oshoro-Maru	Mar. 2013	✓			✓	✓		
MR13-04	Mirai	Jul. 2013	✓	✓	✓	✓	✓		
BO13-20	Bosei-Maru	Nov. 2013	✓	✓	✓	✓	✓		
KS-14-3	Shinsei-Maru	Mar. 2014	✓	✓		✓	✓		
KS-15-13	Shinsei-Maru	Oct. 2015	✓	✓	✓	✓	✓		
KS-15-15	Shinsei-Maru	Nov. 2015	✓	✓	✓	✓	✓	✓	✓
KS-16-2	Shinsei-Maru	Mar. 2016	✓	✓	✓	✓	✓		
KS-17-J05	Shinsei-Maru	Mar. 2017	✓	✓	✓	✓	✓		
KS-17-J08C	Shinsei-Maru	Jun. 2017	✓	✓	✓	✓	✓		
KH-18-J03C	Hakuho-Maru	Aug. 2018	✓			✓	✓		

remineralizes carbon with a very different stoichiometric ratio compared with nitrogen from respiration. The stoichiometric ratios of the remineralization by respiration and denitrification have been described by Anderson (1995) and Gruber and Sarmiento (1997) as follows:

$$C_{106}H_{175}O_{42}N_{16}P + 150\,O_2 = 106\,CO_2 + 16\,HNO_3 + H_3PO_4 + 78\,H_2O,\ \text{and} \quad (1)$$

$$C_{106}H_{175}O_{42}N_{16}P + 104\,HNO_3 = 106\,CO_2 + 60\,N_2 + H_3PO_4 + 138\,H_2O. \quad (2)$$

The amount of consumed NO_3 can be estimated by the relationship between measured NO_3 (NO_{3m}) and PO_4 (PO_{4m}) (Mintrop et al. 1999). By using NO_{3m} and PO_{4m}, apparent NO_3 utilization (ANU) is defined as

$$ANU = 16\,PO_{4m} - NO_{3m}. \quad (3)$$

Thus, we estimated remineralization-corrected DIC and PO_4 in the subsurface water near the seafloor on the slope, as follows:

$$\text{Remineralization} - \text{corrected DIC} = DIC_m - 117/170\,AOU - 106/104\,ANU,\ \text{and} \quad (4)$$

$$\text{Remineralization} - \text{corrected } PO_4 = PO_{4m} - 1/170\,AOU - 1/104\,ANU, \quad (5)$$

where the coefficients 117/170 and 1/170, and 106/104 and 1/104 are the stoichiometric ratios of remineralization of organic matter by respiration (Anderson and Sarmiento 1994) and denitrification (Gruber and Sarmiento 1997), and DIC_m is the DIC measured in the ocean interior.

3 Results and discussion

3.1 Hydrographic features on the continental slope off Sanriku

Figure 2 shows the sections of LTA-derived turbidity measured during 2012–2017 (i.e., after the 2011 Tohoku Earthquake). Turbidity was higher in the upper water between depths corresponding to 0 and 500 dbar owing to the high biomass abundance relative to the deep water. The upper water (shallower than $26.7\sigma_\theta$) is influenced by the Tsugaru Warm Current, the Oyashio, and the Kuroshio proceeded to the region off Sanriku (Fig. 3) and exhibits complicated water mass structures (e.g., Hanawa and Mitsudera 1986) and high primary production and chlorophyll a (e.g., Ishizaka 1998). The intermediate and deep layers below a depth of the $26.7\sigma_\theta$ isopycnal are occupied by the low-salinity North Pacific Intermediate Water (NPIW) ($26.6–27.4\sigma_\theta$) (e.g., Talley et al. 1995) and the high-salinity Circumpolar Deep Water transported from the Antarctic Circumpolar region (Figs. 2 and 3).

Although potential temperature, salinity, DO, AOU, NO_3, PO_4, and DIC became less variable with increasing depth, as did potential density, particularly below ~ 500 dbar (~ $26.8\sigma_\theta$), LTA became more variable with increasing depth (Fig. 4). Values of LTA were high and variable in the bottom water deeper than 500 dbar on the continental slope off Ohtsuchi Bay, Onagawa Bay, and Sendai Bay (Fig. 2). These values were higher than those observed near the bottom off Ohtsuchi Bay in 2017, Onagawa Bay in 2017, and Sendai Bay in 2012. The maximum LTA intensity in the deep-sea bottom water (~ 6%) shown in 2014 (Fig. 4) was lower than the LTA of ~ 36% measured below 2000 dbar on the MR11-02 cruise 36 days after the 2011 Tohoku Earthquake (Kawagucci et al. 2012). Moreover, the large aftershocks of the 2011 Tohoku Earthquake on December 7, 2012, and February 17, 2015, increased turbidity in the bottom water through sediment resuspension from a HDTV camera at the deep-sea station (~ 1000 m depth) off Otsuchi Bay (Fig. 1; Oguri et al. 2016, 2018). The bottom water returned to the pre-earthquake state, 10 days after the large aftershocks (Oguri et al. 2016, 2018). This suggests that the resuspended sediments resettled near the original site or a bottom current flowing southward to southwestward in this area (2.5–4.5 cm/s; Itoh and Sugimoto 2002) flushed or diluted the turbid bottom water. Turbidity in the deep-sea bottom water near the seafloor has been observed to increase as a result of the turbulent resuspension of sediments by the 2011 Tohoku Earthquake and its aftershocks (e.g., Kawagucci et al. 2012; Oguri et al. 2016). Because dense turbidity and high manganese concentration anomaly was observed in the bottom water of the Sagami Bay after large earthquake ($M_w = 5.4$) (Kasaya et al. 2009; Gamo et al. 2007), the annual mean earthquake frequency since the 2011 Tohoku Earthquake ($M_w \geq 5$) has been higher within the aftershock area of Tohoku (JMA 2022). Accordingly, sporadic enhancement in LTA was widely detected in the deep-sea bottom water on the continental slope off Sanriku during 2011 − 2018 (Figs. 2 and 4d). This sporadic enhancement in LTA would be caused by sediment resuspension induced by the 2011 Tohoku Earthquake and frequent large aftershocks.

3.2 Deep-sea bottom-water conditions before and after the 2011 Tohoku Earthquake

As physical and chemical disturbances in seawater in conjunction with the disturbance of surface sediments triggered by earthquakes have been observed previously (e.g., Gamo et al. 2007; Kawagucci et al. 2012), we compared the deep-sea bottom-water environment between 1000 and 1500 dbar before and after the

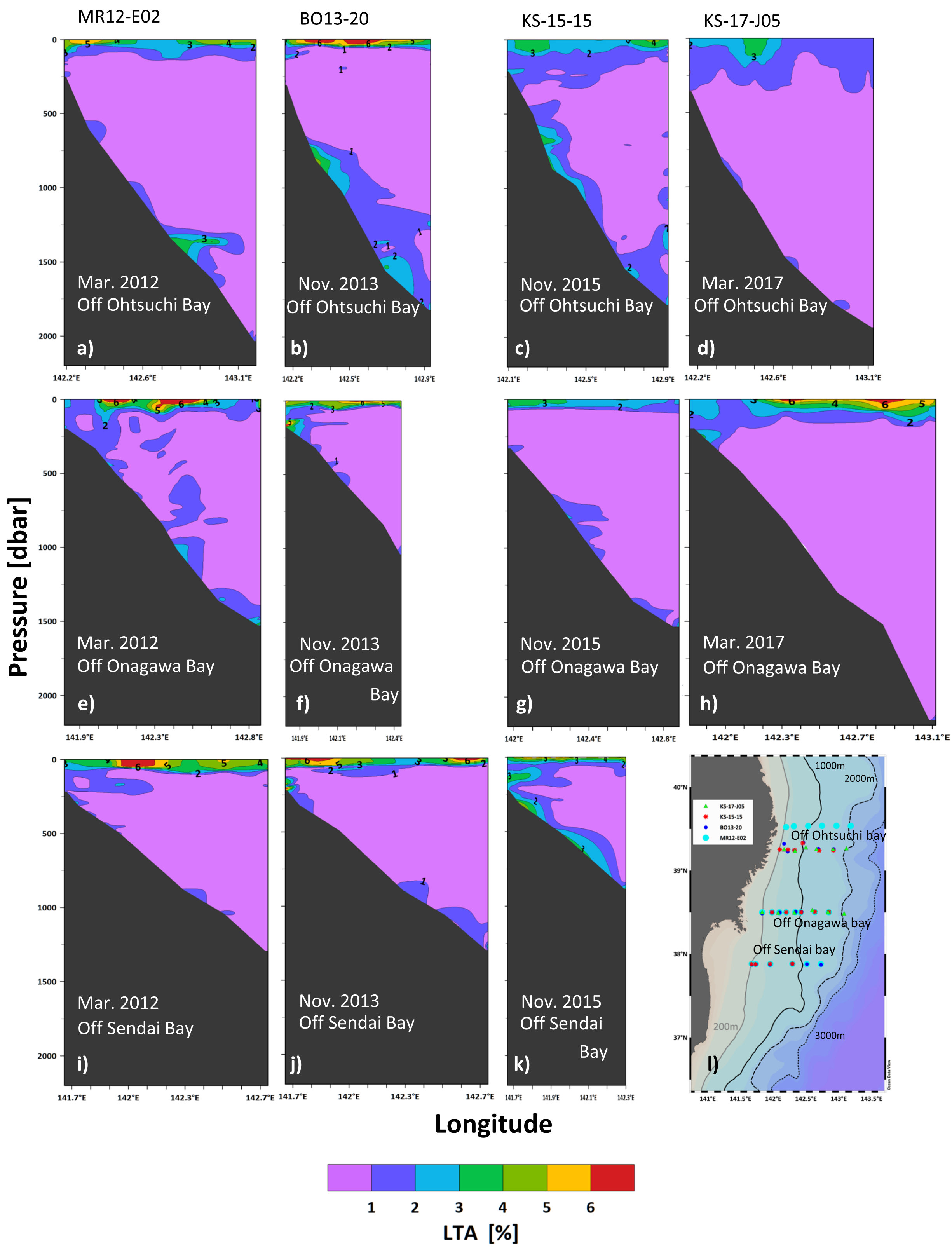

Fig. 2 Vertical distributions of light transmissometer anomaly (LTA) values measured during cruises MR12-E02 (**a**, **e**, and **i**), BO13-20 (**b**, **f**, and **j**), KS-15–15 (**c**, **g**, and **k**), and KS-17-J05 (**d** and **h**) off Ohtsuchi Bay, Onagawa Bay, and Sendai Bay (**l**). Contours of LTA are every 1%

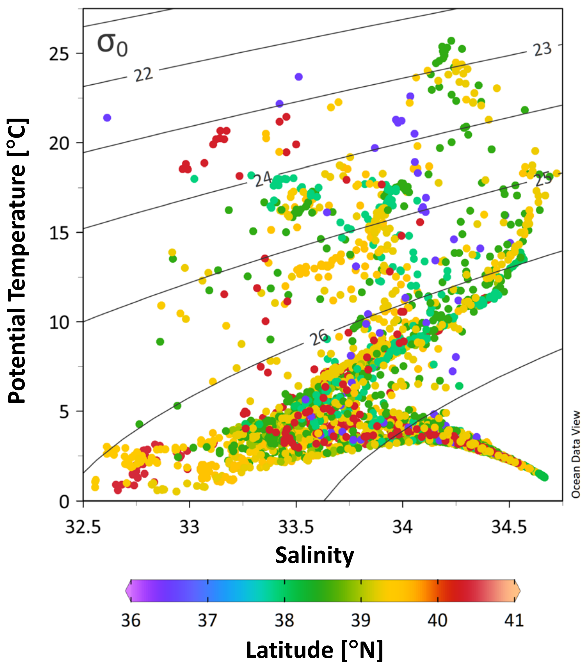

Fig. 3 Potential temperature–salinity diagram for our ship-based hydrographic observations. Contours show isopycnal surfaces. Colored circles denote the latitude of sampling locations

2011 Tohoku Earthquake on the two isopycnal surfaces ($27.38\sigma_\theta$ and $27.56\sigma_\theta$) (Fig. 5). The deep water below 1000 dbar (~ $27.38\sigma_\theta$), comprising a lower NPIW, showed no significant natural variation on a decadal timescale between 1993 and 2005 at the P10 section from 24 to 30°N (Murata et al. 2009). The mean values of potential temperature and salinity off Sanriku are statistically consistent before and after the 2011 Tohoku Earthquake (Fig. 5a and b) and also consistent with those along the P10 section in 2005, 2012, and 2014 (green triangles in Fig. 5a and b). These mean values on the $27.38\sigma_\theta$ surface after the 2011 Tohoku Earthquake (bold red lines in Fig. 5a and b) show no statistically significant difference to those measured at the deep-sea station (orange lines in Fig. 5a and b). The potential temperature and salinity on the $27.38\sigma_\theta$ surface were more variable than those on the $27.56\sigma_\theta$ surface. Thus, the deep-sea bottom water mass on the continental slope was similar to that along the P10 section and showed no significant decadal variation between 2004 and 2018. This deep-sea bottom water mass appears to have been unaffected by the physical disturbance of sediments after the 2011 Tohoku Earthquake.

Our comparison of the deep-sea bottom-water conditions before and after the 2011 Tohoku Earthquake showed that the mean values of DO on the isopycnal surfaces ($27.38\sigma_\theta$ and $27.56\sigma_\theta$) between 1000 and 1500 dbar decreased significantly (with an increase in AOU) by ~ 5 µmol/kg ($p < 0.001$ based on t test), whereas nutrients exhibited no significant differences and wide scatter (Fig. 5c–g). The mean value of DO on the slope was significantly lower (higher for AOU) than that along the P10 section (green triangles in Fig. 5c and d), whereas nutrients values showed no significant differences from those along the P10 section (green triangles in Fig. 5e–g). After the 2011 Tohoku Earthquake, values of DO and AOU on the $27.38\sigma_\theta$ surface varied within the range of values measured at the deep-sea station (orange lines in Fig. 5c–d). These differences between the shipboard surveys and the deep-sea station were not significant. Thus, DO in the deep-sea bottom water on the slope was still observed to be low (high for AOU) in 2018 along the entire Pacific coast off Sanriku.

In order to evaluate the decrease in DO due to sediment resuspension caused by earthquakes, we compared the bottom water at the deep-sea station (~ 1000 m depth) off Otsuchi Bay (Fig. 1) before and after the events of the large aftershocks: February 17, 2015, off Sanriku ($M_w = 6.7$, Ev1), September 17, 2017, off Sanriku ($M_w = 5.9$, Ev2), and July 7, 2018, off Boso Peninsula ($M_w = 5.9$, Ev3) (Fig. 1a and 6). Because the disturbance of surface sediments and subsequent high turbid bottom water at the deep-sea station returned to the pre-earthquake state within 10 days after the large aftershocks on December 7, 2012 ($M_w = 7.3$), and February 17, 2015 (Ev1) (Oguri et al. 2016, 2018), we compared DO values averaged within 9 days before and after the earthquake. Along with the increase in turbidity for the Ev1 (Oguri et al. 2018), a significant decrease in DO (~ 4 µmol/kg) was observed after the earthquake (Fig. 6a). Ev2 occurred 104 km away from the deep-sea station to the hypocenter and also induced a significant decrease in DO (~ 4 µmol/kg) (Fig. 6b). However, Ev3 494 km apart from the station induced no DO change at this station (Fig. 6c).

For the possibility of seafloor turbidity, the intensity of ground motion has been evaluated as the peak ground acceleration (PGA) (e.g., Gomberg 2018). Because of limited seafloor observation, we try to apply PGA to the intensity of ground motion. Sediment resuspension can be linked to the PGA. The value of the PGA for Ev2 (7−200 cm/s/s) was larger than the Ev3 (1−4 cm/s/s); these values were estimated from the negative correlation between distance from hypocenter and PGA for the aftershock observed by the Seafloor observation network for earthquakes and tsunamis along the Japan Trench (S-net) (Dhakal et al. 2021; Dhakal and Kunugi 2021). The PGA value for Ev1 cannot be estimated, as the S-net was constructed in 2016. Nevertheless, note that the hypocentral distance to the deep-sea station for Ev1 (88 km) was almost same as that for Ev2 (106 km) and was much shorter than that of Ev3 off the Boso Peninsula (483 km). Because of the

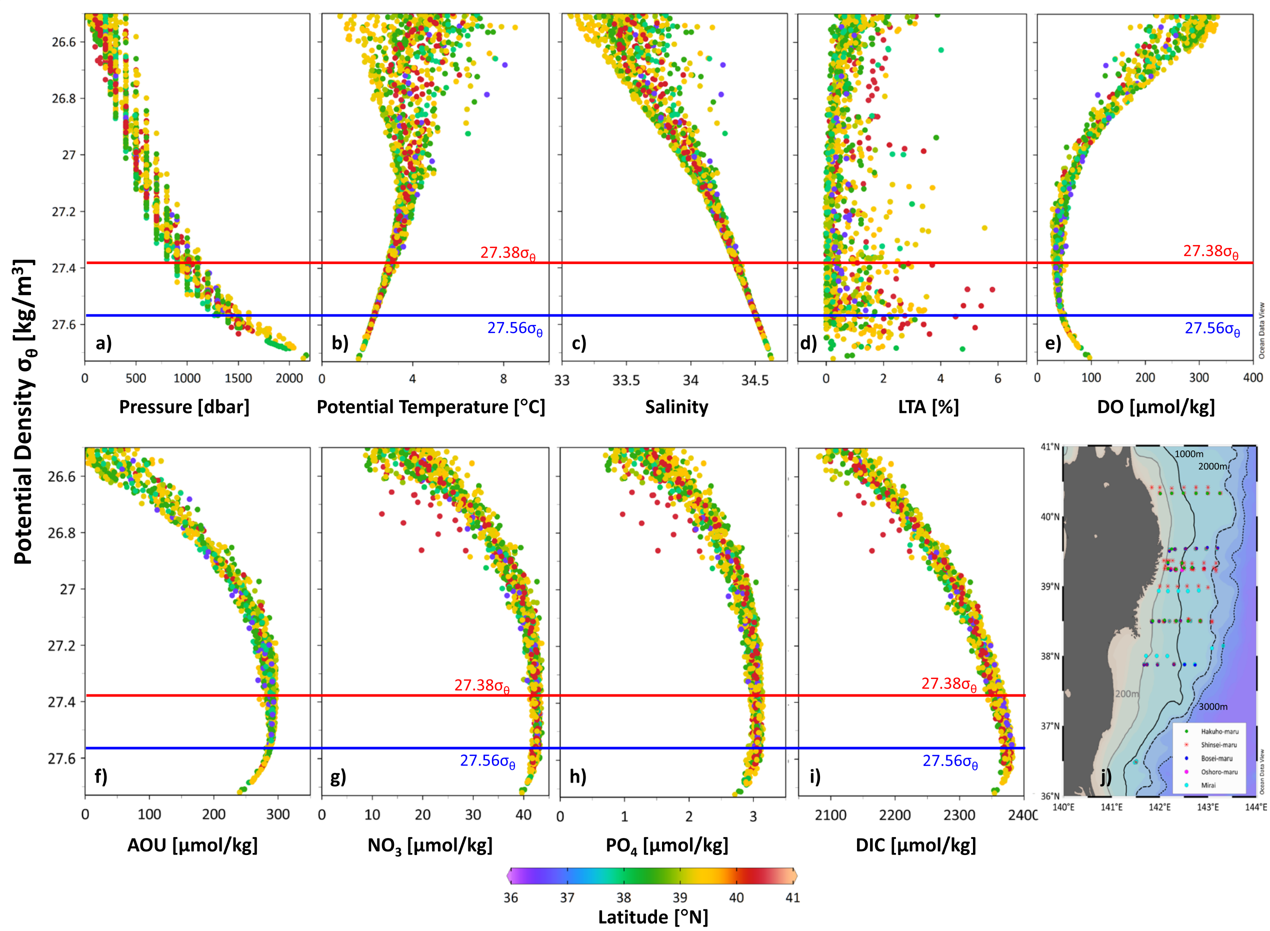

Fig. 4 Vertical profiles of pressure (**a**), potential temperature (**b**), salinity (**c**), LTA (**d**), DO (**e**), AOU (**f**), NO_3 (**g**), PO_4 (**h**), and DIC (**i**) as functions of potential density (σ_θ) and the location map (**j**) by using the cruises (Table 1). Colored circles denote the latitude of sampling locations. Lines show the studied isopycnal surfaces (27.38σ_θ: red; 27.56σ_θ: blue)

negative correlation with the hypocentral distance (e.g., Dhakal et al. 2021; Dhakal and Kunugi 2021), the PGA values for Ev1 are considered to be similar to that for Ev2 and to be much higher than that for Ev3. The difference in the DO changes attributes not to the earthquake magnitudes but to the PGA at the deep-sea station. Thus, high PGA induced by large aftershocks would cause an increase in turbidity/LTA besides the decrease in DO in the bottom water through sediment resuspension.

However, note that the decrease in the bottom-water DO due to sediment resuspension by the large aftershocks is affected by the underlying sediment properties such as sediment grain size and composition. Surface sediments on the upper slope (500−2000 dbar) over the entire area off Sanriku are dominated by silt and muddy sediments with high organic carbon contents (Fontanier et al. 2014; Ikehara et al. 2021; Nomaki et al. 2016). The oxygen penetration depth in the sediments on the upper slope was shallow than 0.5−1 cm, that is typical organic matter-rich sediments (Fontanier et al. 2014; Nomaki et al. 2016). The C/N ratios and stable carbon isotope ratios of the surface sediments within a year after the 2011 Tohoku Earthquake showed no significant difference between the event deposits, including turbidites, and the underlying sediment (Nomaki et al. 2016; Ikehara et al. 2021). These results indicate that high turbidity and LTA on the upper slope are characterized by sediment resuspension, short-distance transport, and resettling near the original site. Thus, the increase in turbidity and LTA by organic matter-rich surface sediment resuspension due to aftershock leads to DO decrease in the bottom water at the upper slope off Sanriku. This process is considered to consist of mixing of bottom water and oxygen-depleted sediment pore water and oxygen consumption due to aerobic decomposition of resuspended organic matter. The latter process is supported by the following report; in the few days after a hurricane passage

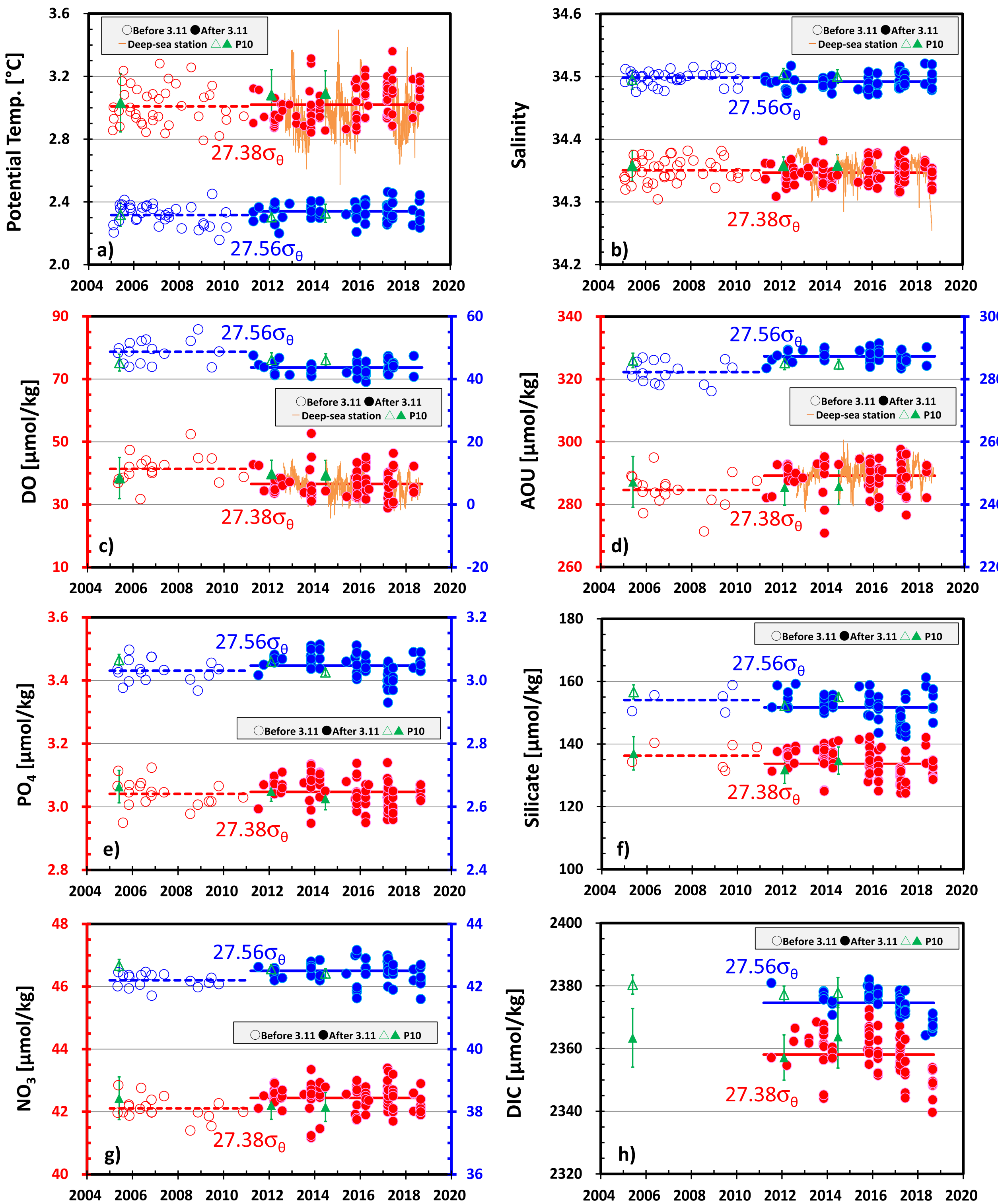

Fig. 5 Time series of potential temperature (**a**), salinity (**b**), DO (**c**), AOU (**d**), PO_4 (**e**), silicate (**f**), NO_3 (**g**), and DIC (**h**) in the Sanriku area (circles) and along the P10 section (green triangles) on the studied isopycnal surfaces (27.38σ_θ: red; 27.56σ_θ: blue). Open and closed symbols show values before and after the 2011 Tohoku Earthquake (3.11), respectively. In panels (**a**–**d**), thin orange lines denote values measured at the deep-sea station off Otsuchi Bay (Fig. 1a). Dashed and bold lines refer to mean values before and after the 2011 Tohoku Earthquake, respectively. Error bars are standard deviations for 2005, 2012, and 2014 along the P10 section, respectively. Right red (left blue) axes of DO (**c**), AOU (**d**), PO_4 (**e**), and NO_3 (**g**) denote the value on 27.38σ_θ (27.54σ_θ), respectively

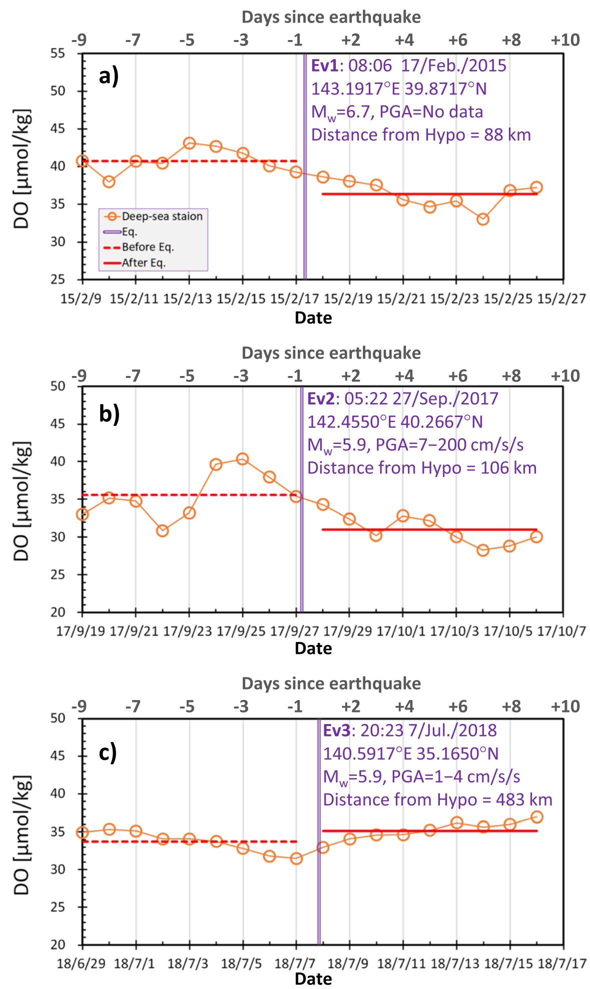

Fig. 6 Time series of DO in the bottom water at the deep-sea station (~ 1000 m depth) off Otsuchi Bay (Fig. 1a) before and after the events of the large earthquakes (purple double lines): February 17, 2015 (Ev1, Fig. 1a), September 17, 2017 (Ev2, Fig. 1a), and July 7, 2018, off then Boso Peninsula (Ev3). Dashed and bold lines refer to the 9-day mean values before and after the large earthquakes, respectively

in the northern Gulf of Mexico, organic matter of resuspended shelf sediments consumes the DO in the bottom water through aerobic decomposition (Bianucci et al. 2018).

To estimate the decrease in bottom-water DO on the upper Sanriku slope after the 2011 Tohoku Earthquake by the pore water/bottom water mixing and oxygen consumption, we calculate the thickness of surface sediments resuspended by the 2011 Tohoku Earthquake and large aftershocks ($\mathbf{x}$ [m]), based on simple box model (Fig. 7), as follows:

$$A = B\,h\,a\,[\mathrm{mmol}] / a\,(h + \mathbf{x})\left[\mathrm{m}^3\right] \quad (6)$$

$$\mathbf{x}[\mathrm{m}] = h\,(B - A) / A \quad (7)$$

where B and A are the DO concentration before and after the 2011 Tohoku Earthquake [mmol/m^3], respectively, a is the entire area at the upper Sanriku slope [m^2], and h is the thickness of bottom water affected by surface sediment resuspension due to aftershock [m]. We use 1 [m] as the h, because a HDTV camera at the deep-sea station off Otsuchi Bay was installed at a height of 0.5–1 m above the seafloor and captured the turbidity through aftershock (Oguri et al. 2016, 2018). We assume that the DO concentration in the porewater is 0 [mmol/m^3], as the depth of oxygen penetration in the upper slope sediments was very shallow (0.5–1 cm) (Fontanier et al. 2014; Nomaki et al. 2016). The DO concentration after the 2011 Tohoku Earthquake (A) and the difference of DO before and after the 2011 Tohoku Earthquake (B–A) on the 27.38σ_θ and 27.56σ_θ surfaces are 37.6–44.9 [mmol/m^3] and 4.9–5.1 [mmol/m^3], respectively. Using these values, $\mathbf{x}$ is estimated to be 0.11–0.13 [m]. These values are almost the same as previously reported earthquake-induced surface sediment remobilization thickness (0.02–0.12 [m]) (Molenaar et al. 2019). Thus, we verified the rationality of the decrease in bottom-water DO on the upper Sanriku slope after the 2011 Tohoku Earthquake by the water mixing and oxygen consumption mechanisms.

The relationships between LTA intensity and contents of chemical components in the deep-sea bottom water were examined to estimate the source of these components (e.g., Mottl et al. 1995; Kawagucci et al. 2012). The disturbance of sediments by the 2011 Tohoku Earthquake is presumed to have been accompanied by the input of sediment porewater into the overlying deep-sea bottom water. Because DO and NO_3 (PO_4) concentrations in the bottom water are higher (lower) than those in porewater in the sediments as a result of remineralization, as shown for the area off Sanriku in March 2012 (Nomaki et al. 2016), we examined the relationship between bottom-water LTA and DO, NO_3, PO_4, and DIC during 2011–2018 after the 2011 Tohoku Earthquake on the continental slope over Sanriku (Fig. 8). LTA was found to be significantly positively (negatively) correlated with AOU, PO_4, and DIC (DO) on the two isopycnal surfaces (27.38σ_θ and 27.56σ_θ) (Fig. 8a–8c, e). No positive correlation between LTA and NO_3 concentration was found, but LTA was positively correlated with ANU (Fig. 8d and f). These results indicate that increased turbidity is associated with higher concentrations of PO_4, and DIC in the deep-sea water on the continental slope and with lower DO and NO_3 concentrations.

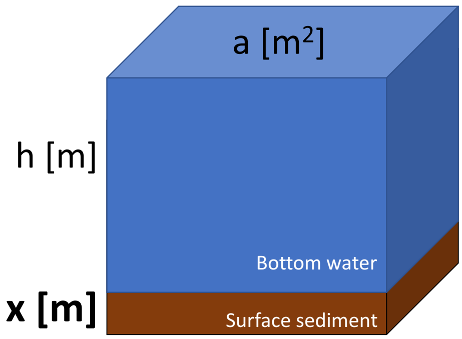

Fig. 7 Schematic simple box model in the bottom water and the surface sediment at the upper Sanriku slope. "x" is the thickness of surface sediments resuspended by the 2011 Tohoku Earthquake and aftershocks. "a" is the area at the upper Sanriku slope [m^2], and "h" is the thickness of bottom water affected by surface sediment resuspension due to the 2011 Tohoku Earthquake and aftershock

The chemical influxes associated with sediment resuspension by the 2011 Tohoku Earthquake and large aftershocks are considered to have modified the deep-sea bottom water on the continental slope by remineralization caused by respiration and denitrification by the microbial community. To examine this effect, we estimated remineralization-corrected DIC and PO_4 (Fig. 8g and h) and found no significant correlation between LTA and remineralization-corrected DIC and PO_4 on either of the studied isopycnal surfaces. The values of remineralization-corrected DIC and PO_4 on the slope after the 2011 Tohoku Earthquake (2154 ± 4 μmol/kg and 1.28 ± 0.03 μmol/kg for 27.38σ_θ, and 2172 ± 3 μmol/kg and 1.29 ± 0.03 μmol/kg for 27.56σ_θ) (Fig. 8g and h) are consistent with those at the P10 section (2156 ± 4 μmol/kg and 1.30 ± 0.01 μmol/kg for 27.38σ_θ, and 2174 ± 3 μmol/kg and 1.32 ± 0.01 μmol/kg for 27.56σ_θ). The values of remineralization-corrected PO_4 on the slope are statistically consistent before (1.31 ± 0.04 μmol/kg for 27.38σ_θ and 1.31 ± 0.03 μmol/kg for 27.56σ_θ) and after the 2011 Tohoku Earthquake. The increases in DIC and PO_4 were therefore due to remineralization from respiration and denitrification by the microbial community as a result of the 2011 Tohoku Earthquake and the large aftershocks, and the chemical influxes caused by earthquake-related sediment resuspension affected the deep-sea bottom water on the continental slope.

Moreover, several large earthquakes before the 2011 Tohoku Earthquake during 2001–2010 occurred off Sanriku (e.g., August 16, 2005, off Miyagi Prefecture, M_w = 7.2; November 15, 2005, off Sanriku, M_w = 7.2; May 8, 2008, off Ibaraki Prefecture, M_w = 7.0) (JMA 2022) and also might have affected the deep-sea bottom water on the continental slope. We compared the increase in PO_4 due to remineralization by respiration and denitrification (1/170 AOU + 1/104 ANU) before and after the 2011 Tohoku Earthquake. The remineralized PO_4 value after the 2011 Tohoku Earthquake (1.76 ± 0.03 μmol/kg for 27.38σ_θ and 1.75 ± 0.02 μmol/kg for 27.56σ_θ) was significantly higher than that before the 2011 Tohoku Earthquake (1.74 ± 0.03 μmol/kg for 27.38σ_θ and 1.72 ± 0.02 μmol/kg for 27.56σ_θ) ($p < 0.01$ based on t test). Although several large earthquakes before the 2011 Tohoku Earthquake during 2001–2010 (JMA 2022) also would affect the deep-sea bottom water on the slope, the 2011 Tohoku Earthquake and large aftershocks would have a greater impact on the deep-sea bottom water. In summary, the post-earthquake chemical changes in the deep-sea bottom-water environment caused by remineralization from respiration and denitrification after the 2011 Tohoku Earthquake are considered to be maintained by sporadic sediment resuspension induced by the persistent occurrence of large aftershocks.

The regression slopes between LTA and DO, AOU, PO_4, NO_3, and DIC on the 27.38σ_θ surface were steeper than those on the 27.56σ_θ surface (Fig. 8a–f). This implies that the sources of chemical input may be different between isopycnal surfaces. To clarify the difference in these chemical input sources, we examined the concentrations and carbon isotope ratios of methane off Ohtsuchi bay and Onagawa bay near the hypocenter of the earthquake on October 23, 2015 (M_w = 4.9), in early November during cruise KS-15-15 (Fig. 9), as methane is an effective chemical tracer for the input of sub-seafloor fluid into deep-sea water (e.g., Tsunogai et al. 2000; German et al. 2010).

The methane contents in the deep-sea bottom water (up to ~ 4 nM) measured in this study are an order of magnitude smaller than the ~ 60 nM measured 36 days after the earthquake during cruise MR11-03 (Kawagucci et al. 2012). This methane in the deep-sea bottom water has two peaks of LTA intensity near the isopycnal surfaces of 27.38σ_θ and 27.56σ_θ (Fig. 9a and b) and is unlikely to have originated from in situ microbial methanogenesis because of the aerobic condition of the seawater (Fig. 4e).

The stable carbon isotope ratio of methane decreased with increasing depth and σ_θ (Fig. 9c). A Keeling plot analysis (Keeling 1958) for each isopycnal surface (Fig. 9e) reveals two sources of methane. The methane source inferred for the 27.56σ_θ surface (~ 1500 dbar) was relatively enriched in ^{13}C (− 55‰). This value is similar to that of methane measured at a depth of > 800 m below the seafloor near the hypocenter during Ocean Drilling Project Sites 1150 and 1151 (Ijiri et al. 2009) and to those detected in the water column close to the hypocenter region 36 days after the earthquake (Kawagucci et al. 2012). Moreover, this δ^{13}C value is also similar

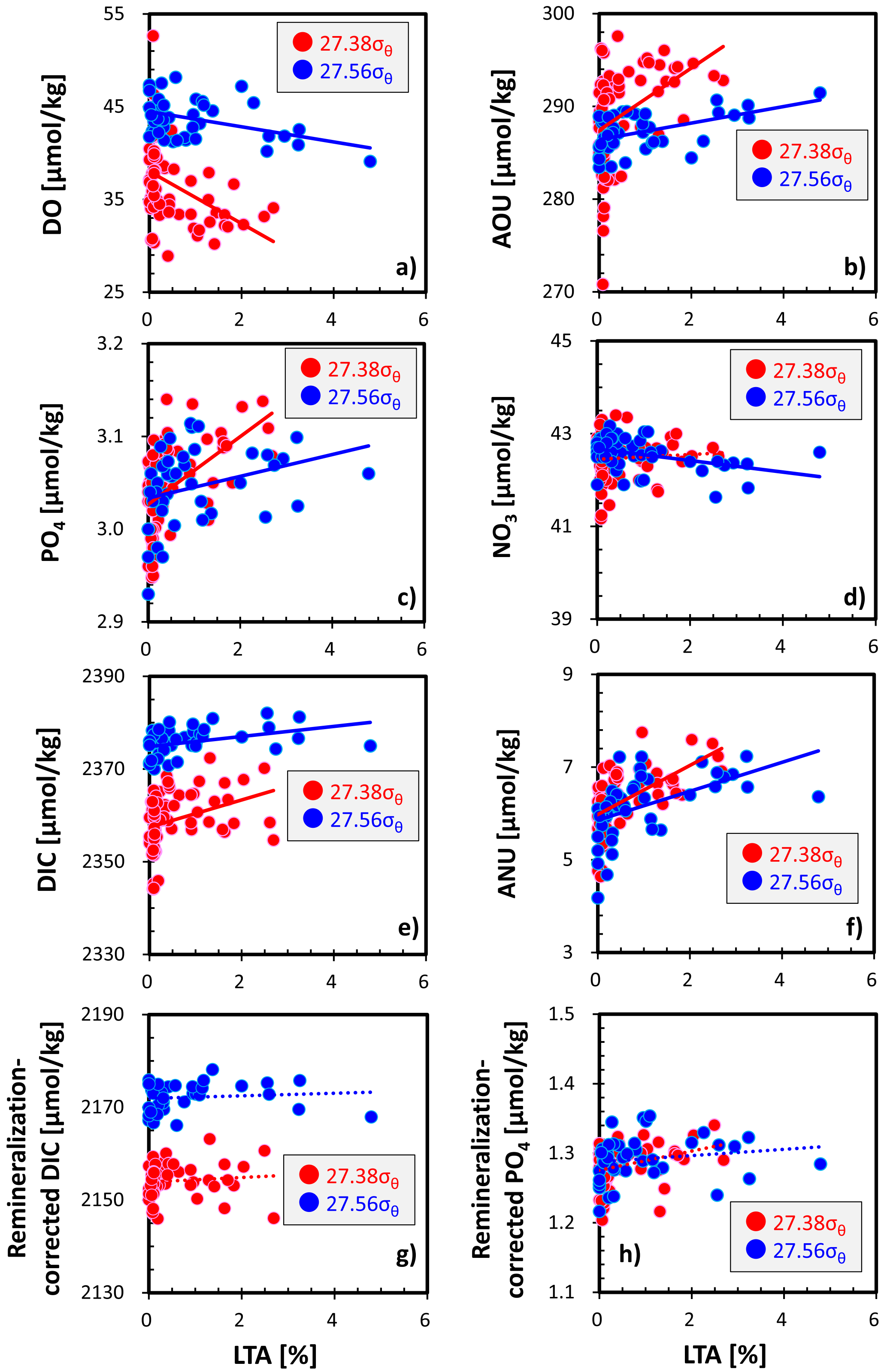

Fig. 8 Relationships between DO (**a**), AOU (**b**), PO_4 (**c**), NO_3 (**d**), DIC (**e**), ANU (**f**), remineralization-corrected DIC (**g**), and remineralization-corrected PO_4 (**h**) and LTA value on the studied isopycnal surfaces (27.38σ_θ: red circles; 27.56σ_θ: blue circles). Solid (dotted) lines indicate statistically significant (insignificant) regressions ($p < 0.05$)

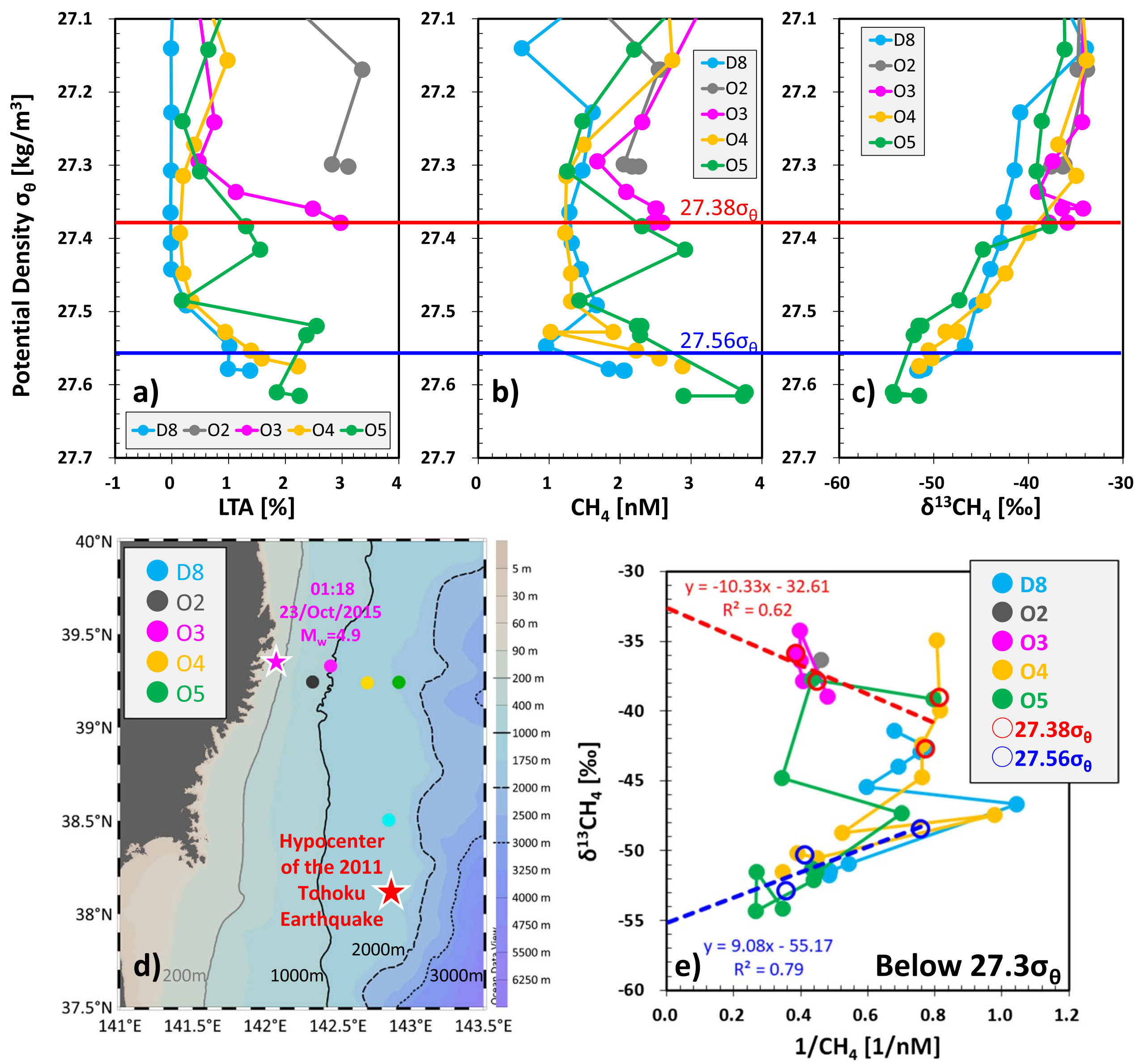

Fig. 9 **a**–**c** Vertical profiles of LTA (**a**), methane (CH_4), **b** and stable carbon isotope ratio of methane ($\delta^{13}CH_4$) as functions of potential density (σ_θ) at five sampling stations (D8, O2, O3, O4, and O5) during cruise KS-15-15. Lines show the studied isopycnal surfaces (27.38σ_θ: red; 27.56σ_θ: blue). **d** Location map and bathymetry of sampling stations during cruise KS-15-15, with the hypocenter of the 2011 Tohoku Earthquake and the earthquake on October 23, 2015 (Mw = 4.9), shown as a red star and a pink star. Bathymetric contours show 200 m depth (solid gray line), 1000 m depth (solid black line), 2000 m depth (dashed black line), and 3000 m depth (dotted black line). The color bar shows the depth of bathymetry. **e** Keeling plot of concentrations of CH_4 and $\delta^{13}CH_4$ at five sampling stations (D8, O2, O3, O4, and O5) during cruise KS-15-15. Open circles denote data for the studied isopycnal surfaces (27.38σ_θ: red; 27.56σ_θ: blue), and dashed red and dashed blue lines show the respective linear regression lines

to that in the hadal water below 8000 m at 34°N in the Izu–Ogasawara Trench (Kawagucci et al. 2018). The 2011 Tohoku Earthquake and aftershocks drive drastic marine organic carbon supply to the hadal Japan trench (Ikehara et al. 2021; Kioka et al. 2021; Schwestermann et al. 2021), which is possibly associated with the relatively ^{13}C-enriched methane in the hadal water at the trench. The sources of methane for the 27.56σ_θ surface by sediment resuspension after the 2011 Tohoku Earthquake might be derived from deep sub-seafloor reservoirs or sedimentary compound releases of marine organic carbon within the trench.

The methane source inferred from the $27.38\sigma_\theta$ surface (~1000 dbar) showed an enriched ^{13}C signature ($\delta^{13}C = -33‰$) (Fig. 9e). After the earthquake on October 23, 2015, DO concentration at the deep-sea station decreased during November (Oguri et al. 2018). Because the hypocentral distance to the deep-sea station and station O3 during KS-15-15 was close (~34 km), the high LTA on the $27.38\sigma_\theta$ surface (Fig. 9a) might be affected by sediment resuspension by the aftershocks. The ^{13}C-enriched methane on the $27.38\sigma_\theta$ surface could have been derived from shallow sediment, in which the deep sub-seafloor-derived methane had been consumed through microbial methane oxidation, resulting in ^{13}C enrichment in the remnant methane (e.g., Yanagawa et al. 2016) and the subsequent release of this methane into the water column by sediment resuspension. Thus, the sources of chemical input on the upper slope by sediment resuspension after the 2011 Tohoku Earthquake would be derived from shallow sediment on the continental slope. The influx of methane into the deep bottom water caused by the 2011 Tohoku Earthquake might have remained until 2015.

4 Conclusions

We conducted shipboard hydrographic observations during 2011–2018 to investigate changes in the deep-sea bottom-water environment on the continental slope off Sanriku, Japan, before and after the 2011 Tohoku Earthquake. Focusing on the deep-sea bottom-water environment between 1000 and 1500 dbar, particularly on the isopycnal surfaces of $27.38\sigma_\theta$ and $27.56\sigma_\theta$, we found that DO underwent a significant drop of about 10% after the 2011 Tohoku Earthquake, whereas nutrients and DIC showed no significant difference and wide variation.

After the 2011 Tohoku Earthquake, turbidity as calculated from LTA was detected in the bottom layer on the continental slope of the entire area off Sanriku. This high turbidity was caused by sporadic sediment resuspension resulting from frequent large aftershocks. LTA was positively correlated with PO_4, DIC, and methane and negatively with DO on the isopycnal surfaces of $27.38\sigma_\theta$ and $27.56\sigma_\theta$. Using these relationships, we ascertained that the deep-sea bottom-water environment was chemically changed by remineralization due to respiration and denitrification by the microbial community after the 2011 Tohoku Earthquake. Change in the deep-sea bottom-water chemical environment was maintained by sporadic sediment resuspension induced by continuing large aftershocks and might have been caused by the variations in DIC and PO_4 on the slope after the mainshock and large aftershocks.

Deep-sea station monitoring at 1000 dbar has shown that benthic biota remained unchanged by the increased turbidity caused by sediment resuspension from large aftershocks (Oguri et al. 2016, 2018) and that the changed deep-sea microbial community recorded 36 days after the earthquake had returned to its original state 98 days after the earthquake (Kawagucci et al. 2012). The present study revealed that the impact of the 2011 Tohoku Earthquake on the deep-sea bottom-water environment expanded in extent across the continental slope area with time through chemical influxes associated with sediment resuspension caused by large aftershocks. This continuous and widespread impact likely affected the marine ecosystem and microbial community on the continental slope. It is therefore essential to continue to monitor the marine ecosystem and microbial community off Sanriku through ship-based hydrographic and chemical observations.

Abbreviations

ANU: Apparent nitrogen utilization; AOU: Apparent oxygen utilization; CTD–CMS: Conductivity–temperature–depth profiler with carousel multiple sampling; DIC: Dissolved inorganic carbon; DO: Dissolved oxygen; JAMSTEC: Japan Agency for Marine-Earth Science and Technology; JMA: Japan Meteorological Agency; LTA: Light transmissometer anomaly; NO_3: Nitrate; NPIW: North Pacific Intermediate Water; M_w: Moment magnitude; PO_4: Phosphate; TEAMS: Tohoku Ecosystems-Associated Marine Sciences; RM: Reference material.

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Author contributions

MW proposed the topic and conceived and designed the study. JY, KO, HN, and SK analyzed the data and assisted in their interpretation. SW, KA, AN, and KF collaborated with the corresponding author in the construction of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets supporting the conclusions of this article are available in the physical and biogeochemical database for 2005–2018 collected off the Pacific coast of Sanriku and along the international repeat hydrography program P10 section (https://www.jamstec.go.jp/j/about/informations/notification_2021_maintenance.html?lang=en; http://www.data.jma.go.jp/gmd/kaiyou/db/vessel_obs/data-report/html/ship/ship_e.php; https://www.ncei.noaa.gov/access/ocean-carbon-data-system/oceans/RepeatSections/clivar_p10.html).

Declarations

Competing interests
The authors declare that they have no competing interests.

Author details
[1]Mutsu Institute for Oceanography (MIO), Research Institute for Global Change (RIGC), Japan Agency for Marine-Earth Science and Technology, 690 Kitasekine, Sekine, Mutsu, Aomori 035-0022, Japan. [2]Tohoku Environmental Science Services Corporation (TESSCO), 330-2, Nozuki, Obuchi, Rokkasho, Aomori 039-3212, Japan. [3]Marine Biodiversity and Environmental Assessment Research Center (BioEnv), Research Institute for Global Change (RIGC), Japan Agency for Marine-Earth Science and Technology, 2-15, Natsushima, Yokosuka, Kanagawa 237-0061, Japan. [4]HADAL and Nordcee, Department of Biology, University of Southern Denmark (SDU), Campusvej 55, 5230 Odense M, Denmark. [5]Super-Cutting-Edge Grand and Advanced Research (SUGAR), Program Institute for Extra-Cutting-Edge Science and Technology Avant-Garde Research (X-star), Japan Agency for Marine-Earth Science and Technology, 2-15, Natsushima, Yokosuka, Kanagawa 237-0061, Japan. [6]Research and Development Center for Earthquake and Tsunami Forecasting (FEAT), Research Institute for Marine Geodynamics (IMG), Japan Agency for Marine-Earth Science and Technology, 3173-25, Showa-machi, Kanazawa, Yokohama, Kanagawa 236-0001, Japan. [7]Global Ocean Observation Research Center (GOORC), Research Institute for Global Change (RIGC), Japan Agency for Marine-Earth Science and Technology, 2-15, Natsushima, Yokosuka, Kanagawa 237-0061, Japan.

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