Abyssal current and water mass in the Main Gap and an adjacent Small Gap of the Emperor Seamount Chain

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Abstract
From 2016 to 2017, we conducted 1-year mooring current observation at the widest, deepest gap, widely known as the Main Gap, and a narrower, shallower gap just south of the Main Gap, called the Small Gap in this study, in the Emperor Seamount Chain, which divides the Northwest Pacific Basin (NWPB) from the Northeast Pacific Basin. We also conducted two hydrographic sections with a conductivity–temperature–depth sensor and a lowered acoustic Doppler current profiler around the two gaps in 2012 and 2016. At the Main Gap, the abyssal current flowed east–northeastward at a statistically significant mean velocity of 1.3–2.4 cm s⁻¹, while the current was dominated by tidal and inertial variability with a magnitude of 3–4 cm s⁻¹.

At the Small Gap, the abyssal current had an eastward mean velocity of 9.4 cm s⁻¹, accompanied by mesoscale variability with a magnitude of 7 cm s⁻¹. These eastward currents carried abyssal water below a depth of 5000 m, which came from the northern part of the NWPB, with a volume transport of 1.6 × 10⁶ m³ s⁻¹ through the Main Gap and 0.5 × 10⁶ m³ s⁻¹ through the Small Gap. Cold, saline, oxygen-rich Lower Circumpolar Deep Water, which occupied the south of the zonal seamount range at 37°N, called the S–E Seamounts in this study, was found near the seafloor north of the S–E Seamounts to the west of the Small Gap; however, it did not extend to the Main Gap or to the east of the Small Gap.

Keywords Deep ocean circulation · North Pacific Ocean · Emperor Seamount Chain · Lower Circumpolar Deep Water · Mooring observation · CTD observation

1 Introduction
The global deep ocean circulation brings cold, saline, oxygen-rich Lower Circumpolar Deep Water (LCDW) below a depth of 3500 m from the Southern Ocean to the world oceans. It plays an important role in transporting heat and materials as the lowest portion of the global meridional overturning circulation (Richardson 2008). Deep western boundary currents (DWBCs) are the major transporter of LCDW in the deep ocean circulation, while deep mesoscale variability has also been recently suggested to have some contribution to the transport of deep waters (Bower et al. 2009, 2011; Miyamoto et al. 2017, 2020).

In the Pacific Ocean, the DWBC enters the Central Pacific Basin through the Samoan Passage carrying LCDW from the south (Fig. 1; Mantyla and Reid 1983; Rudnick 1997). It then bifurcates into a shallower western branch and a deeper eastern branch, due to the sill depth of approximately 4500 m between the Central Pacific Basin and the Melanesian Basin (Johnson and Toole 1993; Kawabe et al. 2003). While a part of the eastern branch separates eastward and enters the Northeast Pacific Basin (NEPB) (Kato and Kawabe 2009), the rest of it enters the southern part of the Northwest Pacific Basin (NWPB) through the Wake Island Passage (Kawabe et al. 2005). Because there is a sill with depth of approximately 5150 m along 37°N between the Shatsky Rise and the Emperor Seamount Chain (ESC), the...
The eastern branch makes an anticlockwise turn south of the sill (Yanagimoto and Kawabe 2007); this sill is called the S–E Seamount in this study. Then, the eastern branch turns clockwise south of the Shatsky Rise (Yanagimoto et al. 2010), joins the western branch to the east of the Japan Trench (Fujio and Yanagimoto 2005), and advances further northward (Ando et al. 2013). Finally, it is believed to flow out from the NWPB to the NEPB (Owens and Warren 2001; Kawabe and Fujio 2010).

The NWPB and the NEPB are separated by the ESC, which ranges meridionally for approximately 2400 km along ~170°E between the Aleutian Trench and the Hawaiian Ridge. The ESC consists of tall and steep guyots rising up to 20–2000 m below the sea surface and crests standing at about 3000–5000 m above the ocean floor (Roden et al. 1982) affecting the shallow flow field at depths less than 2000 m (Wagawa et al. 2012). Moreover, the ESC acts as a barrier for the deep ocean circulation in the two basins. Besides the junction of the Kuril Trench and the Aleutian Trench that is believed to be the most plausible route from the NWPB to the NEPB (broken line in Fig. 1), several gaps in the ESC can be pathways for the deep water (Owens and Warren 2001). Among them, the widest, deepest gap with an approximately 100-km width and 6000-m depth, called the Main Gap, is thought to be the most important pathway.

Owens and Warren (2001) illustrated an eastward current through the Main Gap on their schematic of deep currents in the western North Pacific based on historical studies, including a 17-month mooring observation that detected a strong northeastward flow over the steep slope at the southernmost part of the Main Gap (Hamann and Taft 1987), although they left it unresolved whether the eastward current comes from the north or south (dotted arrows in Fig. 1). Komaki and Kawabe (2009) demonstrated an eastward abyssal flow transporting relatively oxygen-rich and cold water at the center of the Main Gap based on shipboard conductivity–temperature–depth (CTD) profiler and lowered acoustic Doppler profiler (LADCP) observations, speculating that a part of the LCDW separating from the eastern branch and crossing over the S–E Seamounts might pass the Main Gap. Nevertheless, observations around the Main Gap are still very few and fragmentary.
This study focuses on two major questions indicated by a question mark in Fig. 1, that is, whether the abyssal water is carried eastward through the Main Gap on average, and where the abyssal water comes from. To answer these questions, we intensively observed abyssal currents around the Main Gap from 2016 to 2017. In addition, we surveyed deep currents in a small gap just south of the Main Gap for an alternate pathway of deep water across the ESC.

2 Observation and data

2.1 Mooring observations

The KH-16–3 cruise of the R/V Hakuho Maru was carried out in June 2016 (Fig. 2a; Oka et al. 2020). The vessel departed from Tokyo on 31 May, arrived at the ESC area on 9 June, left there on 13 June, and returned to Tokyo on 29 June. Our study area is shown by a broken-line rectangle in Fig. 2a and is enlarged in Fig. 2b. The study area is located to the east of the Shatsky Rise, containing four tall named guyots of the ESC standing in a row: the Nintoku, Jingu, Ojin and Koko Guyots. The Jingu and Ojin Guyots are two peaks of one massive seamount, surrounded by a single isobath of 3000 m. There is a nameless guyot to the north of Koko Guyot, called K–N Guyot hereafter. The Main Gap lies between the Nintoku and Ojin Guyots. Between the K–N and Ojin Guyots lies a small gap of the ESC, called the Small Gap in this study. The Small Gap is a narrow passage with a width of about 30 km and is a low sill with a depth of approximately 5200 m (Fig. 2c). To the west of the K–N Guyot, small seamounts extend zonally along approximately 37°N to the Shatsky Rise (Fig. 2b). We call them the S–E Seamounts hereafter. The S–E Seamounts have a sill depth of approximately 5150 m, preventing the deeper portion of LCDW from passing northward (Yanagimoto and Kawabe 2007).

We deployed two mooring systems ME1 and ME2 in the Main Gap and one mooring system ME3 in the Small Gap on 10, 11, and 12 June 2016, respectively (Fig. 2b). To avoid the effect of steep topography, ME1 and ME2 were moored over the flat seafloor in the Main Gap. ME3 was located near the center of the Small Gap to avoid the steep slopes of the guyots (Fig. 2c). We successfully recovered ME3 and ME1 in the second leg of the C40 cruise of Hokkaido University’s T/V Oshoro Maru on 24 and 25 June 2017, respectively. However, our effort to recover ME2 during the cruise resulted in failure, perhaps due to troubles in the acoustic releaser.

At ME1, we moored four current meters at depths of 4045, 5045, 5445, and 5845 m above the seafloor at 5895 m; the upper three were 3D-ACMs, which were single-point current meters manufactured by Falmouth Scientific, Inc., and the lowest is a downward-looking 300-kHz Workhorse Sentinel, which was an ADCP manufactured by Teledyne RD Instruments. At ME3, two 3D-ACMs and one downward-looking 300-kHz Workhorse Sentinel were moored at depths of 4160, 4760, and 5163 m, respectively, on the seafloor at 5213 m (determined by a ship-mounted precision depth recorder). Both at ME1 and ME3, ADCP records from the vertical cells at 4-m intervals were similar to one another except for the cells near the mooring releasers (~20 m below the instruments), where measured velocities were small probably due to the reflection of the pings (not shown). We adopted ADCP data from the second cell which was 10 m below the instruments. Unfortunately, we failed in accessing records in the two upper instruments at ME1 and the uppermost one at ME3 due to memory trouble. Furthermore, the second upper instrument at ME3 failed in reconstructing current vectors from three-dimensional measurements along instrument coordinates. Overall, we obtained three data sets at 5445 m (ME1–3) and 5855 m (ME1–4) of ME1, and at 5173 m (ME3–3) of ME3 (Table 1).

All the current meters were set to record current velocity components every hour. We call them hourly current in this study. We subsampled them every midnight Coordinated Universal Time after filtering out inertial oscillations and diurnal and semi-diurnal tides using a Gaussian filter called gaus24 (Thompson 1983). We call them daily current hereafter.

2.2 CTD/LADCP observations and hydrographic data sets

Fifteen full-depth CTD casts from the surface to approximately 10 m above the seafloor were conducted around the Main Gap and the Small Gap during the KH-16–3 cruise (stations H01 to H15 in Fig. 2b and Table 2). Two LADCPs (300-kHz Workhorse Monitor) were attached at the top and bottom of the CTD frame with its transducer turned upward and downward, respectively. We obtained absolute current velocity profiles from these LADCPs within the depth range, where bottom-track velocity was available by downward-looking LADCP (below approximately 100 m above the seafloor). To remove noise, we averaged them between 10 and 50 m above the seafloor.

The Japan Meteorological Agency (JMA) operated the RF1206 cruise of R/V Ryofu Maru in July to September 2012 (Fig. 2a) and conducted full-depth CTD/LADCP observations around the Main Gap (R01 to R27 in Fig. 2b and Table 2). We reproduced vertical profiles of LADCP current data by the same method as for KH-16–3. Unlike the KH-16–3 observation, only a downward-looking LADCP was set on the CTD frame.

The CTD data of the KH-16–3 and RF1206 sections in Table 2 were used to identify the abyssal water at the Main
Gap and the Small Gap. To compare water properties among the gaps and their surrounding areas, we classified our CTD/LADCP stations into five geographic regions: NWMG, MG, WSG, ESG and SSES (Fig. 2b). The NWMG region is located along 40°N between the Shatsky Rise and the ESC, the MG region is in the Main Gap, the WSG region is to the west of the Small Gap, and the ESG region is to the east of the Small Gap. The SSES region, to which LCDW is carried...
directly from the south (Yanagimoto and Kawabe 2007), is located to the south of S–E Seamounts.

We also investigated a wider distribution of water properties using recent full-depth hydrographic data sets from the following sections or cruises; P01 in 2014, P02 in 2013, and P10 in 2012 archived by the CLIVAR and Carbon Hydrographic Data Office (CCHDO), and RF1106, RF1107 and RF1108 in 2011, RF1203 in 2012, and RF1505 in 2015 operated by the JMA’s R/V Ryofu Maru (Fig. 2a). Hydrographic data around the Main Gap were enriched by two casts at the RF1505 cruise (blue triangles in Fig. 2b). We also used by Uchida et al. (2020): + 0.0004 for the batch P153 used in of the International Association for the Physical Sciences of the Oceans (IAPSO) Standard Seawater (SSW) evaluated of the Oceans (IAPSO) Standard Seawater (SSW) evaluated.

The histograms of daily current direction are plotted with

| Table 1  | Moored instruments recovered successfully and statistics of eastward and northward velocity components ($u$, $v$) of their daily current (smoothed as in text) |
|---------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Data ID | Depth [m] | Record length [days] | Average [cm s$^{-1}$] with standard error $\frac{u \pm \varepsilon_u}{\tau_u}$ | Integral time scale [days] |
|---------|----------|----------------------|-------------------------------------------------|----------------------|
| ME1–3   | 5445     | 380                  | $2.1 \pm 0.6$ | $1.2 \pm 1.4$ | 7.2 21.2 |
| ME1–4   | 5855     | 380                  | $1.1 \pm 0.3$ | $0.6 \pm 0.9$ | 3.3 17.9 |
| ME3–3   | 5173     | 377                  | $9.2 \pm 1.9$ | $-1.7 \pm 0.6$ | 11.7 11.4 |

We used current records from the second cell of Workhorse ADCP as ME1–4 and ME3–3

3 Abyssal current

3.1 Temporal characteristics of currents observed by moorings

Time series of daily current vectors at the mooring systems ME1 and ME3 are shown by stick diagrams in Fig. 3. The histograms of daily current direction are plotted with
current speed of about 4 cm s\(^{-1}\). Thus, tidal and inertial variability was dominant at the Main Gap and was equivalent to 3–4 cm s\(^{-1}\) at both the Main Gap and the Small Gap. Incidentally, T > 20 band was the smallest among u components; this is the cause of the short integral time scale and extremely small standard error for u at ME1 (Table 1). On the other hand, the u component of T > 20 band at ME3–3 had the largest value equivalent to a current speed of about 7 cm s\(^{-1}\). Mesoscale variability was dominant at the Small Gap; its kinetic energy of 27.2 cm\(^2\) s\(^{-2}\) was approximately

| Table 2 | Full-depth CTD/ LADCP stations carried out in this study |
|---------|----------------------------------------------------------|
| Station number | Original stn. number | Latitude | Longitude | Seafloor depth [m] | Reaching-bottom time (UTC) |
| R/R Hakuho Maru KH-16–3 cruise |
| H01 | C014 | 39°25.08′N | 170°00.27′E | 5842 | 10 Jun. 2016, 10:34 |
| H02 | C015 | 39°24.49′N | 170°24.56′E | 6236 | 10 Jun. 2016, 16:23 |
| H03 | C016 | 38°59.81′N | 170°25.13′E | 6339 | 10 Jun. 2016, 23:10 |
| H04 | C017 | 38°59.55′N | 170°00.44′E | 5860 | 11 Jun. 2016, 07:54 |
| H05 | C018 | 38°39.88′N | 170°00.34′E | 6261 | 11 Jun. 2016, 13:44 |
| H06 | C021 | 37°29.89′N | 170°54.08′E | 5183 | 12 Jun. 2016, 08:55 |
| H07 | C022 | 37°36.05′N | 171°34.00′E | 5659 | 12 Jun. 2016, 16:06 |
| H08 | C023 | 37°05.32′N | 171°35.56′E | 5622 | 13 Jun. 2016, 01:46 |
| H09 | C025 | 37°00.02′N | 170°55.30′E | 5284 | 13 Jun. 2016, 11:25 |
| H10 | C026 | 36°59.71′N | 170°29.63′E | 5280 | 13 Jun. 2016, 16:52 |
| H11 | C027 | 36°59.53′N | 169°59.65′E | 5201 | 13 Jun. 2016, 22:14 |
| H12 | C028 | 36°59.33′N | 169°29.85′E | 5145 | 14 Jun. 2016, 03:47 |
| H13 | C030 | 37°29.99′N | 169°10.48′E | 5248 | 14 Jun. 2016, 18:48 |
| H14 | C032 | 37°30.48′N | 168°40.04′E | 5210 | 15 Jun. 2016, 04:48 |
| H15 | C33B | 37°32.26′N | 168°03.35′E | 5199 | 16 Jun. 2016, 05:37 |
| R/R Ryofu Maru RF1206 cruise |
| R01 | RF4503 | 40°00.29′N | 164°20.07′E | 5333 | 10 Aug. 2012, 22:43 |
| R02 | RF4502 | 40°00.88′N | 164°59.83′E | 5582 | 10 Aug. 2012, 15:32 |
| R03 | RF4501 | 40°00.75′N | 165°40.62′E | 5553 | 10 Aug. 2012, 07:35 |
| R04 | RF4500 | 40°00.77′N | 166°21.27′E | 5504 | 09 Aug. 2012, 23:43 |
| R05 | RF4499 | 39°59.39′N | 167°00.98′E | 6001 | 09 Aug. 2012, 14:26 |
| R06 | RF4504 | 40°00.58′N | 167°40.70′E | 5815 | 25 Aug. 2012, 04:10 |
| R07 | RF4505 | 40°00.39′N | 168°21.18′E | 5851 | 25 Aug. 2012, 13:55 |
| R08 | RF4507 | 39°58.64′N | 168°59.30′E | 6008 | 27 Aug. 2012, 19:37 |
| R09 | RF4509 | 39°29.27′N | 169°59.80′E | 5917 | 28 Aug. 2012, 09:44 |
| R10 | RF4510 | 38°58.61′N | 170°01.62′E | 6077 | 28 Aug. 2012, 16:55 |
| R11 | RF4512 | 37°59.41′N | 169°58.98′E | 4804 | 29 Aug. 2012, 08:34 |
| R12 | RF4513 | 37°31.18′N | 170°00.47′E | 5415 | 29 Aug. 2012, 15:06 |
| R13 | RF4514 | 37°01.50′N | 169°59.99′E | 5314 | 29 Aug. 2012, 22:43 |
| R14 | RF4515 | 36°30.70′N | 169°57.52′E | 4536 | 30 Aug. 2012, 05:55 |
| R15 | RF4516 | 35°59.50′N | 169°59.26′E | 5325 | 30 Aug. 2012, 12:49 |
| R16 | RF4517 | 35°29.64′N | 169°58.38′E | 5516 | 30 Aug. 2012, 19:43 |
| R17 | RF4518 | 34°59.50′N | 170°00.06′E | 5598 | 31 Aug. 2012, 02:35 |
| R18 | RF4519 | 34°29.33′N | 170°02.11′E | 5531 | 31 Aug. 2012, 09:23 |
| R19 | RF4520 | 33°59.33′N | 169°59.95′E | 5754 | 31 Aug. 2012, 16:12 |
| R20 | RF4521 | 33°29.35′N | 169°59.09′E | 5842 | 31 Aug. 2012, 23:15 |
| R21 | RF4522 | 33°00.03′N | 169°58.52′E | 5843 | 01 Sep. 2012, 06:39 |
| R22 | RF4523 | 33°59.55′N | 169°16.96′E | 5682 | 01 Sep. 2012, 16:24 |
| R23 | RF4524 | 34°30.31′N | 168°56.76′E | 5705 | 01 Sep. 2012, 23:47 |
| R24 | RF4525 | 35°00.12′N | 168°34.54′E | 5711 | 02 Sep. 2012, 07:17 |
| R25 | RF4526 | 35°29.61′N | 168°13.44′E | 5713 | 02 Sep. 2012, 14:44 |
| R26 | RF4527 | 36°00.30′N | 167°51.49′E | 5551 | 02 Sep. 2012, 22:05 |
| R27 | RF4528 | 36°28.99′N | 167°29.88′E | 5718 | 03 Sep. 2012, 05:41 |
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five times larger than that of 5.4 cm$^2$ s$^{-2}$ at most at the Main Gap (mesoscale kinetic energy was calculated as a half of the summation of the variances of $u$ and $v$ for $T > 20$ band shown in Fig. 5).

3.2 Horizontal distribution of currents

We next examined the horizontal distribution of LADCP current vectors averaged between 10 and 50 m from the seafloor in comparison with the record-length mean current vectors by the moored instruments (Fig. 6). Though snapshot measurements by LADCP cannot reveal mean currents, they are helpful for examining the horizontal expanse of current variability. Weak currents equivalent to or smaller than the $T < 2$-day band variability detected at ME1 existed at H01–H04, R09 and R10 around ME1. In addition, current directions were scattered at H01–H04 on the same day (Table 2). These results are consistent with the dominance of the tidal and inertial fluctuations at ME1.

Compared to the currents in the Main Gap, the LADCP currents around and to the west of the Small Gap seemed to have coherent structures with a horizontal scale of several tens to one hundred kilometers. Relatively strong westward to northwestward currents existed around ME3: 5.5 cm s$^{-1}$ (335°T) at H09, 6.8 cm s$^{-1}$ (265°T) at H08, and 9.4 cm s$^{-1}$ (288°T) at H06. These were measured on 12 and 13 June 2016, which were the first 2 days of the period that ME3–3

![Fig. 3 Stick diagrams and statistics of daily current vectors at ME1–3, ME1–4, and ME3–3. Statistics are shown by the same scale as the stick diagrams on the right side; mean currents are shown by arrows, and standard errors and deviations are shown by solid-line and broken-line ellipses, respectively.](image)

![Fig. 4 Histograms of current direction at a ME1–3, b ME1–4, and c ME3–3. Solid lines are for daily currents and broken lines are for hourly currents. Histograms are expressed as percentages of every 30-degree bin.](image)
**Fig. 5** Variances of current velocity components $u$ and $v$ in three period bands of $T > 20$, $20 > T > 2$, and $T < 2$ days at ME1–3, ME1–4, and ME3–3.

**Fig. 6** LADCP currents and current-meter mean currents around the Main Gap. Blue and green arrows show vertically averaged currents by LADCP between 10-m and 50-m heights above the seafloor at the KH-16–3 and RF1206 sections, respectively. Red arrows show temporally mean currents by current meters at ME1–3 (450-m above the seafloor) and ME3–3 (40-m above the seafloor). Black arrow annotated with HT shows the mean current at a 3947-m depth at 38°58'N, 171°06'E (5070-m bottom depth according to ETOPO1) by Hamann and Taft (1987).
detected a westward current for about 1 month just after
the deployment (Fig. 3). The westward mesoscale fluctua-
tion at ME3 would occur within the range of H06, H08, and
H09. On the other hand, eastward currents were domi-
ant at H10–H12 and R13 to the west of the Small Gap.

Near the southern end of the Main Gap, a strong south-
eastward current with a velocity of 16.8 cm s\(^{-1}\) (127°T) at
H05 was prominent. A northeastward mean current veloc-
ity of 4.7 cm s\(^{-1}\) (56°T) was also observed at a depth of
3947 m at the north flank of the Jingu Guyot with moorings
by Hamann and Taft (1987) (shown as HT in Fig. 6). These
currents flowed along the isobaths north of the tall two-peak
seamount that consists of Ojin Guyot and Jingu Guyot. It
is suggested that an intensified eastward flow exists on the
steep northern slope of the seamount. Furthermore, there
could exist a clockwise circulation around the seamount,
which consists of these eastward currents on the northern
slope and the westward current on the southern slope, as
observed by LADCP at H06. It is actually known that sev-
eral guyots of the ESC to the north of the Main Gap have
individual clockwise circulations through various genera-
tion mechanisms (Wagawa et al. 2012). However, we cannot
distinguish the westward current at H06 from the westward
fluctuation shown at ME3 in the Small Gap. Therefore, it
is difficult to conclude that a clockwise circulation exists
around the two-peak seamount. Estimation of the net trans-
port of abyssal water through the Main Gap will depend on
the existence of clockwise circulation.

4 Abyssal water around the gaps

We investigated water properties around the two gaps using
CTD data of KH-16–3 and RF1206 to judge what water
mass was being transported by the eastward abyssal current
through the gaps. In Fig. 7, vertical profiles of potential
temperature (\(\theta\)), practical salinity (\(S\)), and dissolved oxygen (\(O\))
are plotted, color-coded by area classification of CTD loca-
tion in Fig. 2a. Abyssal water below a depth of 4000 m in the
SSES region was the coldest, the most saline and the most
oxygen-rich among the five regions. \(S\) exceeding 34.692 and
\(\theta\) below 1.07 °C near the seafloor, as shown in Fig. 7, show
the characteristics of LCDW carried to the south of 37°N by
the DWBC (Kawabe and Taira 1998). There was a distinct
bifurcation of \(\theta\), \(S\) and \(O\) at a depth of approximately 5000 m
between the SSES and the other regions. Abyssal water in the
MG region had similar \(\theta\), \(S\) and \(O\) profiles to those from a
depth of 4000 m to the seafloor in the NWMG region. \(\theta-S\)
relationships also had different curves between the SSES and
MG/NWMG regions below a bifurcation point at \(\theta=1.09 \, ^\circ\)C
that existed at a depth of approximately 5000 m in the Main
Gap (not shown).

To track the origin of abyssal water in the Main Gap, we plotted \(\theta\) near the seafloor over a depth of 5000 m in
a wider map using JMA and CCHDO data sets (Fig. 8).
The bottom \(\theta\) was averaged within the lowest 10 m of
each CTD cast, which was lowered to approximately 10 m
above the seafloor. Abyssal water in the Main Gap had \(\theta\) of
1.081–1.087 °C. It was as warm as not only those at 40°N
between the Shatsky Rise and the ESC but also those to the west of the ESC at 47°N, where $\theta$ was 1.080–1.083 °C. Thus, the abyssal water flowing eastward through the Main Gap is considered to originate in the northern part of the NWPB.

To the west of the Small Gap (the WSG region), abyssal water below a depth of approximately 5100 m (about 200 m above the seafloor) had $\theta$, $S$ and $O$ of intermediate values between SSES and the others (Fig. 7); these $\theta$, $S$ and $O$ were close to the values at a depth of approximately 5000 m in the SSES region (about 300 m above the seafloor of the WSG region). It can be inferred that this water was LCDW spilling through the S–E Seamounts from the SSES region. Furthermore, potential temperature had a spatial contrast within the WSG region in the KH-16–3 section, while the bottom $\theta$ was below 1.07 °C at the WSG stations, except for H06 and H12 (Fig. 9); H12 was a relatively shallow site. The abyssal water at H06 was presumably affected by the westward current of the clockwise circulation around the two-peak seamount or the temporary westward current in the Small Gap at the time of the KH-16–3 section. On the other hand, the abyssal water at the other WSG stations seemed to be outside the mesoscale structure of the temporary westward current in the Small Gap (Fig. 6) and was presumably less affected by it. A group of the coldest bottom waters was found at H14 and H15, and their depths were shallower than those at H09 and H10. The bottom waters at H13, H11, H10, and H09 formed a group of the second coldest waters. It is suggested that LCDW spills into the middle part of the S–E Seamounts around H14 and H15 and then spreads to the deeper portions of the WSG region, such as H09 and H10.

To the east of the Small Gap (the ESG region), abyssal water lacked the low $\theta$ and high $S$ and $O$ characteristics shown in the WSG region and resembled those in the MG and NWMG regions (Fig. 7). The bottom waters in ESG and MG/NWMG regions were also as warm as those in the northern NWPB (Fig. 8). LCDW from the SSES region spread only over the seafloor of the WSG region and did not extend further. The temporary westward current in the Small Gap at the time of the ESG casts may have caused some anomalous water properties in the ESG region. When the abyssal current flowed eastward through the Small Gap, LCDW would possibly have been carried by the eastward current and existed in the ESG region. However, the
eastward extent of LCDW lying below a depth of 5100 m in the WSG region was believed to be mostly blocked by the sill depth of 5150–5200 m in the Small Gap (Fig. 2c). It is suggested that the strong eastward mean current at ME3 carried the warmer abyssal water, which probably came from the northern NWPB and overlay LCDW in the WSG region.

5 Estimation of volume transports of abyssal water

We obtained statistics of abyssal current at the Main Gap from the single mooring. Moreover, LADCP currents suggested that the abyssal flow on the flat portion of the Main Gap would have velocity magnitudes comparable to the mooring result. Therefore, the volume transport of the abyssal water through the Main Gap is roughly estimated as $1.6 \times 10^6$ m$^3$ s$^{-1}$, assuming a 100-km width and a 1000-m thickness below a depth of 5000 m over the seafloor at a depth of 6000 m, and an eastward current speed of 1.6 cm s$^{-1}$ as the average of the mean $u$ at ME1–3 and ME1–4. In this estimation, we excluded the volume transport carried by the intensified eastward current over the steep slope of the two-peak seamount south of the Main Gap, because this current would probably constitute a clockwise circulation around the two-peak seamount, as above.

We also estimate the volume transport of the abyssal water through the Small Gap roughly as $0.5 \times 10^6$ m$^3$ s$^{-1}$, assuming a 30-km width of the Small Gap and a 200-m thickness from the sill depth of 5200 m to the bifurcation depth of 5000 m between the LCDW in the SSES region and the abyssal water in the MG/NWMG regions, and 9 cm s$^{-1}$ mean current speed at ME3–3.

6 Summary and discussion

We carried out 1-year mooring observation at the abyssal depth of the Main Gap and the Small Gap from 2016 to 2017. The abyssal current flowed slowly eastward but statistically significantly on the flat portion of the Main Gap. Its temporal current variation was dominated by tidal and inertial fluctuations. Snapshots of abyssal current observed by LADCP indicated that the currents were also very weak within the tidal and inertial variability on the flat bottom occupying most of the gap. On the other hand, at the Small Gap, the abyssal current flowed eastward at a high mean speed of 9 cm s$^{-1}$ and had large mesoscale variability with a zonal deviation of $\pm$ 7 cm s$^{-1}$.

The mesoscale variability at 39°20′N in the Main Gap had only approximately one-fifth the kinetic energy of that at 37°20′N in the Small Gap. The source of the mesoscale variability is thought to be the Kuroshio Extension (KE), which flows eastward with the current axis between approximately 32°N and 36°N at 170°E in 2016 and 2017 (Qiu et al. 2020). The abyssal mesoscale variability in the North Pacific is known to decrease meridionally with distance from the axis of the KE and to decrease eastward along the KE from a maximum at 147°E–152°E (Schmitz 1984, 1988; Miyamoto et al. 2020). At 147°E, the abyssal mesoscale variability at a depth of 4000 m is strong even at 30°N about 500 km away from the KE (Miyamoto et al. 2020), while it could decrease more rapidly with distance from the KE at 170°E. Schmitz (1988) showed that the mesoscale variability was extremely weak at a depth of 4000 m at 39°N, 175°E from 2-year mooring. The horizontal distribution and the mechanisms of the abyssal mesoscale variability around the ESC are expected to be clarified by future accumulation of current observations as well as advanced modelling based on high-resolution topographic data.

Hydrographic data analysis showed that the abyssal water flowing eastward through the Main Gap was dominated by the abyssal water coming from the northern part of the NWPB. Its volume transport was roughly estimated as $1.6 \times 10^6$ m$^3$ s$^{-1}$ without counting the strong eastward current on the steep slope at the southern end of the Main Gap. This conflicts with the observation results by Komaki and Kawabe (2009) in 2003; they concluded that a part of the LCDW, which is carried to the south of the S–E Seamounts by the DWBC, crosses over the S–E Seamounts, passes the Main Gap and is transported eastward. CTD data in 2012–2016 also showed that LCDW existed to some extent near the seafloor to the north of the S–E Seamounts (WSG region). However, LCDW from the south was not dominant at the Main Gap or further north. It was not detected to the east of the Small Gap (ESG region) either. The strong eastward mean current at the Small Gap was estimated to carry the abyssal water coming from the northern NWPB, with a volume transport of $0.5 \times 10^6$ m$^3$ s$^{-1}$.

Because abyssal water is not formed in the Pacific, the abyssal water in the northern NWPB should be a remnant of LCDW, which is brought by the DWBC advancing northward east of the Japan Trench. Kawabe et al. (2009) estimated the volume transport of LCDW with $\theta < 1.2$ °C as approximately $6 \times 10^6$ m$^3$ s$^{-1}$, summing the two branches of the DWBC southwest of the Shatsky Rise, which join east of the Japan Trench (Fig. 1). Therefore, the inflow transport of LCDW into the NWPB would be $6 \times 10^6$ m$^3$ s$^{-1}$, even though a small amount of LCDW spills through the S–E Seamounts, upstream of the DWBC above the Shatsky Rise. On the other hand, the remnant of LCDW from the northern NWPB flowed out to the NEPB with a volume transport of $1.6 \times 10^6$ m$^3$ s$^{-1}$ through the Main Gap and $0.5 \times 10^6$ m$^3$ s$^{-1}$ through the Small Gap. The upwelling of LCDW in the NWPB is estimated as $1 \times 10^6$ m$^3$ s$^{-1}$ (Kawabe and Fujio 2010). These lead to approximately $3 \times 10^6$ m$^3$ s$^{-1}$ as
the outflow transport of LCDW from the NWPB along the northern route through the junction of the Kuril and Aleutian Trenches (broken line in Fig. 1). This route was only inferred from sediments (Owens and Warren 2001). Future current and water–mass observations of the northern route are expected for clarification of the volume budget of deep ocean circulation in the North Pacific.

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Data Availability The data presented in this paper are available from the corresponding author upon request.

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