Local steady circulation observed by moored current-meters at 4000 m depth in the western North Pacific

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Abstract

A high-density mooring-array observation was carried out during 1984–1985 in mid-ocean of the western North Pacific. A curious steady anticyclonic circulation is found at 4000 m depth on an almost flat bottom deeper than 6000 m, having a diameter of more than 100 km and a rotating speed of 2 cm s^{-1} . The vorticity of $-1 \times 10^{-6} \text{ s}^{-1}$ is comparable in magnitude to mesoscale eddies. The circulation could be either an isolated vortex or a part of some larger circulation, depending on the unknown flow in the eastern part.

Keywords Steady circulation · Moored current-meter · Abyssal depth · Mid-ocean · Seamount

1 Introduction

Velocities were intensively measured by moored current-meters at abyssal depths east of the Izu-Ogasawara Ridge, in mid-ocean of the western North Pacific during 1978–1985, to primarily investigate low-frequency velocity-fluctuations, or mesoscale eddies (Imawaki and Takano 2018; hereafter abbreviated IT18). The final observation was carried out as a high-density mooring-array, to estimate the advection of relative vorticity in the vorticity balance of mesoscale eddies. Thirteen moorings were deployed in an area 70 km square and 11 of them were recovered. The horizontal distribution of mean velocities for 1 year at abyssal depths clearly shows a curious local anticyclonic circulation, unexpectedly. The present paper describes this steady circulation in detail and suggests a working hypothesis for its generation mechanism.

2 Location and measurements

The inset of Fig. 1 shows the location of observation site centered at 30°N , $147^\circ40'\text{E}$. At shallow depths, the site center is located about 400 km south of the Kuroshio Extension and on the indistinct southern boundary of the broad west-southwestward Kuroshio Countercurrent (Uchida and Imawaki 2003). At abyssal depths, the site is distant from the weak deep western-boundary current located east of the Izu-Ogasawara Ridge (Kawabe and Fujio 2010). The inset also shows that the site center is located more than 500 km east of the Ridge.

The bottom topography based on ETOPO1 (Amante and Eakins 2009) is shown as background color in Fig. 1. The water depth varies mostly between 6000 and 6300 m within 100 km of the center. The topography is generally flat with small gentle undulations and no apparent large-scale slopes. Exception is several small seamounts, including those labeled S1, S2 and S3.

Current-meter moorings were deployed at 13 stations in July 1984 and recovered at 11 stations in July 1985. The observation and data-processing are detailed in IT18, and fundamental statistics are given there. Table 1 shows the summary of measurements and mean velocities for 1 year obtained mostly at a nominal depth of 4000 m. At Stn. RB (RR), the record at that depth was not obtained and is justifiably made up for by the record at 5000 (4100) m depth because those mean velocities at abyssal depths at the same station are similar to each other (IT18). Therefore, the

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Fig. 1 Horizontal distribution of mean velocities for 1 year (1984–1985) at 4000 m depth measured by moored current-meters (black arrows). Thick arrows indicate that their eastward or northward components are positive or negative significantly at the 95% confidence level (Table 1). Station names are shown with the first “R” omitted. Two white dots show stations where moorings were not recovered. For comparison, mean velocities for 1.4–2 years (2014–2016) at 4000 m depth (Miyamoto 2019) are shown by gray arrows. Back-

ground color illustrates the bottom topography based on ETOPO1, with contours of 500 m interval. Three seamounts are labeled S1, S2 and S3; depths of their summits are shown in kilometer. The small-scale inset illustrates the observation site, the Kuroshio system, whose mean path during 1993–2000 is shown by shading, and the Izu-Ogasawara Ridge, whose horizontal extent at 3000 m depth is shown by dotted lines

present mean velocities are regarded to have been obtained at the nominal depth of 4000 m, which is hereafter called simply “4000 m depth.” Measurement errors of mean zonal and meridional velocity-components for more than several months are estimated to be 0.2 cm s^{-1} , from standard deviations of differences between two records obtained at almost same depths (only 20 m apart vertically near 4000 m depth) on the same mooring-lines at four stations, mostly before the present array observation.

3 Steady circulation

Black arrows in Fig. 1 show the temporal mean velocities at 4000 m depth at the 11 stations. The means are calculated from data for 339–364 days, except 138 days at Stn. RV. Distribution of the mean velocities clearly shows a clockwise rotation, or anticyclonic circulation, centered near Stn. RP. The circulation extends horizontally over the whole array area and therefore, its diameter is more than 100 km. Flow speeds vary in space between 1.0 and 3.1 cm s^{-1} with an average of 1.9 cm s^{-1} (Table 1).

Errors of the temporal mean velocities estimated from time series dominated by low-frequency fluctuations are

evaluated at the 95% confidence level by the same way as described in IT18; errors of mean zonal (meridional) components are evaluated to be 1.3 – 1.4 (1.1 – 1.2) cm s^{-1} for all the stations, except Stn. RV, for which the error is evaluated to be 2.4 (2.0) cm s^{-1} . This evaluation indicates that the following three flow-directions are significant at that confidence level (Table 1; Fig. 1): the westward in the southern part (Stns. RQ, RU and RV), the northward in the western part (Stns. RX and RT) and the eastward in the northern part (Stns. RR, RS and RO). Therefore, the clockwise-rotating flow pattern is certain at the 95% confidence level, except in the eastern part, where significant flows are not detected, possibly because of inadequate station distribution.

The vertical component of relative vorticity is estimated at five central stations by finite difference of velocities with a spatial interval of 50 km, in a straightforward manner. Here missing data at Stn. RP (RW) are filled by averaging data from Stns. RO, RN, RQ and RT (RR and RB). The estimated vorticity is negative at all the five stations. It is strongest ($-1.1 \times 10^{-6} \text{ s}^{-1}$) at Stns. RT and RP, moderate ($-0.8 \times 10^{-6} \text{ s}^{-1}$) at Stn. RS and weakest ($-0.6 \times 10^{-6} \text{ s}^{-1}$) at Stns. RX and RU. The vorticity at Stn. RT on a larger scale (100 km interval) is estimated from velocities at Stns. RR, RN, RV and RB; it is moderate ($-0.7 \times 10^{-6} \text{ s}^{-1}$). On the other hand,

Table 1 Summary of mooring observation and mean velocities for 1 year (1984–1985) at abyssal depths in the western North Pacific

Station	Location Lat. (N)	Long. (E)	Water depth (m)	Meter depth (m)	First data	Last data	Duration (days)	U (cm s ⁻¹)	V	Speed	K_M (cm ² s ⁻²)	K_L	K_H
RB	30°01.9'	147°08.9'	6260	5000	3 July 1984	1 July 1985	363	0.4	1.0	1.1	0.6	12.4	3.2
RN	30°02.4'	148°11.0'	6200	4000	5 July 1984	4 July 1985	364	-1.0	-0.3	1.0	0.5	11.2	4.1
RO	30°15.6'	147°55.8'	6180	4000	7 July 1984	2 July 1985	360	1.8	0.1	1.8	1.6	16.6	3.5
RQ	29°48.6'	147°55.5'	6230	4000	5 July 1984	3 July 1985	363	- 2.3	0.2	2.3	2.6	9.3	4.9
RR	30°29.1'	147°39.0'	6320	4100	7 July 1984	2 July 1985	360	2.9	-0.1	2.9	4.1	15.1	3.3
RS	30°15.6'	147°40.0'	6180	4000	7 July 1984	1 July 1985	359	2.5	0.8	2.6	3.4	20.3	3.8
RT	30°02.0'	147°40.0'	6160	4000	6 July 1984	2 July 1985	361	-0.7	1.2	1.4	0.9	13.9	4.1
RU	29°48.5'	147°40.1'	6160	4000	4 July 1984	3 July 1985	364	- 2.0	0.6	2.1	2.2	10.5	5.5
RV	29°35.2'	147°39.7'	6200	4020	4 July 1984	19 Nov. 1984	138	- 3.0	0.7	3.1	4.7	6.8	4.6
RX	30°01.9'	147°24.5'	6250	4000	3 July 1984	8 June 1985	340	-0.3	1.4	1.4	1.0	14.0	3.8
RY	29°48.5'	147°24.3'	6210	4000	4 July 1984	8 June 1985	339	-1.4	0.9	1.6	1.4	10.5	4.9
Spatial average			6214				337	-0.1	0.6	1.9	1.9	13.1	4.1

Current-meter depths are nominal. Dates of first and last data are in the Coordinated Universal Time. Symbol U (V) denotes the eastward (northward) velocity-component. Bold numerals indicate that values are positive or negative significantly at the 95% confidence level. Also shown are kinetic energies per unit mass of the temporal mean flow (K_M), low-frequency fluctuations (K_L) and high-frequency fluctuations (K_H). At bottom, spatial averages calculated with a weight of duration are shown

the 20-day mean vorticity of mesoscale eddies at Stn. RT (with 50 km interval) varies in time between -1.4×10^{-6} and $0.9 \times 10^{-6} \text{ s}^{-1}$ with the standard deviation of $0.7 \times 10^{-6} \text{ s}^{-1}$ (IT18). That is, the relative vorticity of the local steady circulation is strongest near the center, being about $-0.02 f_0$, where f_0 is the planetary vorticity (Coriolis parameter) at this latitude, and comparable in magnitude to the relative vorticity of mesoscale eddies.

A time sequence of horizontal distribution of 10-day mean velocities at the site during the present period (Fig. 15 of IT18) is dominated by travelling mesoscale eddies and the steady circulation is hardly recognized, but the flow field shows a tendency of dominance of anticyclonic patterns. It is because the flow field is heavily biased by the strong steady anticyclonic circulation.

4 Discussion

The record length at Stn. RV is only one-third of a year, which might be too short to provide a reliable mean. For the zonal velocity-component, low-frequency fluctuations are almost the same as those at the next station (Stn. RU) during their common period, and the simple average of the record is close to a value of subtracting those fluctuations from that record. Those two facts suggest that the mean and fluctuations are separated adequately and the present estimate of mean zonal component happens to be close to the unknown 1-year mean.

One may feel strange that the mean flow at Stn. RR is directed normal to the slope of seamount (S1 in Fig. 1). At that station, low-frequency velocity-fluctuations are uniquely dominated by meridional fluctuations (IT18), which are preferable flows west of the seamount elongating meridionally. The fluctuations are stronger than the mean flow, having almost three times larger kinetic energy. Therefore, instantaneous flows (the mean flow plus low-frequency fluctuations) are mostly directed obliquely to the slope of seamount.

Other current measurements inside the present circulation area are as follows. The hydrographic section carried out in 1993 as the P10 section of the World Ocean Circulation Experiment Hydrographic Program (WHP) accidentally ran almost exactly on Stns. RN, RO and RR, after leaving the original $149^\circ 20' \text{E}$ meridian at $28^\circ 30' \text{N}$ (Wijffels et al. 1998), but geostrophic velocities based on a wide station-spacing (84 km) and assumption of no motion at a reference level can hardly describe a compact slow circulation like the present one. The site was revisited by moored current-meters in 2014–2016 (Miyamoto 2019); mean velocities for 1.4–2 years at abyssal depths at four stations in the western part of the present circulation (gray arrows in Fig. 1) are consistent with the circulation both in flow-direction and magnitude, except the northwestward velocity near Stn. RW.

Other current measurements outside the present site are as follows. On the western and northwestern sides, velocities were intensively measured by moored current-meters at abyssal depths at several stations during 1978–1984, showing no apparent steady circulations related with the present circulation (Fig. 6 of IT18). A hydrographic section with a lowered acoustic Doppler current profiler (LADCP) was carried out in 2001 along $146^\circ 25' \text{E}$ meridian down to 30°N , showing only a marginally eastward flow in the deep layer south of 31°N (Yoshikawa et al. 2004). The above-mentioned recent deep current measurements also provided mean velocities for 1.4 year at three stations on the western side (Miyamoto 2019); their flow-directions do not imply any connections to the circulation.

The present circulation could be either an isolated vortex, which is dynamically interesting, or a part of some larger scale circulation located possibly to the east. The unknown flow in the eastern part would determine which one is the case. Other current measurements on the eastern side are as follows. The WHP P10 section was revisited twice; the second and third sections ran along $149^\circ 20' \text{E}$ meridian up to 34°N . Zonal-velocity sections obtained by LADCP's with a station-spacing of 74 km show weak westward flows at 4000 m depth between 29° and 31°N , both in 2005 (Kawano and Uchida 2007) and in 2012 (Uchida et al. 2014); the flows do not seem to be related with the present circulation directly. That is, reports so far available cannot solve the uncertainty of the circulation mentioned above.

About the persistency and steadiness of the circulation, velocities observed for a long period at 5000 m depth at Stn. RB, located at the western-end of the circulation, may provide some hint. Temporal mean velocities for nine consecutive observations over several months to 1 year each during 1978–1985 are all, except for the first observation, directed to the northward (Fig. 7 of IT18), which is the flow-direction in the western part of the circulation, with a speed of about 1 cm s^{-1} . The overall mean northward component during these 7 years (0.7 cm s^{-1}) is positive significantly at the 95% confidence level. Those results suggest that the steady circulation may have existed for at least several years continuously.

The mechanism for the generation of this curious steady circulation is not known. The bottom topography is generally flat but there are several seamounts, which might play a crucial role, as suggested by previous studies shown below. It is well-known that the path of the Kuroshio Extension is controlled by the Emperor Seamounts and the variability of the Gulf Stream Extension is affected by the New England Seamounts. A small isolated seamount called Koshu Seamount located south of Japan plays a crucial role in the development of a small meander of the Kuroshio to the stationary large meander (Ambe et al. 2009; Endoh and Hibiya 2009). Barotropic flows are generated over a cluster of low

topographic-rises (about 500 m high) in the deep western subarctic region of the North Pacific (Mitsudera et al. 2018); they were explained as eddy-induced flows on a broad low topographic-rise by a numerical model (Miyama et al. 2018). On a smaller scale, an anticyclonic mean circulation is generated over a tall isolated seamount called Fieberling Guyot in the eastern North Pacific (e.g., Brink 1995), being caused by rectification of tides around the seamount (Beckmann and Haidvogel 1997). Various possible interactions between flows and bottom topography were discussed comprehensively (Roden 1987). Interactions between geostrophic eddies and a mean circulation over variable topography were investigated (e.g., Holloway 1987; Adcock and Marshall 2000). An anticyclonic mean flow was detected over the Suiko Seamount in the Emperor Seamounts and its generation mechanism was speculated to be eddy-topography interaction (Wagawa et al. 2012).

Those studies suggest a working hypothesis that the present circulation is an eddy-driven circulation with the aid of a set of seamounts; mesoscale eddies traveling from the east may be partly trapped and transferred to a stationary anticyclonic circulation continuously by seamounts located under the rim of the circulation (S1 and S3 in Fig. 1, and possibly S2 if the circulation is an isolated vortex). Note that flows associated with the circulation probably extend well beyond the seamounts S1 and S3. If the potential vorticity $(\zeta + f)/H$ is conserved, where ζ is the relative vorticity, f the Coriolis parameter and H the water depth, the negative relative-vorticity is induced and amplified by a seamount. The present seamounts are 10–15 km wide and 600–900 m high, rising from the almost flat horizontal bottom of 6200–6300 m depth; their summits are at 5600–5400 m depth (Fig. 1). The circulation is observed at 4000 m depth, which is about 1500 m shallower than the summits; the effect of bottom topography up to shallower depths can be understood as the Taylor column. One may doubt whether such slim seamounts can affect the flow field considerably, but a set of distributed seamounts as a whole might play a role efficiently if their distribution fits to the horizontal scale of the circulation. Previous studies are mostly on an isolated seamount or a mass of seamounts, and no studies are available on effects of a set of distributed seamounts.

Abyssal depths at the present site are filled with mesoscale eddies traveling from the east to west, which are characterized mostly by plane barotropic Rossby waves with possible modification (IT18). As shown in Table 1, the kinetic energy of low-frequency fluctuations, or mesoscale eddies ($13 \text{ cm}^2 \text{ s}^{-2}$ on an average) is high enough compared with that of temporal mean flow ($2 \text{ cm}^2 \text{ s}^{-2}$). In general, tidal currents could be a source of the circulation over seamounts but the kinetic energy of high-frequency fluctuations ($4 \text{ cm}^2 \text{ s}^{-2}$) is low at the present depth and site, compared with mesoscale eddies. Here the high-frequency fluctuations

are velocity-fluctuations filtered out by a low-pass-filter with half power gain at 3.9 days (Godin 1972), including tides and inertial oscillations (IT18). The low-frequency fluctuations are the remaining fluctuations.

Probably, a compact slow circulation like the present one at an abyssal depth has not been reported elsewhere. It might be simply because a high-density mooring-array observation like this has seldom been carried out; similar local steady circulations might be found by some chance in future.

5 Summary and remarks

A unique local steady circulation is discovered from moored current-meter data obtained in 1984–1985 at 4000 m depth east of the Izu-Ogasawara Ridge, in mid-ocean of the western North Pacific. Horizontal distribution of mean velocities for 1 year at 11 stations clearly shows a local anticyclonic circulation having a diameter of more than 100 km and a mean rotating speed of about 2 cm s^{-1} . The clockwise-rotating flow pattern is certain at the 95% confidence level, except in the eastern part. The relative vorticity of $-1.1 \times 10^{-6} \text{ s}^{-1}$ near the center is comparable in magnitude to that of mesoscale eddies. The steady circulation seems to exist for at least several years continuously. Recent deep current measurements at the site support some of those results. The circulation could be either an isolated vortex or a part of some larger circulation. As for the generation mechanism of the circulation, a working hypothesis is suggested that mesoscale eddies traveling from the east are partly trapped and transferred to a stationary circulation continuously by a set of distributed seamounts located under the rim of the circulation.

To examine whether the circulation is an isolated vortex, further measurements by moored current-meters are needed in a wider area, especially on the eastern side of the circulation. The generation mechanism of the steady circulation should be clarified; theoretical and numerical studies are required on how a set of distributed seamounts can trap traveling mesoscale eddies partly and transfer them to a stationary circulation, and on what are necessary conditions for the circulation to be maintained.

The present study as well as IT18 shows that seamounts seem to affect abyssal flows quite significantly. When current measurements at abyssal depths are planned to investigate large-scale circulations, close attention should be paid on possible local effects of seamounts on the abyssal flow field, on the basis of latest detailed charts of the bottom topography.

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