Title	Low Frequency Ocean Variability between Mindanao and New Guinea
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Citation	Journal of the Faculty of Science, Hokkaido University. Series 7, Geophysics, 11(2), 411-439
Issue Date	1998-03-30
Doc URL	http://hdl.handle.net/2115/8842
Type	bulletin (article)
File Information	11(2)_p411-439.pdf

Jour. Fac. Sci., Hokkaido Univ., Ser. VII (Geophysics), Vol. 11, No. 2, 411-439, 1998.

Low frequency ocean variability between Mindanao and New Guinea

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(Received November 30, 1997)

Abstract

In order to investigate ocean circulation and its variability, direct current measurement and three hydrographic observations between Mindanao and New Guinea at the Pacific entrance of the Indonesian Throughflow, were performed from 1994 to 1996. Moorings were deployed at 4°1′N, 127°31′E and 3°11′N, 128°27′E between Talaud Islands and Morotai Island, Indonesia, from February 1994 to June 1995.

During boreal winter, north-northwestward flow is dominant between Talaud and Morotai, especially, at Morotai side. Results from hydrographic observations suggest that this flow is a part of the Halmahera Eddy, which shifts southward associated with the seasonal Asian monsoon change from boreal summer to winter. From spring to autumn 1994, westward flow transporting the mixed water between the North Pacific and South Pacific waters was observed at the southern mooring.

Clear interseasonal variability with period of 50 days was also revealed during all period of moorings' deployment. This oscillation may be induced by wind variability associated with Madden and Julian Oscillation, otherwise related to eddy activity, such as the Halmahera Eddy, around this region.

The Halmahera Eddy appears to be a key regarding these fluctuations which may influence the Indonesian Throughflow.

1. Introduction

There is an entrance of the Indonesian Throughflow between Mindanao (Philippines) and New Guinea. This flow which transports sea water between the Pacific and Indian Ocean has been a focus in oceanography during this decade. One of the reasons is that the Indonesian Throughflow is a part of "The Great Ocean Conveyer" (Broecker, 1991), which probably plays an important role in the global thermohaline circulation and is one of the elements contributing to the earth climate change.

Another reason is that there is a warm water pool influencing the ENSO (El Nino/Southern Oscillation) phenomena at the surface in this region. The Indonesian throughflow is also the path of this warm water, which may influence the sea surface temperature in the Indian Ocean (Hirst and Godfrey, 1994). Therefore, research for the Indonesian Throughflow variability is a part of Climate Variability and Predictability (CLIVAR) project.

The Pacific low-latitude western boundary currents between Mindanao and New Guinea also have an interesting aspect in oceanography. Their general distribution around the Indonesian Seas including the boundary area of the western equatorial Pacific were shown by Wyrtki (1961) from historical data. Since then, to understand the circulation in the western equatorial Pacific, some new ocean observations were conducted, but only an incomplete zero-order description was drawn from them (Lukas et al., 1996). These results are generally shown in Figure 1a by Fine et al. (1994), which shows a very complicate flow pattern. Its pattern in the western boundary region is shown in Fig. 1. The Mindanao Current (MC) flows southward along the Mindanao coast and enters into the Celebes Sea (Bingham and Lukas, 1994; Wijffels et al., 1995). One part of the MC retroflects to the Pacific, and the other goes through the Makassar Strait as the western route of the Indonesian Throughflow (Gordon and Fine, 1996). Under the MC, the Mindanao Undercurrent (MUC) flows northward (Hu et al, 1991; Qu et al., submitted). Along the New Guinea coast, the New Guinea Coastal Current (NGCC) and New Guinea Coastal Undercurrent (NGCUC) flows northwestward (Tsuchiya et al., 1989). The NGCC retroflects off the Halmahera (Fine et al., 1994), and joining with the retroflected flow of the MC, and flows eastward as the North Equatorial Counter Current (NECC) (Kashino, et al., 1996). In the retroflection point of the MC and NGCC, the Mindanao and Halmahera Eddies exist (Wyrtki, 1961). Because of these currents, water masses originating in the North and South Pacific reach this region and make a property (e.g., salinity) front, as "Water mass crossroads" (Fine et al., 1994). However, as Lukas et al., (1996) said, this description remains incomplete because observational data are limited in the western boundary region, which is entirely almost in the Indonesian and Philippine exclusive economical zones, and their territorial waters.

Some numerical modeling efforts (e.g., Masumoto and Yamagata, 1991) have suggested many interesting results concerning not only the description but also the variability and mechanism of the circulation in the western equatorial Pacific and Indonesian Seas. Although their current patterns are similar to the observational results suggested by Lukas et el., (1991) and Fine et al., (1994), variability and mechanism derived from the numerical results have not been sufficiently confirmed. Time series observations as well as hydrographic observations are needed to obtain knowledge regarding them.

Ocean variability in this region was studied by Wyrtki (1987) and Lukas

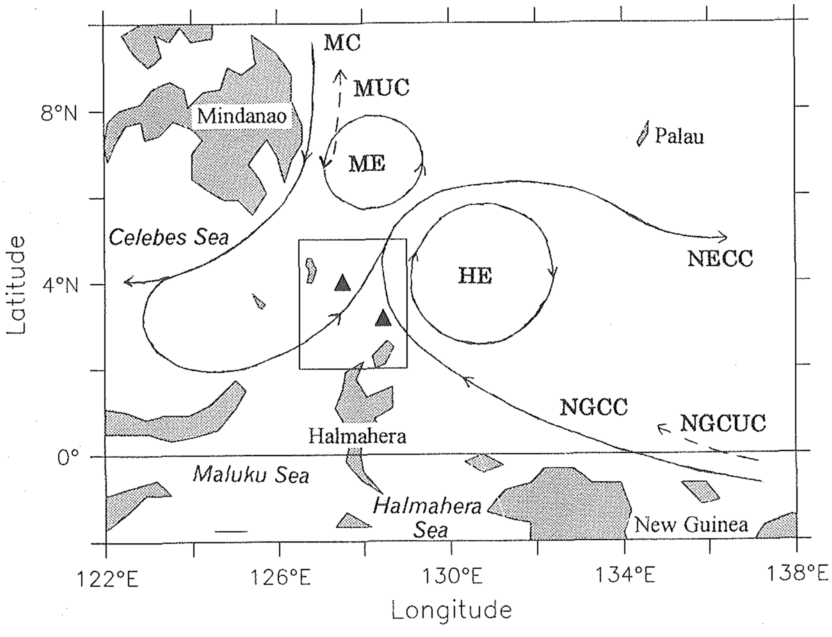


Fig. 1. Schematic of the current pattern between Mindanao and New Guinea after Fine et al., (1994). Solid lines denote surface-subsurface flow, i.e., Mindanao Current (MC), North Equatorial Countercurrent (NECC), New Guinea Coastal Current (NGCC) with the Mindanao Eddy (ME) and Halmahera Eddy (HE). Dashed lines indicate flow below subsurface-intermediate layer, Mindanao Undercurrent (MUC) and New Guinea Coastal Undercurrent (NGCUC). Solid triangles denote mooring sites referred in this paper. An area in the frame including the mooring sites is corresponding to that shown in Fig. 2.

(1988) using data from tide gages in Davao (Philippines) and Malakal (Palau). They noted sea level variability at these sites has a large seasonal signal. The transport of the MC estimated from sea level difference between these sites shows dominant fluctuation with period of two years (Lukas, 1988). On the other hand, numerical experiments by Inoue and Welsh (1993) and Qiu and Lukas (1996) suggest that the western equatorial Pacific is an eddy-dominated region in time scale of 20-80 days. Especially, according to Inoue and Welsh (1993), the eddy activity in this region largely relates to the transport of the MC, which is the main source of the Indonesian Throughflow (Gordon and Fine, 1996). These results imply that it is difficult to complete the description only from one-shot hydrographic observation, such as Western Equatorial Pacific Ocean Circulation Study (WEPOCS) III (Lukas et al., 1991).

As discussed before, time-series observation as well as repeated hydrographic observation are needed in the western equatorial Pacific. Japan Marine Science and Technology Center (JAMSTEC, Japan) and Badan Pengkajian Dan Penerapan Teknologi (BPPT, Indonesia) conducted five cruises in the southernmost Philippine Sea from 1992 to 1996. We carried out not only repeat hydrography but also mooring observation during these cruises. In this paper, We focus on current variability between Mindanao and New Guinea, i.e., at the Pacific entrance of the Indonesian Throughflow, using data from moored instruments from February 1994 to June 1995, and hydrographic data obtained during these cruises.

The following section describes the expeditions. In section 3, the description of the mooring results is given. We discuss the phenomena revealed in the mooring data, comparing with hydrographic and wind data during their deployment in section 4. Conclusions are summarized in section 5.

2. Summary of observations

2.1 *Moored observations*

Two subsurface moorings were deployed during February 21- 22, 1994, and recovered on July 3, 1995. The mooring locations are between Talaud Islands and Morotai Island, Indonesia (Figs 1 and 2). The northern mooring, hereafter called TMN, (Talaud-Morotai-North) was located at 4°1.239′N, 127°30.634′E (2570 m water depth), and the southern one is called TMS (Talaud-Morotai-South) at 3°10.793′N, 128°27.367′E (2277 m). Between these sites, there is a sill shallower than 300 m. We determined these mooring locations because we

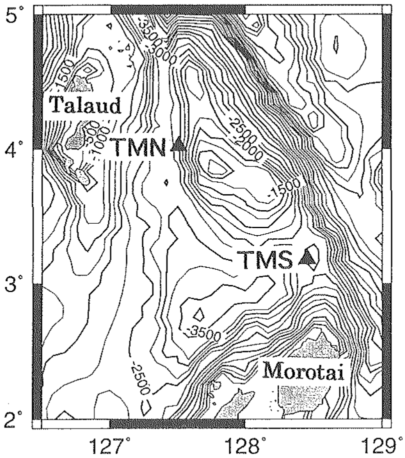


Fig. 2. Map of the mooring sites, named TMN (Talaud-Morotai-North) and TMS (Talaud-Morotai-South) between Talaud and Morotai from February 1994 to June 1995. Counter interval of topography is 250 m.

thought that this sill influences current pattern between Talaud Islands and Morotai Island (Fig. 2). A water mass front between the North Pacific and South Pacific waters, and retroflected flow of the MC were observed at subsurface between TMN and TMS when these moorings were deployed (Kashino et al., 1996).

Mooring line is shown in Fig. 3. Both moorings are designed as the same line except for wire length below the lowest instrument (1050 m). Three Aanderaa recording current meters (RCM), a conductivity-temperature-depth profiler (CTD, SBE-16 with a pressure sensor) and an upward looking RD Instrument broad-band acoustic Doppler current profiler (ADCP) with frequency of 150 kHz, were equipped in each mooring. We installed temperature sensors in all RCMs, conductivity sensors in three RCMs (TMN-350 m, TMS-350 m and TMS-550 m) and pressure sensors in two RCMs (TMN-1050 m and TMS-1050 m). Unfortunately, these ADCPs did not work well because of its system bug. Data from RCMs and CTDs were successfully acquired every one hour and 30 minutes, respectively.

Accuracy of these instruments is 1 cm/sec (current velocity by RCM), 5 degree (current direction by RCM), 0.002 K (CTD temperature), 0.02 Practical Salinity Unit (PSU, CTD salinity), and 0.4 db (CTD pressure). Although accuracy of temperature, salinity and pressure values from the sensors attached to RCM is not better than those of CTD values, these data are available because

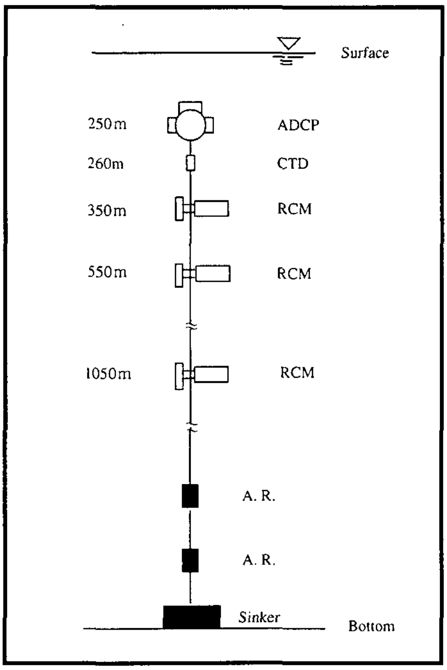


Fig. 3. Schematic mooring line at TMN and TMS.

the error estimated from comparison of values from these instruments and onboard CTD observations near the mooring stations before/after their deployment is small (e.g., 0.05 PSU in salinity).

As tidal current in the Indonesian Seas is dominant (Wyrtki, 1961; Hatayama et al., 1996), vivid tidal signals were also observed in the raw data obtained from RCMs and CTDs (Watanabe et al., 1997). Since we focus on the variability with time scale>20 days in this research, 48 hours tide-killer filter, hereafter called 48TK filter, (Hanawa and Mitsudera, 1985), designed accepting the concept shown by Thompson (1983), is used to remove tidal signals shorter than diurnal one from raw RCM and CTD data.

2.2 Cruises and hydrographic data

From 1992 to 1996, five cruises were carried out in the southernmost Philippine Sea on board the R/V *Kaiyo*. In this paper, data during among three cruises which tracks are shown in Fig. 4 is used.

Two of these cruises were conducted not only to understand the Indonesian Throughflow and low latitude western boundary currents, but also to contribute

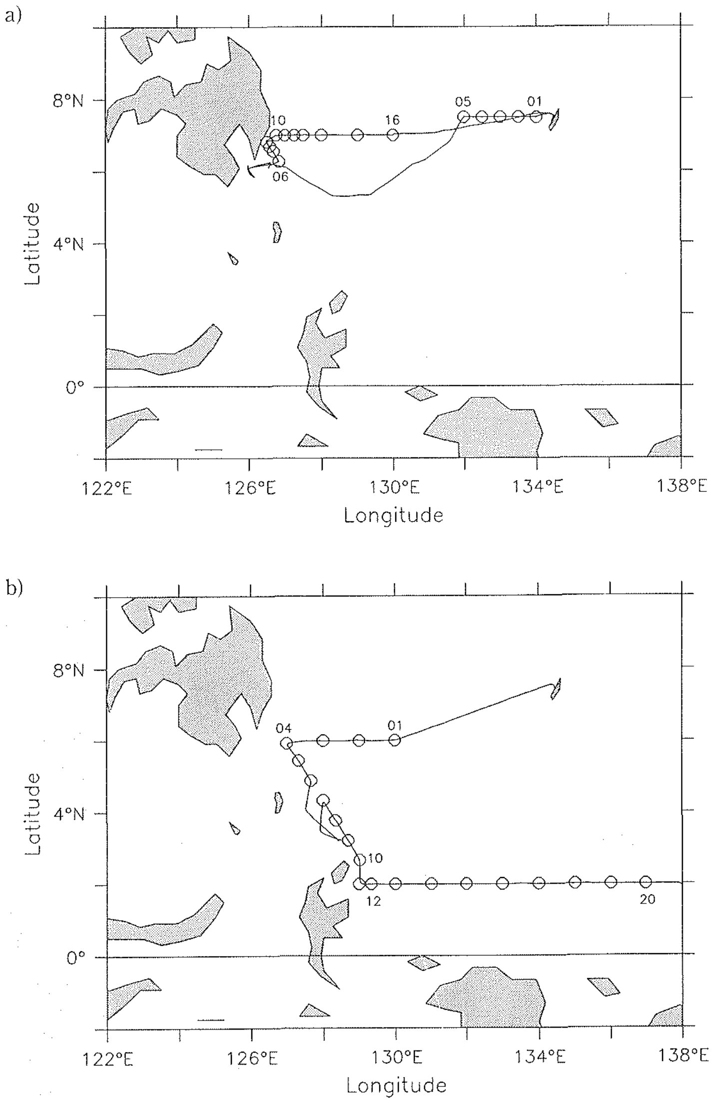


Fig. 4. Cruise tracks with locations of hydrographic observation denoted circles during a) R/V Kaiyo World Ocean Criculation Experiment (WOCE) III cruise in January 1995, b) Tropical Ocean Climate Study (TOCS) July 1995 cruise, and c) *Kaiyo* WOCE IV cruise. Although more hydrographic stations during TOCS July 1995 cruise locate out of area in Figure 4b, they are not shown because their result not used here.

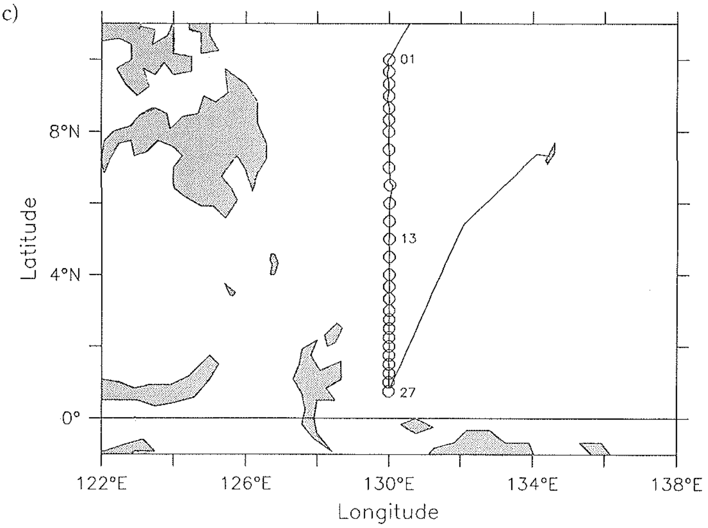


Fig. 4. (*Continued*)

to the World Ocean Circulation Experiment (WOCE) project. Because of this aim, these observations were designed to satisfy the requirements of WOCE Hydrographic Programme (WHP) (Joyce and Corry, 1993).

First cruise, *Kaiyo* WOCE III cruises (Fig. 4a), was conducted during January 1995 between Mindanao and Palau including the Philippine Exclusive Economical Zone near the Mindanao coast where the MC is trapped. Although hydrographic observations were performed during this cruise, we show only results from a 75 kHz RD Instrument narrow-band ADCP.

The second cruise, named TOCS (Tropical Ocean Climate Study) July 1995 cruise, was performed on board R/V *Kaiyo* under the TOCS project, which is an original one of JAMSTEC, to study ocean-atmosphere interaction in the tropical Pacific (Fig. 4b). Because of this research purpose, CTD observations were limited to the upper 1000 dbar, and the station interval was wider than those of *Kaiyo* WOCE cruises. Its parameters are CTD, ADCP velocity, oxygen from sampled water and meteorological ones (e.g., air temperature). In this paper, CTD and ADCP results are used. During TOCS July 1995 cruise, the moorings mentioned in 2.1 were recovered.

Final cruise (*Kaiyo* WOCE IV cruise) was carried out during June 1996 as a WHP one-time observation along the southern part of P8 line (130°E line, Fig. 4c). Instruments used during this cruise are also the same as during *Kaiyo* WOCE II (see Kashino et al., 1996). Total dissolved inorganic carbon, pH, total alkalinity, and C-14, helium and tritium were added to the parameters of *Kaiyo* WOCE II. The accuracy and precision of parameters during this cruise are a little better than those during *Kaiyo* WOCE II (Kashino et al., 1996).

2.3 Other data

In order to discuss the phenomena revealed in the mooring data, the objective analyzed data, called GANAL (global objective analysis data), obtained by the numerical weather forecasting model by Japan Meteorological Agency was analyzed. We used the wind data of this dataset on the pressure surface of 1000 hPa with a 1.875° grid, every 12 hours, during the mooring's deployment. According to Nishi and Sumi (1995), this wind data is reliable below 100 hPa around the western Pacific.

3. Mooring observation result

3.1 TMN (Talaud-Morotai-North)

Figure 5a shows time series of temperature, salinity, pressure and current velocity after an application of the 48TK filter at TMN. North-northwestward flow which direction is probably influenced by the near shallow sill (Fig. 2), is dominant. This dominant flow has an intermittent increasing with period of around 50 days. Its amplitude reaches 30 cm/sec. An oscillation with the similar period is also found in the current velocity from other RCMs at TMN with an amplitude of 10-15 cm/sec. At 550 m and 1050 m, current variability is out of phase to that at 350 m, which means a baroclinic signal with a node between 350 m and 550 m. Because of increasing trend of north-northwestward flow, this oscillation became unclear after November 1994 in the time series only through the 48TK filter.

To examine this interseasonal variability, stick diagram, temperature and salinity variability after filtering variability outside of the band of periods between 30 days and 120 days are shown in Fig. 5b. Because of this filter, this oscillation is seen clearly in TMN-350 m current meter data after November 1994, although its pattern changed comparing before then, e.g., amplitude became small (Fig. 5b). This change is maybe related to rush of north-westward flow at TMS after November 1994 (see 3.2).

Similar oscillation is also revealed in temperature and salinity time series at 260 m and 350 m (Fig. 5). Temperature and salinity values there tend to rise up with decrease of north-westward current velocity at 350 m. A trend of

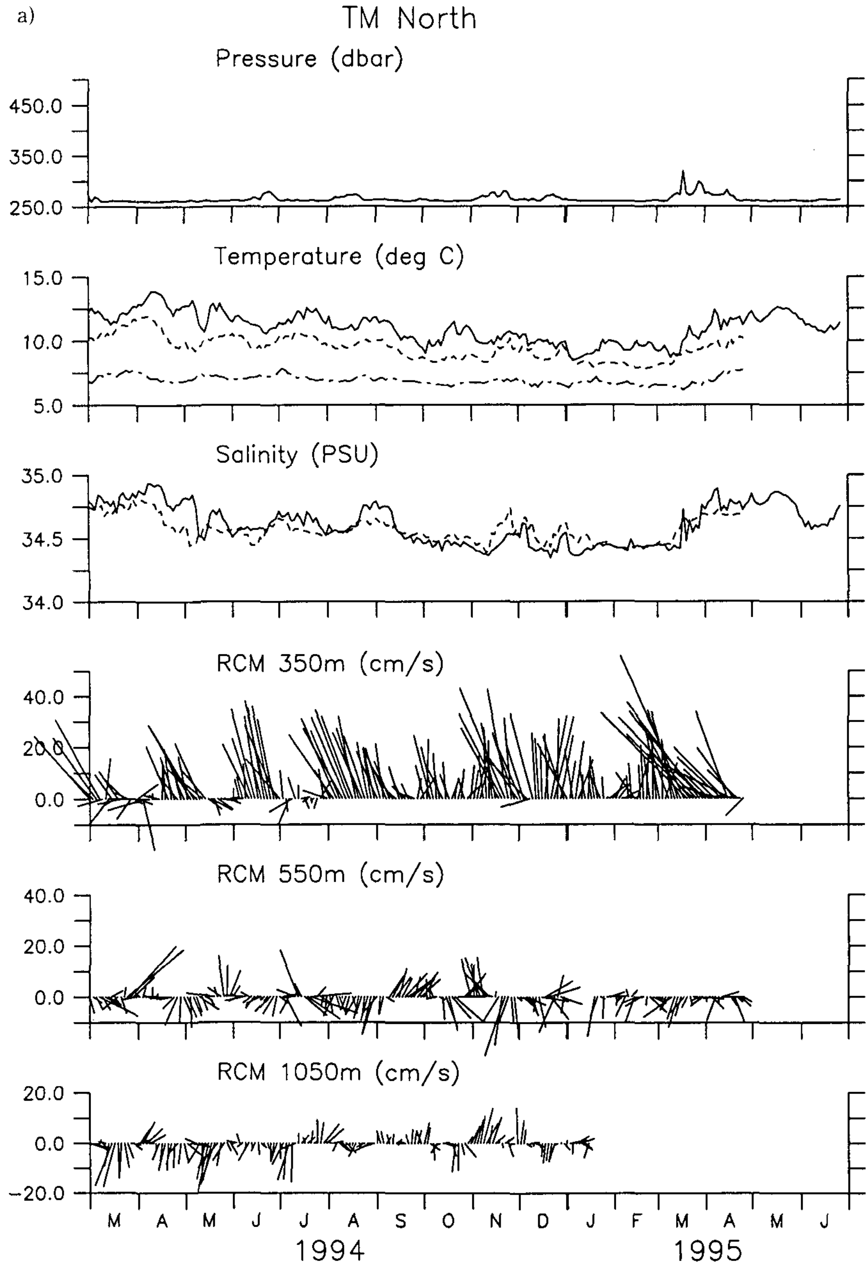
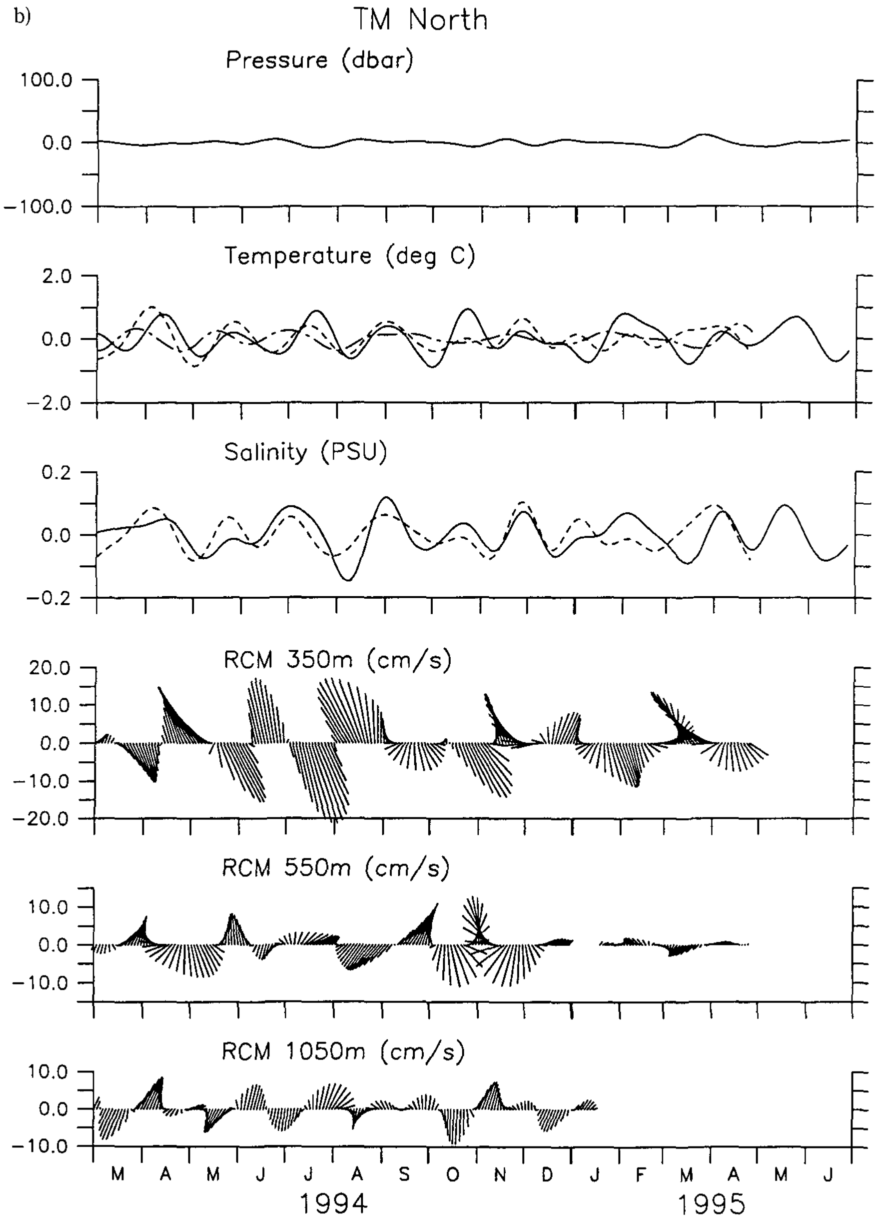


Fig. 5. Time series of RCM velocity, RCM and CTD temperature, salinity and pressure at st. TMN after application of a) the 48TK filter, and b) 30-120 days band-passed filter. Thick solid lines, thin solid lines and broken lines in temperature and salinity time series denote those from CTD (260 m depth), RCM-350 (350 m depth) and RCM-550 (550 m depth), respectively. Pressure time series is that from CTD.



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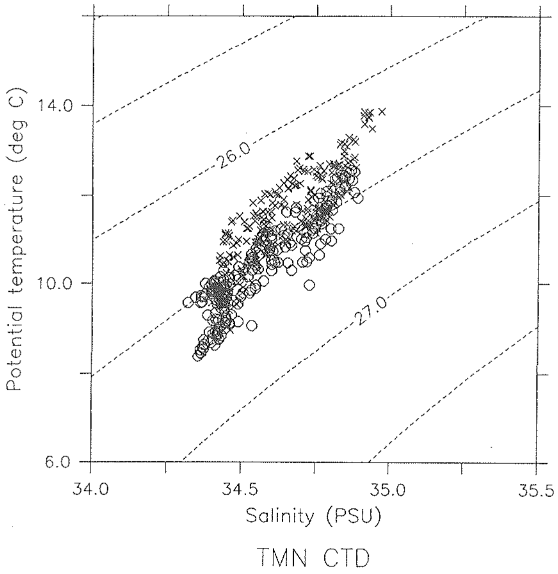


Fig. 6. Potential temperature and salinity scatter plot of daily CTD value though the 48TK filter at TMN. Crosses and circles denote the data before October 31, 1994, and after November 1, 1994, respectively. Counter interval of σ_θ is 0.5 kg/m^3.

temperature and salinity falling down is also seen from spring 1994 to winter 1995, together with the increase of current velocity.

Scatter plot on potential temperature-salinity diagram from CTD data at 260 m is shown in Fig. 6 in order to identify water passed through there during the mooring period. Figure 6 shows that CTD moored at 260 m depth measured water with $26.2<\sigma_\theta<26.7$, 8.2°C < Temperature < 13.8°C, 34.3 PSU < Salinity < 34.9 PSU. According to θ-S relation shown by Kashino et al., (1996), this property is that of the mixed water of remnant of the North Pacific Intermediate Water (NPIW) originating in the North Pacific (Bingham and Lukas, 1994), and deep part of the South Pacific Tropical Water (SPTW) from the South Pacific (Kashino et al., 1996). Because of the confluence zone of these water masses, the mixed water between them was observed. After November 1994, σ_θ of water measured by CTD became large with temperature falling. Because pressure did not become high except during March and April 1995 (Fig. 5a), this is due to change of the water property at CTD depth but not to mooring incline.

The South Pacific water with high-salinity (>34.8 PSU) and high temperature (>12°C) was seen before May 1994 and after April 1995 at 260 m (Fig. 5a). On the other hand, low-salinity (<34.6 PSU) and low-temperature water (<

12°C) from the North Pacific was found from autumn 1994 to winter 1995 at 260 m and 350 m. As described before, comparing with the current variability at 350 m, this South Pacific water tends to be seen when the north-northwestward flow becomes weak.

3.2 TMS (Talaud-Morotai-South)

At TMS-350 m and -550 m, west-northwestward to west-southwestward flow was observed before November 1994 (Fig. 7). Subsequently the deep part of the SPTW and the NPIW was seen at 260 m and 350 m, respectively. In spite of 90 m depth difference between CTD depth and RCM depth, these results suggest that South Pacific water enters into the Maluku Sea by this westward flow. This is consistent with the results by Ffield and Gordon (1992), and Ilahude and Gordon (1996). It is interesting that the North Pacific water (at RCM-350 m) is below the South Pacific water (at CTD depth), because the NPIW was observed above the wedge-shaped SPTW at the Mindanao side along the section between Mindanao and New Guinea during the *Kaiyo* WOCE II cruise (Kashino et al., 1996, Fig. 5).

From November 1994 to March 1995, northwestward current was strong enough to tilt the mooring line substantially (estimated angle of inclination reached 20 degree). The CTD pressure variations indicate that this strong current fluctuated with various time scales but not tidal, however the current direction was stable. During this period, because of the increase of the mean depth of the instruments by about 100 m, and large vertical fluctuations due to this flow, these instruments did not measure properties at the depth designed. For example, salinity value from CTD became lower than 34.55 PSU (Figs 7a and 8), and that derived from temperature and conductivity sensors at 350 m rose about 0.2 PSU. Previous one is close to the water property of the NPIW, and the latter is nearly that of the South Pacific water. After April 1995, current direction changed to west-northwest, its strength became weak, and water property measured by CTD and the sensors of RCM returned as those before May 1994.

Although the mooring instruments were not settled at the intended depth, we can make time-depth plots for parameters making use of their vertical motion. The velocity vector and salinity time-depth plots during the intensity of the north-westward flow from November 1994 to March 1995 are shown in Figure 9. Pressure values of RCM (350 m and 550 m) without pressure sensor are calculated by linear interpolation of the pressure values of CTD (260 m) and RCM-1050 with pressure sensor. (Error due to the interpolation is thought to

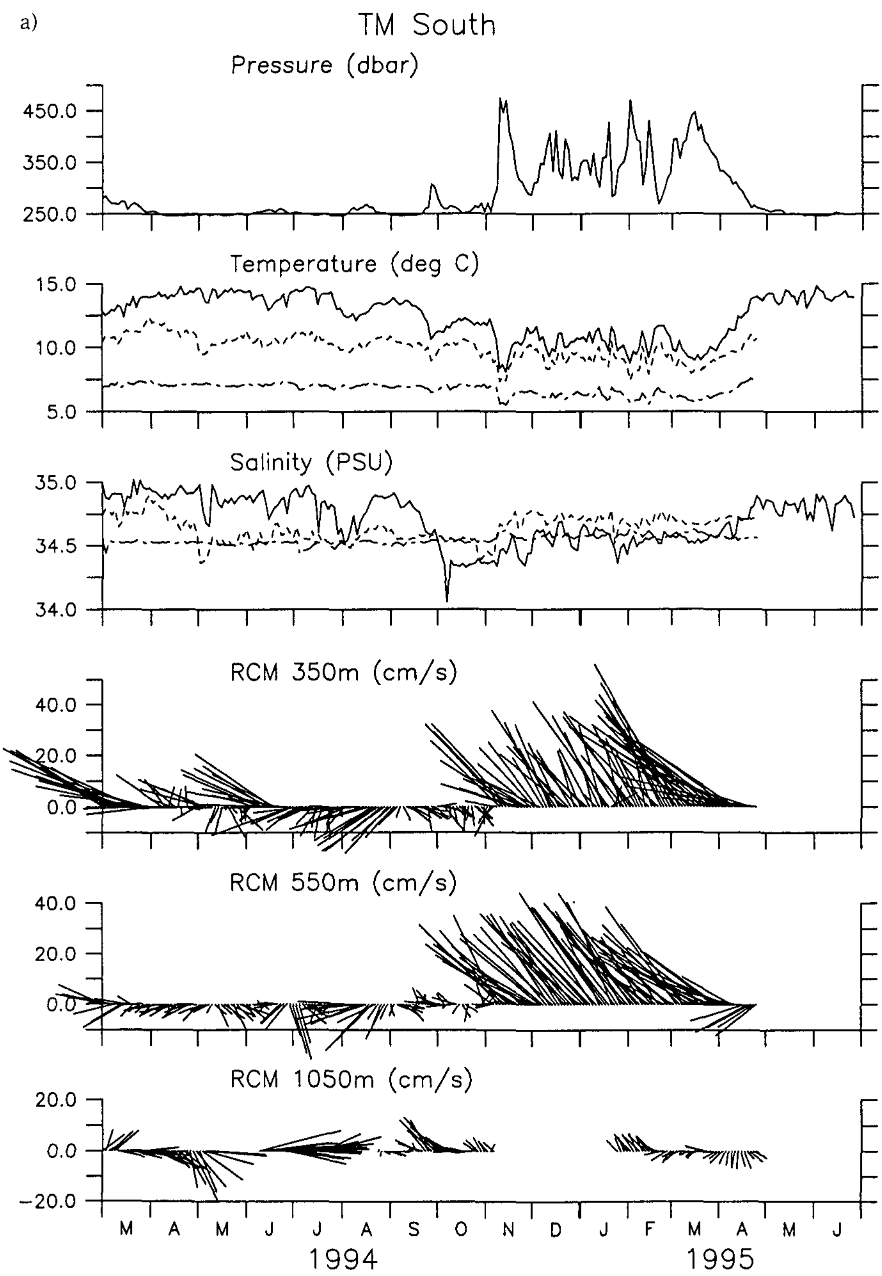
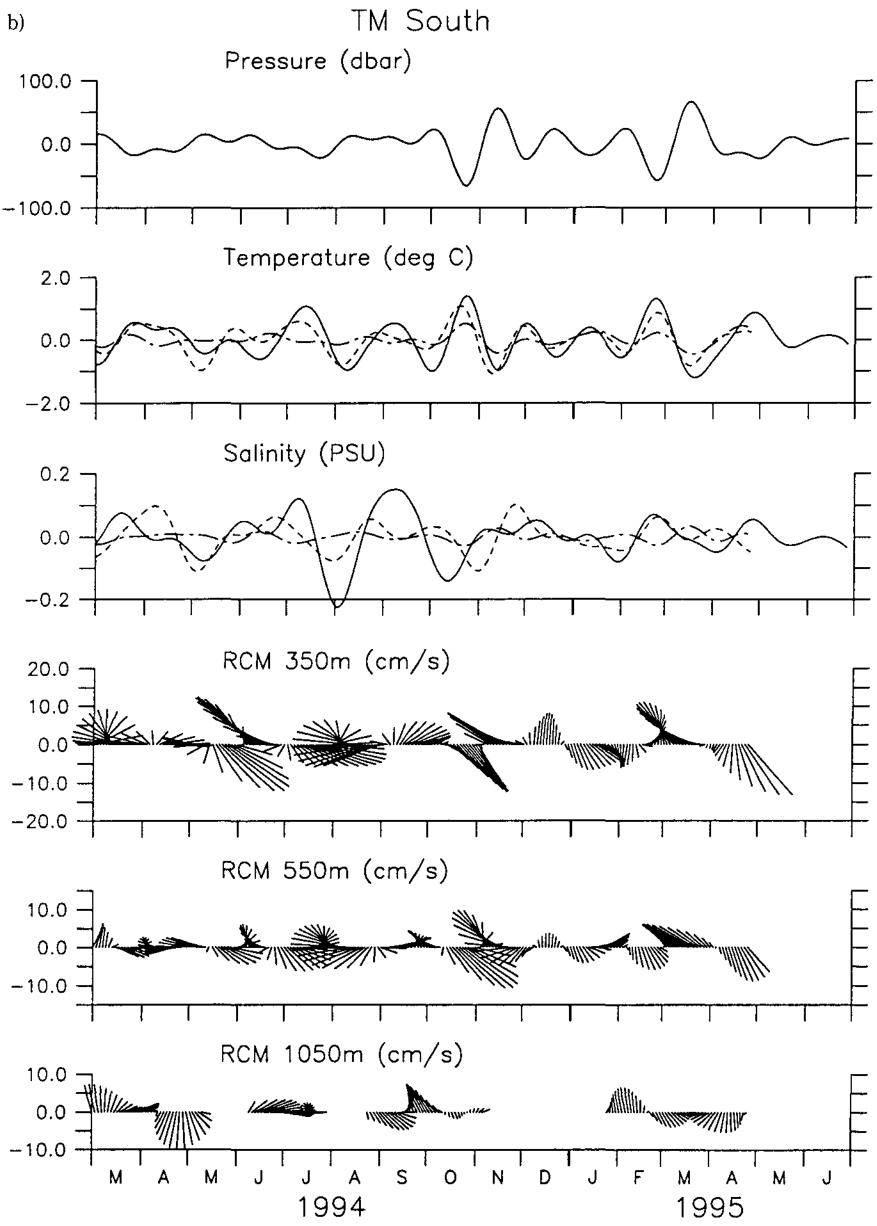


Fig. 7. Same as Fig. 5, but at TMS.



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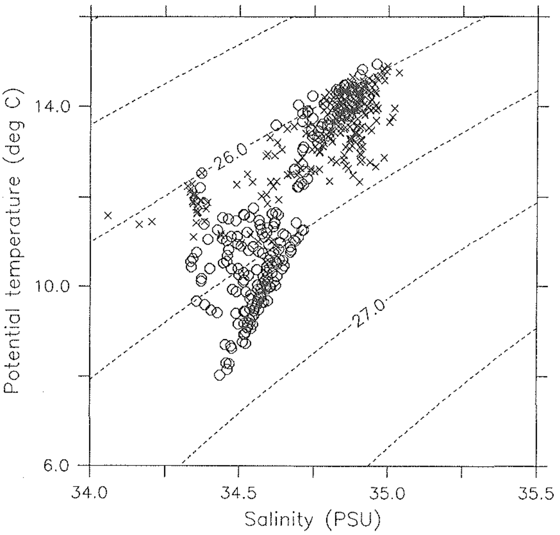
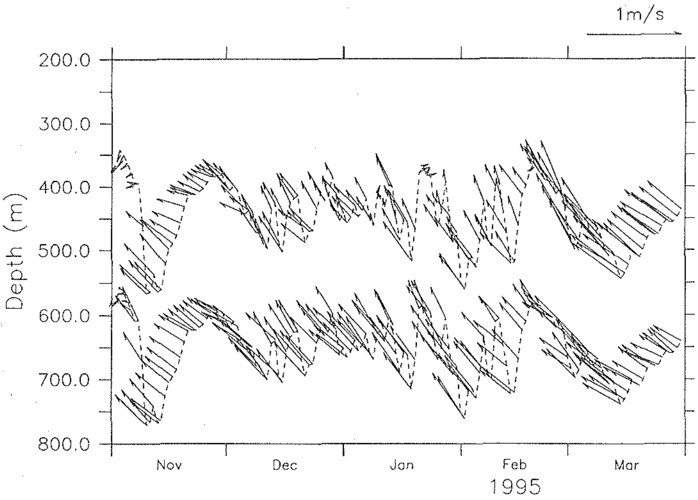


TMS CTD

Fig. 8. Same as Fig. 6, but at TMS.

be insignificant because the pattern of pressure variability at 260 m and 1050 m is very similar to each other.) Figure 9a shows that this strong flow appears to have its thickness of at least 300 m. Salinity measured by CTD above 400 m is almost lower than 34.6 PSU during this period (Fig. 9b). T-S scatter plot shown in Fig. 8 suggests that this low salinity water located from 250 m depth to 450 m is the NPIW or mixed water between the NPIW and South Pacific water. This low salinity water appears to advect north-westward with high-salinity water (>34.7 PSU) by this flow because of the current structure shown in Figure 9a, i.e., it is strange for the North Pacific water to come from the southeast. We discuss this matter in 4.2.

The 50 days oscillation mentioned in 3.1 is also revealed clearly in the band-passed time series from 30 days to 120 days at TMS (Fig. 7b). It is interesting that the variability between TMS-350 m and TMS-550 m is almost in phase, but not between TMN-350 m and TMN-550 m (Fig. 5). The phase difference of this oscillation between TMN and TMS is negligible (<1 day). During the intensification of north-westward flow at TMS, this oscillation at TMS can be traced and its pattern at TMS-350 m is very similar to that at TMN-350 m. This implies that velocity value by TMS-RCMs is not unreliable even though its mooring line was tilted due to the rush of northwestward flow and the 50 days a)



b)

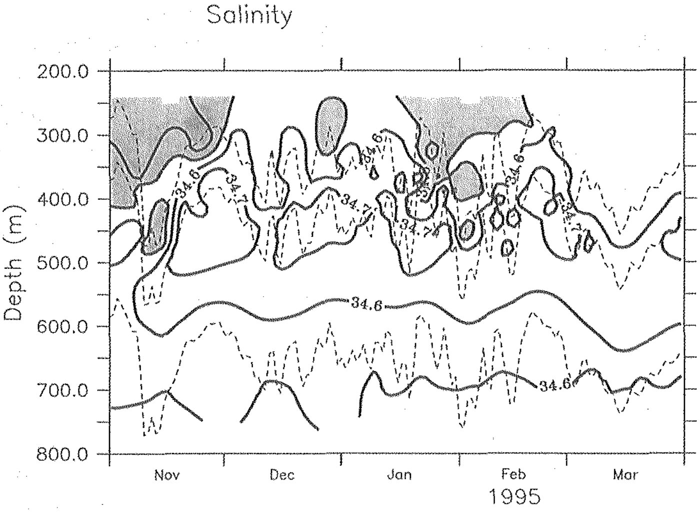


Fig. 9. Depth - time plots for a) velocity from RCM-350 m and RCM-550 m, b) salinity from CTD and RCM-350 at TMS from November 1994 to March 1995. Thin broken lines denote tracks of the moored instruments. Interval of thick contour in Fig. 9b is 0.1 PSU. Lower salinity water than 34.5 PSU is hatched.

oscillation continued during this phenomenon.

4. Discussion

In this section, we discuss the interesting phenomena described in the previous section, i.e., the 50 days oscillation, and the rush of northwestward flow at TMS.

4.1 50 days oscillation

As shown in Fig. 5 and Fig. 7, the oscillation with period of about 50 days was observed during all period of the moorings' deployment. One of its characteristics is that fluctuations at TMS-350 m and TMS-550 m are in phase, but those at TMN-350 m and TMN-550 m are not so. That is, some wave without a node between 350 m and 550 m depth at TMS is thought to come from southeast or east, and meet the shallow sill between TMN and TMS with depth of 300 m, resulting in the higher mode wave with a node between these depths at TMN.

Kutsuwada and Inaba (1995) also observed 60 days oscillation in ADCP velocity moored at 147°E and 154°E on the equator, although the depth with its spectrum peak seen is shallower than our observation. They commented that this oscillation cannot be explainable by the linear equatorial waves, but maybe derived from non-linear effect as shear instability. In our observation area, as Lukas et al. (1991) showed by drifter paths, ocean variability from eddy activity is also thought to be significant. Especially, because there are the Halmahera and Mindanao Eddies near the mooring stations and the ocean front due to the North and South Pacific waters locates with the NECC, these eddies appear to be active. Numerical experiments by Inoue and Welsh (1993), and Qiu and Lukas (1996) also suggested current variability due to eddy activity with time scale of 20-80 days. Furthermore, result from the global eddy resolving model developed in JAMSTEC (1/4 degree × 1/4 degree, 55 layers, driven by monthly climatological data) also shows that the Mindanao and Halmahera Eddies repeat growth and decay, and walk around this area with period of 40 days maybe associated with the instability of the front at the NECC (Ishida, personal communication). Although we cannot identify this wave only from this mooring data, it is possible that the wave observed is a non-linear one derived from these eddy activity.

Local wind variability is also a participant influencing the circulation in western equatorial Pacific. Madden and Julian (1994) suggested that eastward propagating cloud complexes with period of 40-50 days (Madden and Julian Oscillation, hereafter called MJO) is seen in the tropical atmosphere, and pressure and wind field also oscillate together with their moving. According to Molcard et al., (1996), time series at the Timor Passage, where is thought to be the main exit of the Indonesian Throughflow, also shows an oscillation with the similar period to our observation, which may be derived from the MJO (Molcard et al., 1996).

In order to check the relation between the 50 days oscillation and MJO, objective analysis wind data (GANAL) mentioned in section 2.3 is analyzed. The MJO is well revealed in the GANAL because cross-spectrum at 3°N, 140°E and 3°N, 140°W shows peak around 40 days, and its eastward propagation speed estimated from phase difference is ~ 10 m/sec (not shown). Power spectrums of velocity component of 339 degree from north (main axis of the current) at TMN-350 m and u-component of wind on 1000 hPa surface at 3N, 131° 15'E from the GANAL, are shown in Fig. 10. We can see peaks around 40-50 days in power spectrums both of current and wind. Coherency between them around this period is >0.4. This result suggests that the MJO is also correlated with the 50 days oscillation because null hypothesis (correlation =0) is rejected when its correlation is larger than 0.137 with confidence level of 95%. Local wind variability associate with the MJO might let the low-latitude boundary current

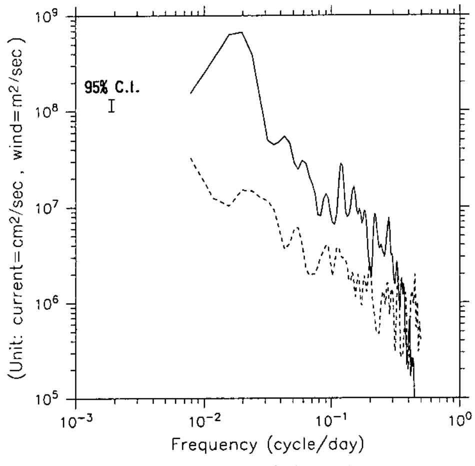


Fig. 10. Power spectrums of velocity component of 339 degree from north through the 48TK filter at TMN-350 m (solid line) and u-component of wind on the surface of 1000 hPa at 3°N, 131°15'E from the GANAL (broken line). 95% confidence interval is indicated by a vertical bar.

system oscillate, and induce topographic waves with this period.

As another possibility, we thought that the MC variability associated with coastal Kelvin wave along the Mindanao coast or Rossby wave in the North Equatorial Current relates with the current variability at TMN and TMS. As shown in Fig. 1, the MC retroflects in the Celebes Seas, and returns to the Pacific between Mindanao and Halmahera. If the MC fluctuates interseasonaly as shown by Inoue and Welsh (1993), it is also possible that this fluctuation influences on the circulation near the mooring sites. However, as shown by Lukas (1988), interseasonal variability as the 50 days oscillation is not clear in the sealevel time series at Davao (Mindanao) and Malakal (Palau) as shown in the time series at TMN and TMS. Therefore, the 50 days oscillation appears not to be related with MC variability.

4.2 Rush of north-westward flow at TMS

From November 1994 to March 1995, the intensification of north-westward flow was seen (Fig. 7a). Notice that low-salinity water (~34.5 PSU), the remnant of the NPIW, appears to be advected by this flow from the southeast at the depth of 300-400 m (Fig. 9) although the NGCUC, which transport the SPTW and AAIW from the South Pacific, flows along the western boundary in this region (Fine et al., 1994 ; Kashino et al., 1996).

As mentioned in 3.2, it is interesting that the low-salinity North Pacific water has come from the southeast during this phenomenon, and it seems to be a key of understanding its mechanism. When the moorings were recovered, the low-salinity water (<34.5 PSU) was not observed at the CTD depth (260 m depth), but an isolated low salinity core water existed near TMS at 350 m depth (st. 9 and 10 in Fig. 11a). Probably, this is the remnant of the low salinity water advected by the strong northwestward flow during winter.

We examine where the above isolated low salinity water came from. Salinity section measured by CTD along 130°E during *Kaiyo* WOCE IV expedition is shown in Figure 11b. Low-salinity tongue (<34.5 PSU) going southward below salinity maximum (SPTW) is revealed in this section. ADCP velocity vectors at 350 m depth during *Kaiyo* WOCE IV (along 130°E in Fig. 12b) shows southeast-southwestward flow along 130°E at the south of 5°N. The low salinity water tongue crosses the salinity front at 6N and sinks below SPTW along $\sigma_\theta=26.5$ by this southward flow.

σ_θ contours shown in Fig. 11b suggested that there is an anticyclonic eddy whose center is located at 4°N. This is the Halmahera Eddy. Its structure is revealed clearly in ADCP velocity vectors along tracks during TOCS July 1995

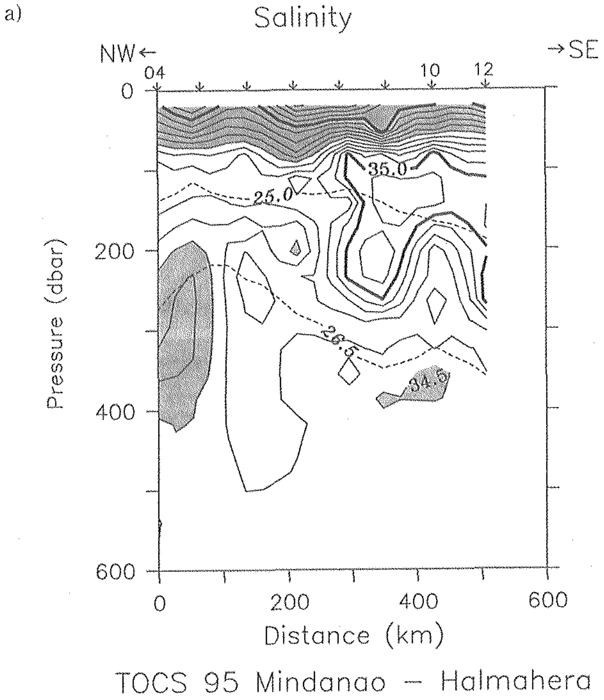


Fig. 11. Salinity section a) between Mindnao and Morotai (st.4 and st.12 in Fig. 4b) during TOCS July 1995 cruise, and b) along 130°E during *Kaiyo* WOCE IV cruise. Lower salinity water than 34.5 PSU is hatched. Contour interval is 0.1 PSU. σ_θ contours of 25.0 and 26.5 denoted broken lines are included.

and *Kaiyo* WOCE IV cruises (Fig. 12). In spite of time lag of a year between these cruises, current pattern is similar to each other because of the same season. At the depth of 50 m, its center locates east of 130°E, and its horizontal scale reaches 500 km (Fig. 12a). Increasing with depth, the center shifts west and its scale become small (300 km at 350 m depth).

These results indicate that the low salinity water observed along 130°E has intruded from north of the salinity front by the Halmahera Eddy. Furthermore, This water is continuously thought to advect around the eddy, and goes north-westward between Talaud and Morotai. That is, the Halmahera Eddy probably transported the low-salinity water observed at TMS during the rush of north-westward flow, which seemed to be a part of the eddy. It is explainable why the low-salinity water from the North Pacific was seen below the high-salinity water from the South Pacific at TMS because of this intrusion to the high-salinity water (Fig. 11).

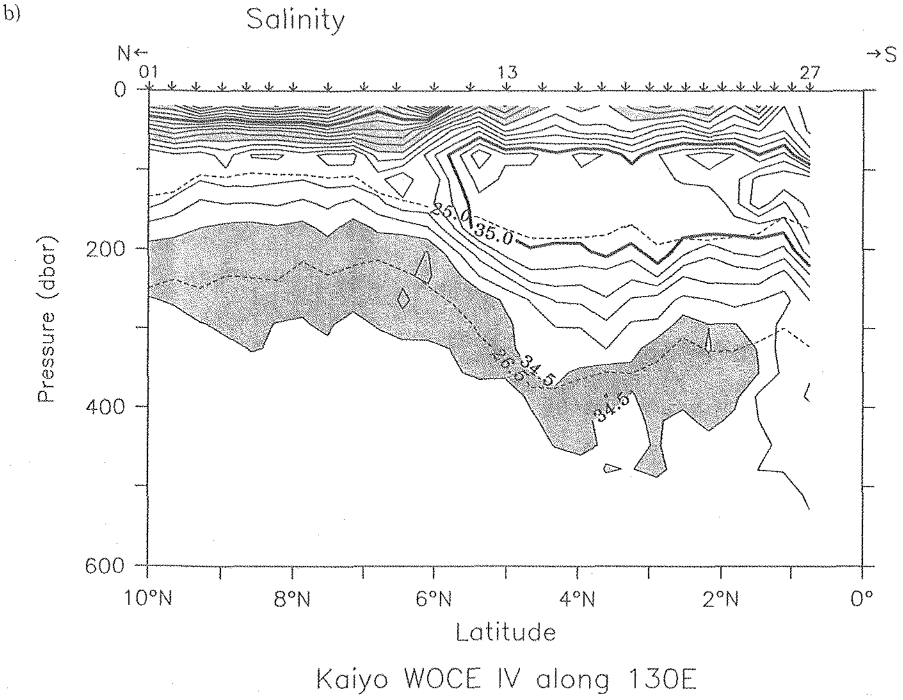


Fig. 11. *(Continued)*

We suspect that the strong north-westward flow observed from November 1994 to March 1995 was due to movement of the Halmahera Eddy. During this phenomenon, the northwestward velocity was not strong at TMN as TMS because the shallow sill between these sites prevented the Halmahera Eddy from going near TMN. According to Masumoto and Yamagata (1991), an upwelling area off the Philippine, called the Mindanao Dome, enlarges associated with change of the positive wind stress curl distribution in boreal winter. Together with generation of the Mindanao Dome, the NECC shifts southward in winter (Masumoto and Yamagata, 1991). Probably, the Halmahera Eddy, which locates at the south of the Mindanao Dome, also shifts southward in winter. As shown in Figure 12, the NECC located at 6N during boreal summer, but cannot be seen at this latitude during *Kaiyo* WOCE III (January 1995) performed just during this phenomenon (Fig. 13).

Monthly mean wind vectors and curl of its stress (used drag coefficient of 1.5×10-3^{-3}) distribution of the GANAL in October and November 1994 are shown in Figure 14. In October, weak southwesterly wind (<5 m/sec) and

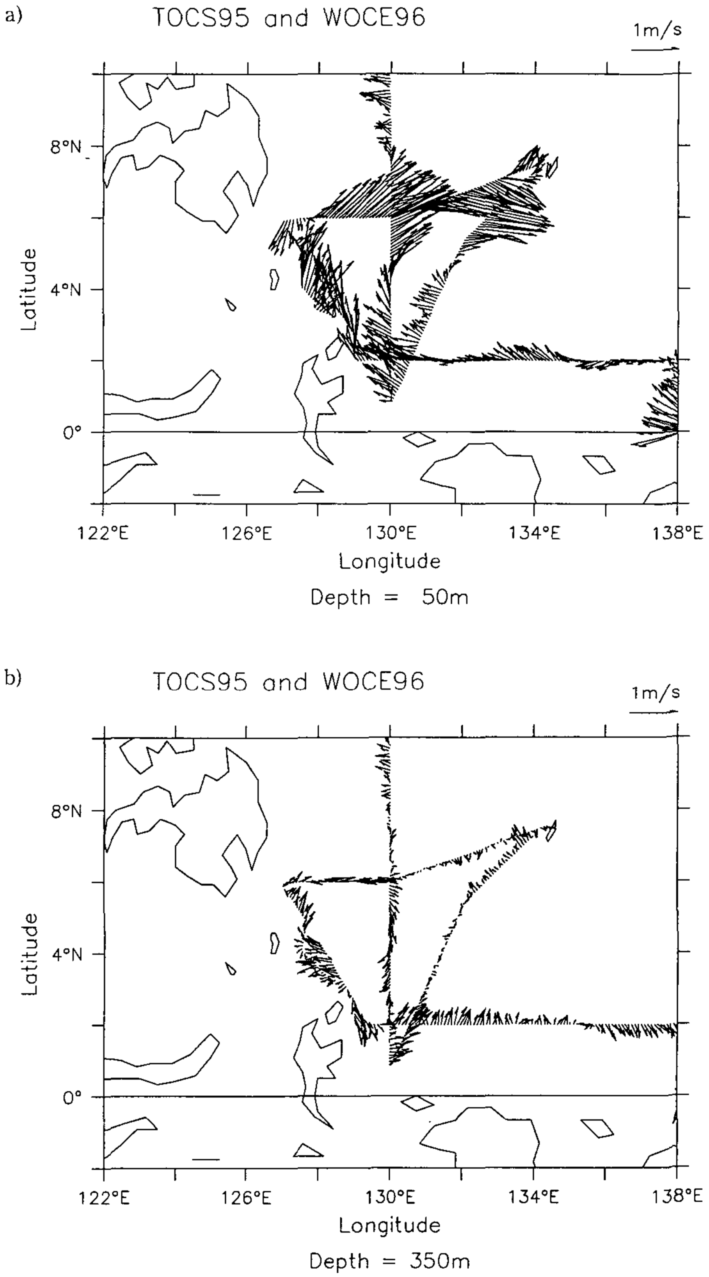


Fig. 12. Currents measured by the shipboard ADCP at a) 50 m, and b) 350 m depth during TOCS July 1995 and *Kaiyo* WOCE IV cruises.

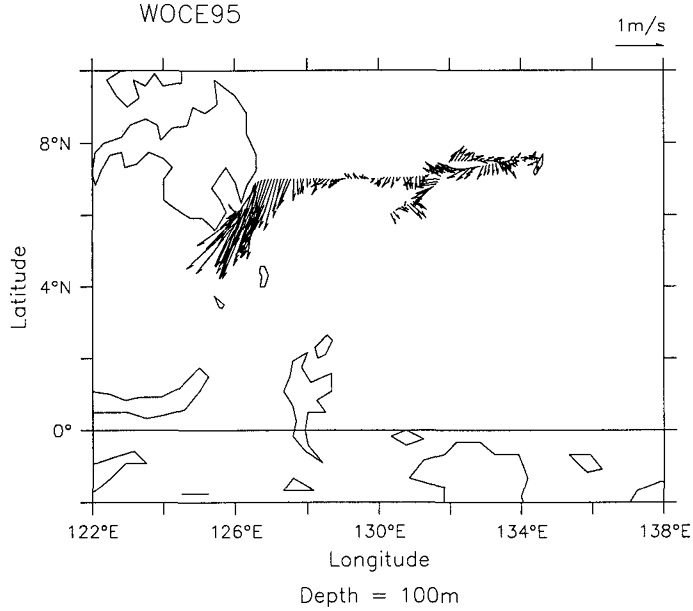


Fig. 13. Currents measured by the shipboard ADCP at 50 m depth during *Kaiyo* WOCE III.

negative curl of its stress was seen off the Philippines. Near the mooring sites, wind velocity was negligible. After November, wind stress curl changed to positive with strong northeasterly monsoon (6~8 m/sec) in the southernmost Philippine Sea. These patterns of wind and curl of its stress continued until April 1995, when the phenomenon at TMS terminated. This wind pattern change is consistent with the current pattern change.

5. Conclusions

In order to study the ocean variability between Mindanao and New Guinea at the Pacific entrance of the Indonesian throughflow, we deployed two moorings with a CTD and three current meters between Talaud and Morotai (Indonesia) from February 1994 to June 1995. Hydrographic observations were also conducted in the western boundary region of the equatorial Pacific, and the global objective analysis data obtained by the numerical weather forecasting model is used to understand the phenomena revealed in the mooring observation. Their results are as follows:

1. Clear oscillations with period of 50 days were observed during all period of

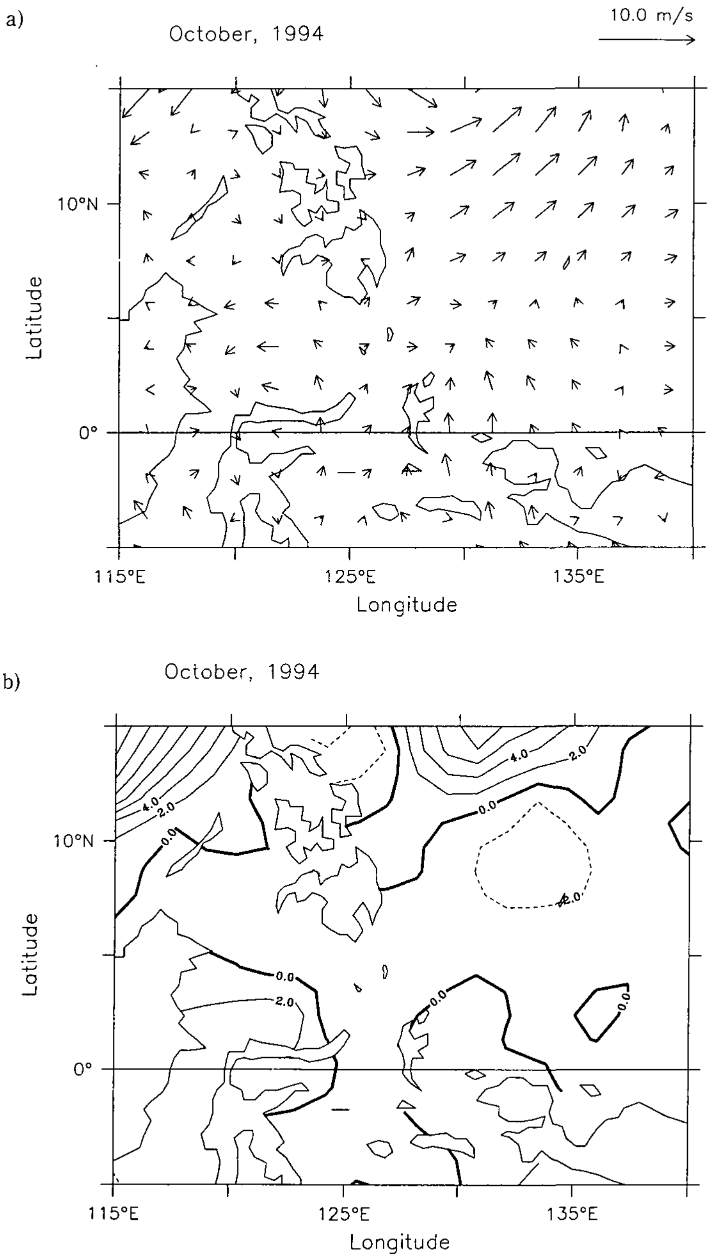


Fig. 14. a) Monthly mean wind field on 1000 hPa pressure surface at October 1994 from the global objective analysis data (GANAL), obtained by the numerical weather forecasting model by Japan Meteorological Agency, and b) its wind stress curl distribution. c) and d) are the same as a) and b) but at November 1994. To calculate wind stress, drag coefficient of 1.5×10^{-3} is used. Contour interval in b) and d) is 2.0×10^{-8} N/m^3.

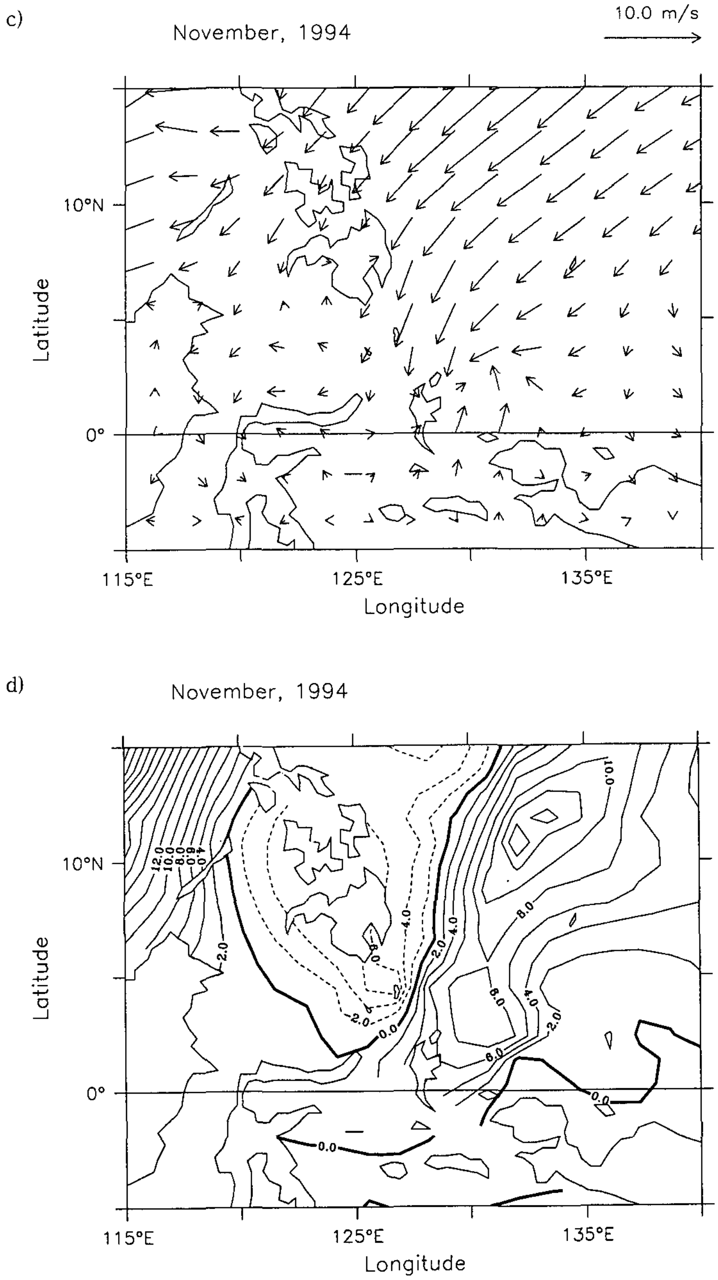


Fig. 14. (*Continued*)

their deployment at the both stations between Talaud and Morotai. Because of the correlation between local wind variability with similar period in the tropical atmosphere, i.e., Madden and Julian Oscillation (Madden and Julian, 1994) and current oscillation, wind fluctuation associated with the MJO may induce topographic waves, or eddy activity due to instability at the NECC front may result in the 50 days oscillation at both mooring sites.

2. At the south site (TMS), rush of northwestward flow was observed from November 1994 to March 1995. This flow advected the low-salinity water (<34.5 PSU) originating in the North Pacific with the high-salinity water from the South Pacific, and is probably a part of the Halmahera Eddy transporting the low-salinity water from the north of the salinity front at the NECC. Perhaps, this phenomenon occurred by southward shift of the Halmahera Eddy associated with wind stress change at November 1994. During boreal summer, north-southwestward flow transporting high-salinity water from the South Pacific was seen at the southern mooring.

First result implies that not only seasonal variability but also interseasonal one is large in the western boundary region of the equatorial Pacific. As shown in the numerical result by Inoue and Welsh (1993) and Qiu and Lukas (1996), and drifter paths by Lukas et al. (1991), eddies around the NECC are active. Furthermore, the current variability in this region also is probably influenced by the MJO. To complete description of the circulation there, these matters should be considered.

Around the mooring sites, the Halmahera Eddy was observed during *Kaiyo* WOCE cruises and TOCS July 1995 cruise. ADCP results during these cruises showed its structure. This eddy extracts the North Pacific water from the north of the ocean front at the NECC. This water goes round the eddy with the South Pacific water through the mooring stations. As discussed by Kuroda et al. (1995), mixed water from the North Pacific and South Pacific might be created by the eddy during this process. The Halmahera Eddy may be key concerning water masses entering into the Indonesian Seas as the eastern route of the Indonesian Throughflow, and its variability.

Acknowledgments

The *Kaiyo* WOCE cruises and TOCS July 1995 cruise were done as a joint project by Japan Marine Science and Technology Center (JAMSTEC), Japan, and Badan Pengkajian Dan Penerapan Teknologi (BPPT), Indonesia. Part of this research was performed through the Special Coordination Funds of the

Science and Technology Agency of Japanese Government. We thank colleagues in JAMSTEC and BPPT making efforts for execution of these cruises. During the cruises, crew of *Kaiyo*, scientists of JAMSTEC, BPPT and Central Research Institute Electric Power Industry, and technicians of Nihon Marine Enterpris Co. Ltd., Sanyo Techno Marine Inc., and Kansai Environmental Engineering Center Co. Ltd, who participated to these cruise helpfully supported us. K. Muneyama supervised JAMSTEC WOCE and TOCS projects. The moorings mentioned in this paper were designed by A. ITO and T. Kawano. The moored CTD data was offered by K. Ando. Y. Kuroda pleasantly gave us permission for using TOCS July 1995 cruise data. K. Yoneyama offered us much information concerning the wind data of the GANAL. Many comments by R. Lukas, T. Yamagata, H. Mitsudera and B. Qiu were useful for this study. The staffs and students of Department of Oceanography in University of Hawaii helped the author for writing this paper during author's stay there.

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