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Observations of the North Equatorial Current, Mindanao Current, and Kuroshio Current System during the 2006/07 El Niño and 2007/08 La Niña

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Two onboard observation campaigns were carried out in the western boundary region of the Philippine Sea in December 2006 and January 2008 during the 2006/07 El Niño and the 2007/08 La Niña to observe the North Equatorial Current (NEC), Mindanao Current (MC), and Kuroshio current system. The NEC and MC measured in late 2006 under El Niño conditions were stronger than those measured during early 2008 under La Niña conditions. The opposite was true for the current speed of the Kuroshio, which was stronger in early 2008 than in late 2006. The increase in dynamic height around 8°N, 130°E from December 2006 to January 2008 resulted in a weakening of the NEC and MC. Local wind variability in this region did not appear to contribute to changes in the current system.

Keywords:
· North Equatorial Current,
· Mindanao Current,
· Kuroshio,
· 2006/07 El Niño,
· 2007/08 La Niña.

1. Introduction

The North Equatorial Current (NEC) flows westward and bifurcates into the southward flowing Mindanao Current (MC) and the northward flowing Kuroshio in the Philippine Sea. The NEC-MC-Kuroshio (NMK) current system has been investigated by a number of authors, particularly since 1990 (e.g., Toole *et al.*, 1990; Qiu and Lukas, 1996; Qu and Lukas, 2003; Kim *et al.*, 2004). It is believed to play an important role in the heat budget of the warm water pool and in supplying water to the Indonesian Throughflow (Lukas *et al.*, 1996). In addition, because the NEC and MC form a probable pathway by which water parcels in the mid-latitudes reach the equatorial region, they are also potentially important factors in interdecadal climate variability (e.g., Gu and Philander, 1997). Therefore, details of the NMK system are required for a better understanding of the climate variability in the Asia-tropical Pacific region.

To date, research on the NMK system has been mainly involved numerical studies or the analysis of climatological data due to the limited availability of systematic onboard observations in the Philippine Sea. For example, based on numerical results, Qiu and Lukas (1996) and Kim *et al.* (2004) suggested that the NEC bifurcation latitude is well correlated with the El Niño/Southern Oscillation (ENSO) phenomenon. Qu and Lukas (2003) discussed the seasonal variability of the NEC bifurcation latitude and its depth dependence using historical data.

Some onboard observations of the NMK system have been conducted; these include observations taken during the United States-People's Republic of China Cooperative Studies of Air-Sea Interaction in the Tropical Western Pacific (US-PRC) (Toole *et al.*, 1990). Two hydrographic surveys were conducted along lines at 8°N, 130°E and 18°20′ N in September 1987 and April 1998. Toole *et al.* (1990) showed that the NEC bifurcation latitude was located at 13°N during these cruises, with a large transport difference between the two periods. However, because no onboard observations concentrating on the NMK system have been published since those of Toole *et al.* (1990), the numerical results of Qiu and Lukas (1996),

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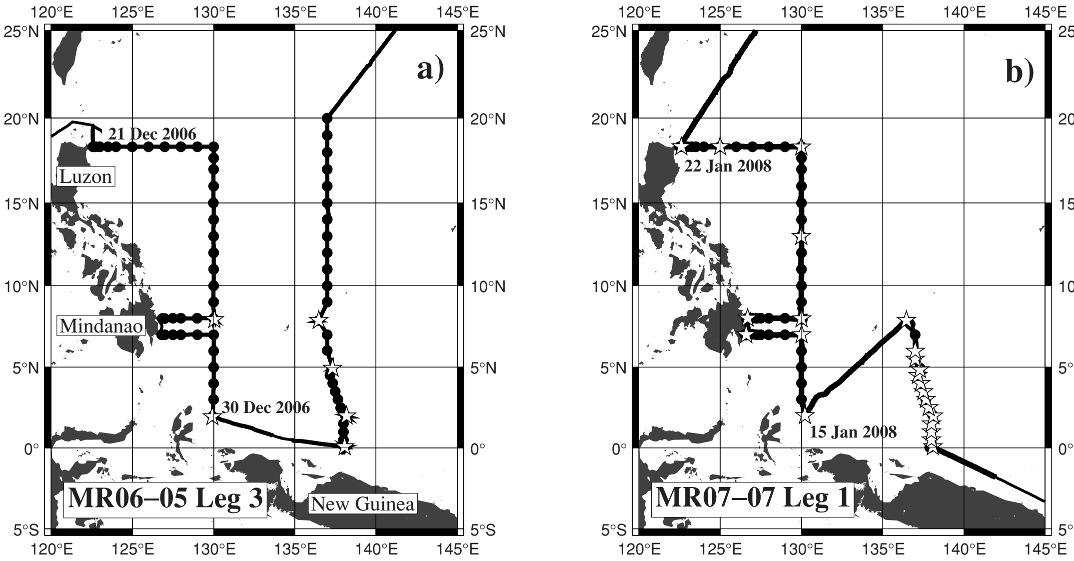

Fig. 1. Ship track and observation stations during a) MR06-05 Leg 3 (December 2006) and b) MR07-07 Leg 1 (January 2008) cruises of the R/V *Mirai*. Solid stars and circles denote CTD and XCTD stations, respectively.

Kim *et al.* (2004), and others have not yet been fully confirmed. In particular, the relationship between the ENSO phenomenon and the NMK system is still not clear. To partially rectify this situation, we describe the results from two cruises by the R/V *Mirai* that revisited the US-PRC lines in December 2006 and January 2008.

In addition, some numerical simulation results have suggested that the Mindanao Dome develops in the boreal winter due to positive wind stress curl in the Philippine Sea (Masumoto and Yamagata, 1991; Tozuka *et al.*, 2002). Because both cruises were conducted during the boreal ("boreal" is omitted hereafter) winter, it is also of interest to investigate the state of the Mindanao Dome in these two winters.

2. Observations

The two cruises of the R/V *Mirai* were MR06-05 Leg 3 from 21 to 30 December 2006 and MR07-07 Leg 1 from 15 to 22 January 2008 along 7°N, 8°N, 130°E, and 18°20′ N lines (Fig. 1). The last three lines were selected for comparison with the results of Toole *et al.* (1990).

Values of the Nino 3.4 index anomaly provided by the Climate Prediction Center of the National Oceanic and Atmospheric Administration (NOAA) during these periods were 1.29 in December 2006 and –1.81 in January 2008 (http://www.cpc.ncep.noaa.gov/data/indices/). Thus, our observations were conducted under the 2006/07 El Niño and 2007/08 La Niña conditions and are suitable for comparing differences in the ocean state between these conditions.

In 2006, during the MR06-05 cruise, we could not conduct observations in the territorial waters of the Philippines (within approximately 40 km of the coast), where large portions of the MC and Kuroshio flow. We conducted observations in these waters during the MR07-07 cruise.

Data from a conductivity-temperature-depth (CTD) profiler, expendable CTD (XCTD) system, and a shipboard acoustic Doppler current profiler (SADCP) were used. CTD and XCTD observations were conducted from the surface to a depth of 1000 m. There was a negative salinity bias of –0.05 to –0.1 (Practical Salinity Scale 78) in the XCTD data, which was corrected using the CTD data. The SADCP data were processed as described by Firing (1991).

3. Results

There were some significant differences between December 2006 and January 2008 in the vertical sections of the meridional component of velocity measured by the SADCP of R/V *Mirai* along 7°N, 8°N, and 18°20′ N lines (Fig. 2). The most striking difference was the weakness of the MC in January 2008 compared to that in December 2006. In December 2006, the maximum current speed of the MC core at 7°N was 2.0 m s^{-1}, decreasing to 1.3 m s^{-1} in January 2008. The core speed also decreased from 1.3 to 1.0 m s^{-1} at 8°N. Because the cruises were conducted during the same season and the standard deviation of the MC current speed is reported to be <0.2 m s^{-1} (Kashino *et al.*, 2005), this difference is thought to be attributable to the difference in the oceanic/atmospheric conditions between the 2006/07 El Niño and the 2007/08 La Niña.

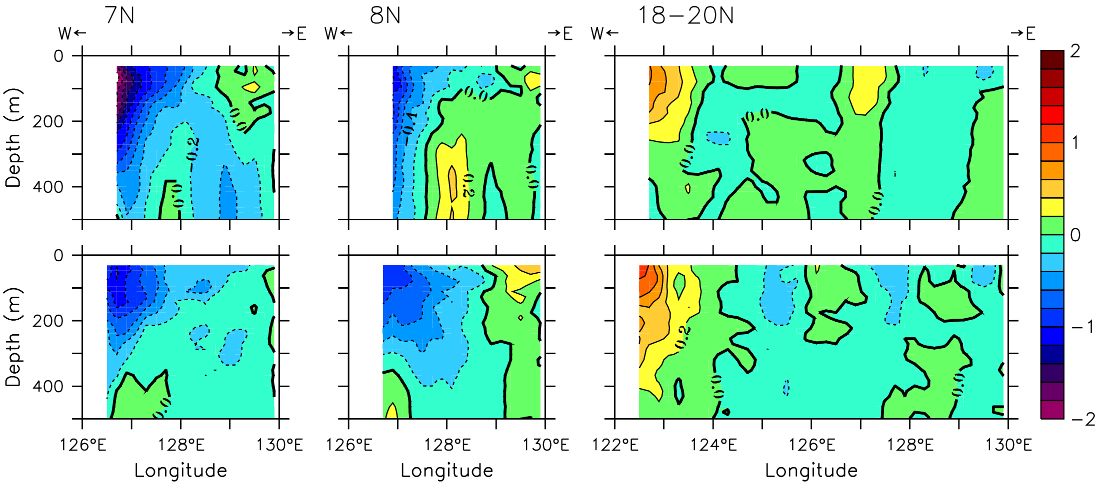

Fig. 2. Vertical sections of meridional velocity measured using the SADCP along the 7°N, 8°N, and 18°20′ N lines in December 2006 (upper panels) and January 2008 (lower panels). Positive values indicate northward flow. Contour interval is 0.2 m s^{-1}.

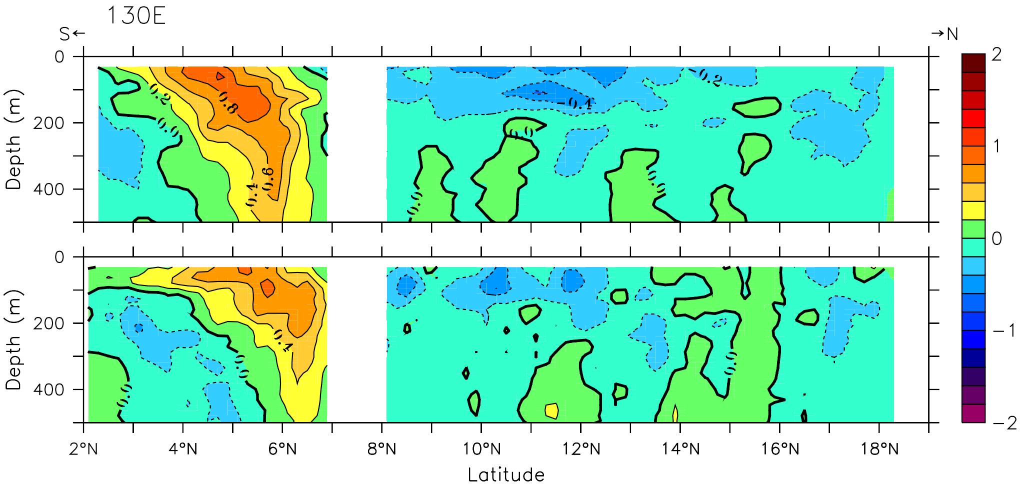

Fig. 3. Vertical sections of zonal velocity along the 130°E line in December 2006 (upper panels) and January 2008 (lower panels). Positive values indicate eastward flow.

Moored current meters in the axis of the MC (Kashino *et al.*, 2005) showed an increase in the speed of the MC from 2001 to the onset of the 2002/03 El Niño. The stronger flow during El Niño conditions is consistent with our findings and with the numerical results of Kim *et al.* (2004). Ueki *et al.* (2003) found that the New Guinea Coastal Current/Undercurrent in the South Pacific is stronger during El Niño conditions, suggesting a general strengthening of the low-latitude western boundary currents of the Pacific under such conditions.

Figure 2 shows a northward subsurface flow below a depth of 200 or 400 m around 127–128°E at the 7°N and 8°N lines. This subsurface northward flow is perhaps the Mindanao Undercurrent (MUC) (Hu *et al.*, 1991). The structure and strength of this northward flow differed between the two periods; it was particularly strong in December 2006, exceeding 0.4 m s^{-1}. It is therefore possible that the MUC is also affected by the ENSO phenomenon, although active subsurface ocean eddies were observed in this region (Firing *et al.*, 2005).

In contrast, the northward flow of the Kuroshio on the western side of the 18°20′ N line (Fig. 2) strengthened slightly from 0.9 m s^{-1} in winter 2006 to 1.1 m s^{-1} in winter 2007. It is difficult to conclude that this change is associated with the ENSO phenomenon based on this small difference, although a numerical model has indicated an intensification of the Kuroshio during the La Niña period (Kim *et al.*, 2004). As shown later, the total trans-

Table 1. Ekman transport plus geostrophic transport of the MC, NEC, and Kuroshio relative to 1000 db above $26.7\sigma_\theta$ surface in December 2006 and January 2008. Units are Sv. Wind data used for estimating the Ekman transport are provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). Drag coefficient value used for calculation of wind stress was 1.5×10^{-3}.

	December 2006	January 2008
MC (southward)	31.8	25.9
NEC (westward)	61.1	44.0
Kuroshio (northward)	24.7	16.2

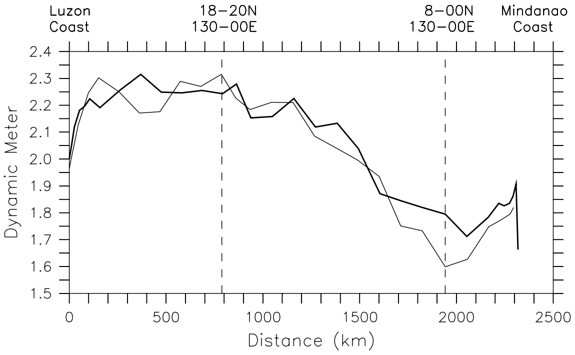

Fig. 4. Dynamic height along the 18°20′ N, 130°E, and 8°N lines relative to 1000 db in December 2006 (thin lines) and January 2008 (thick lines).

port across this section decreased from December 2006 to January 2007 due to a southward flow exceeding 0.2 m s^{-1} east of 124°E.

The difference in the zonal current structure and strength between the two periods was clear along the 130°E line (Fig. 3). The westward flowing NEC between 8°N and 14°N was significantly stronger in December 2006 than in January 2008. The maximum westward velocity during the 2006/07 El Niño exceeded 0.6 m s^{-1}. In December 2006 the eastward flowing North Equatorial Counter Current (NECC), appearing around 4–6°N, was also strong, with a current speed >1.0 m s^{-1} and a core located south of 5°N. In January 2008 the speed was reduced to 0.8 m s^{-1} and its core shifted north of 5°N. Similar changes were observed along the 137–138°E line (not shown). It is interesting to note the multi-core structure of the NEC located between 8°N and 13°N above 200 m and the northward tilt of the core of the NECC increasing with depth. These structures seem to be associated with meso-scale eddies in this region. In particular, the northward core shift of the NECC was perhaps related to the Halmahera Eddy, which was also observed south of the NECC and had an axis that shifted west-northward, increasing with depth (Kashino *et al.*, 1999).

Values of the Ekman transport plus geostrophic transport of the MC (southward transport between the coast and 130°E across 8°N), NEC (westward transport between 8°N and 18°20′ N across 130°E), and Kuroshio (northward transport between the coast and 130°E across 18°20′ N) relative to 1000 db above the $26.7\sigma_\theta$ surface are given in Table 1. Because we did not collect data in Philippine territorial waters in December 2006, we estimated the transport of the MC and Kuroshio through the Philippine territorial waters in this period by assuming that the current structure in this region resembled that in January 2008. Although there are small net transport imbalances in the NMK system, a similar imbalance was found by Qu *et al.* (1998).

The difference in NEC transport between the two periods was notable. Some model results (e.g., Qiu and Lukas, 1996) have shown large intraseasonal timescale variation in the transport of the NEC of approximately 20 Sv; however, this difference does not seem to be associated with temporary eddies, but rather with differences in the current strength in the wide area between 8°N and 15°N (Fig. 3). Because of the decrease in NEC transport from December 2006 to January 2008, the net transport of the MC and Kuroshio also decreased. The observed decrease in the transports of the MC and NEC during La Niña, compared to El Niño, is consistent with the report published by Kim *et al.* (2004). Our result is also consistent with the findings of Qiu and Joyce (1992), who showed the transport difference of the NEC and NECC across 137°E line between the ENSO year and non-ENSO year.

However, the Kuroshio transport is not in agreement with finding of Kim *et al.* (2004). There is a wide southward flow with a maximum speed >0.2 m s^{-1} east of 124°E (Fig. 2), which reduces the net northward transport across 18°20′ N despite the strong northward western boundary current in January 2008. Interestingly, the difference in transport of the MC between the two observation periods is not as large as expected because of the difference in the strength of the northward subsurface countercurrent (MUC), which was strong in December 2006 and weak in January 2008.

Considering the mass balance (Table 1), we estimated the bifurcation latitude of the NEC at 130°E, which is far from the Philippine coast. In both periods, we estimated the bifurcation latitude to lie approximately at 14°N, and it was difficult to find a clear difference within the mass transport imbalance of our observations. These results differ from those of some numerical studies (Qiu and Lukas, 1996; Kim *et al.*, 2004), which showed a northward shift in the bifurcation latitude of the NEC in El Niño periods. The reason for this difference may lie in

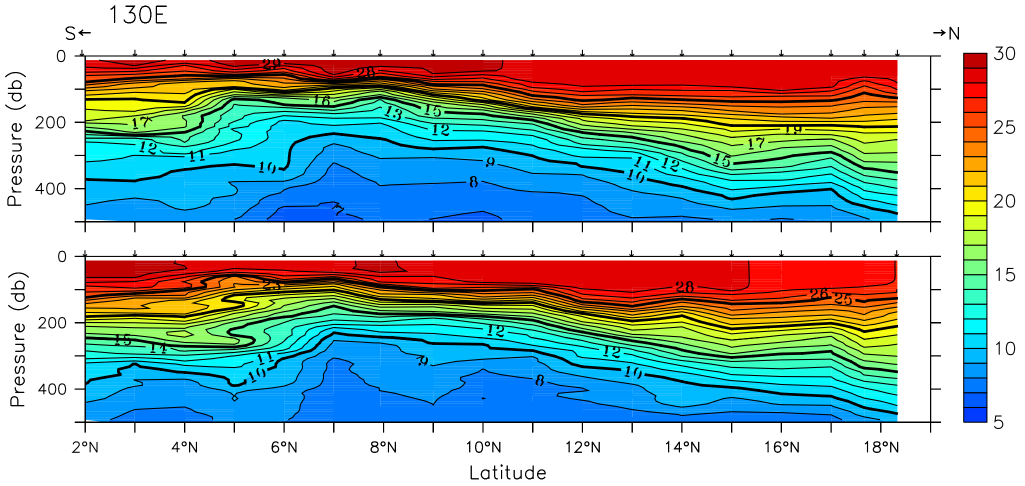

Fig. 5. Vertical sections of temperature along the 130°E line in December 2006 (upper panels) and January 2008 (lower panels).

the longitude where the bifurcation is estimated, and temporal eddies in this region; the numerical studies defined the bifurcation point as the point where the meridional component of velocity is zero near the Philippine coast. Eddies between 130°E and the Philippine coast, as observed by Firing *et al.* (2005), might account for this difference. For example, a cyclonic eddy was seen between 130°E and the Philippine coast in January 2008 in sea level anomaly provided by Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO, http://www.aviso.oceanobs.com/en/home/index.html) (not shown).

For comparison with Toole *et al.* (1990), the dynamic heights along the 18°20′ N, 130°E, and 8°N lines are shown in Fig. 4 (similar to figure 3 in Toole *et al.*, 1990). This plot indicates that the difference in the currents between the two observation periods was associated with dynamic height changes south of 10°N; the increase in dynamic height around 8°N, 130°E from December 2006 to January 2008 resulted in a weakening of the NEC and MC. This change differs from that observed by Toole *et al.* (1990), who found a large dynamic height difference on the northern part of the 130°E line, which contributed to the transport change of the NEC. However, Toole *et al.* (1990) did not conclude that this change was related to the ENSO evolution; it is possible that the difference shown by Toole *et al.* (1990) is associated with seasonal variability in this region or a cyclonic eddy located at the northernmost section of the 130°E line.

Temperature sections along 130°E during two cruises are shown in Fig. 5. A dome-like structure was found around 6–8°N. A similar structure was also observed around the same latitude at 137°E during the MR06-05 cruise (not shown). This structure therefore appears to be due to the Mindanao Dome rather than the Mindanao Eddy, which has a horizontal scale of an ocean eddy (e.g., Lukas *et al.*, 1991). It is interesting that its structure is not simple, but has multiple peaks above 150 m. The vertical temperature gradient in December 2006 was larger than that in January 2008, which suggests that ocean upwelling generating the Mindanao Dome was strong in December 2006.

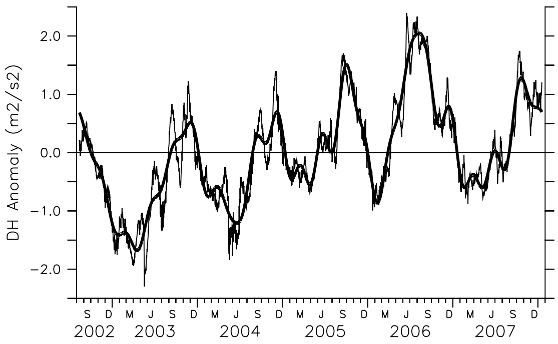

Fig. 6. Time series of dynamic height anomaly relative to 500 db measured by the TRITON buoy at 8°N, 130°E. Thin and thick lines denote daily time series and 90-day low-pass time series, respectively.

4. Discussion and Conclusions

The observations presented here are the first direct *in situ* current measurements contrasting the NMK system between two different phases of ENSO, namely the 2006/07 El Niño and the 2007/08 La Niña. Two of the US-PRC cruises (Toole *et al.*, 1990) were conducted in September 1987 with a Nino 3.4 index of 1.03 and in April 1988 with a Nino 3.4 index of –0.25; the difference in these Nino 3.4 indices was much smaller than that in our

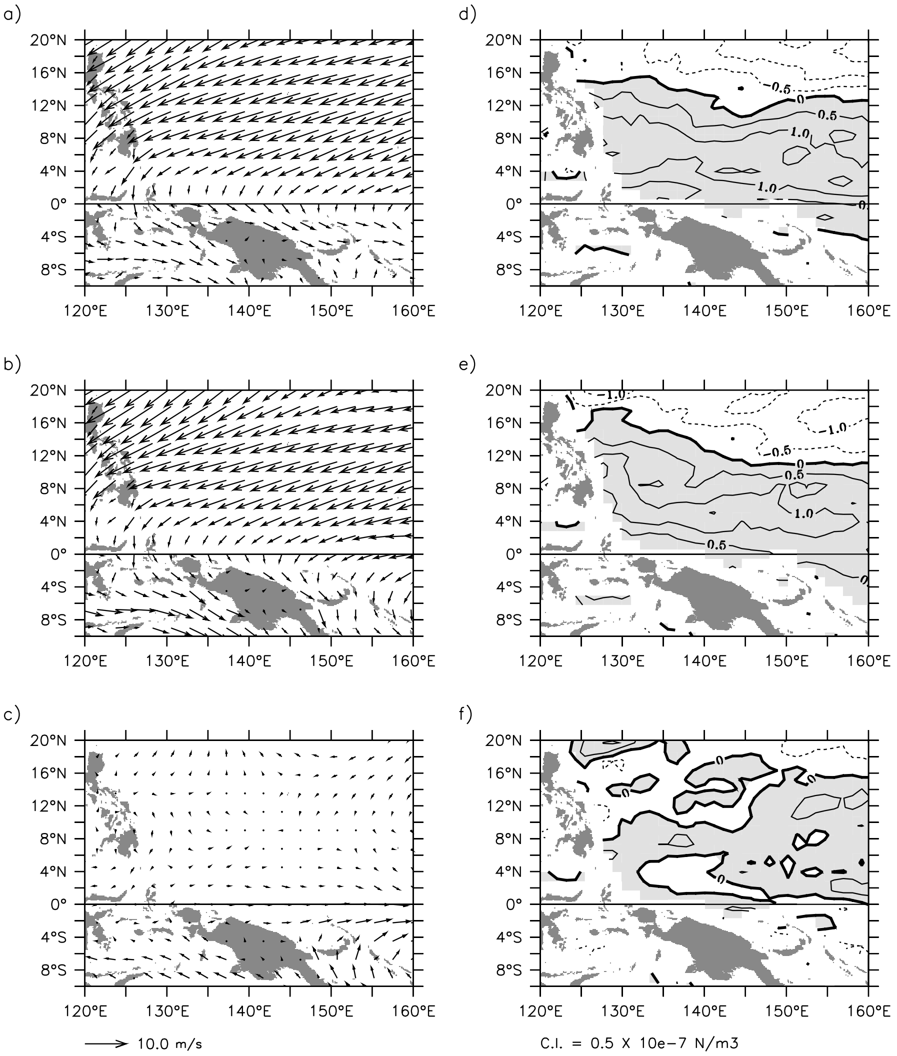

Fig. 7. Map of surface wind vector field averaged a) from December 2006 to February 2007 (2006/07 winter), and b) from December 2007 to February 2008 (2007/08 winter) provided by the ECMWF. c) Vector map of wind during the 2006/07 winter minus wind during the 2007/08 winter. Wind stress curl distribution in d) 2006/07 winter, e) 2007/08 winter, and f) 2006/07 winter minus 2007/08 winter. Drag coefficient value used was 1.5×10^{-3}. Contour interval of wind stress curl in d), e), and f) is 5×10^{-8} N m^{-3}.

study.

We found a clear difference in current strength and transport between the two periods. The MC, Kuroshio, and NECC were stronger during the 2006/07 El Niño than during the 2007/08 La Niña, whereas the current speed of the Kuroshio during the 2007/08 La Niña was strong, although the net northward transport across 18°20′ N was larger during the 2006/07 El Niño. Interestingly, the bifurcation latitude of the NEC did not change significantly between the two periods, in contrast to the variability indicated by numerical models. To resolve this discrepancy, further frequent observations are needed, especially near the Philippine coast.

Since 2002, the Triangle Trans-Ocean Buoy Network (TRITON) buoy (Kuroda and Amitani, 2001), in which 12 underwater conductivity and temperature sensors are installed, has been deployed at 8°N 130°E. To check the variability of the dynamic height seen in Fig. 4, the dynamic height anomaly relative to 500 db using data from these underwater sensors is plotted in Fig. 6. Dynamic height anomaly increased year-on-year after the 2002/03 El Niño until 2006, decreased drastically when the 2006/07 El Niño occurred, and recovered during the 2007/08 La Niña. Although clear intraseasonal variability with a timescale of 50–70 days is apparent in the daily time series in Fig. 6, the change of dynamic height anomaly from

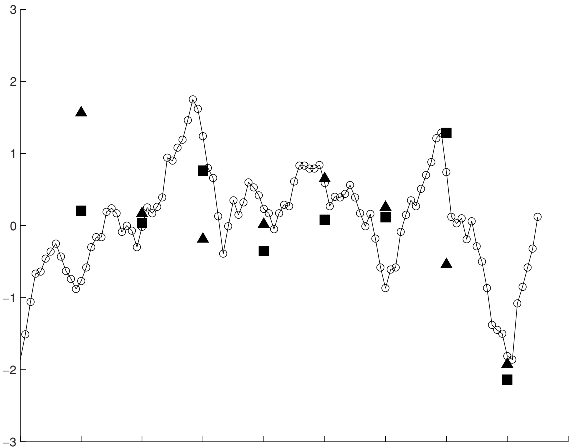

Fig. 8. Time series of Nino 3.4 index from 2000 onwards, indicated by solid line with open circles. Also plotted are the DJF average values of the MC transport (solid squares) and minus the KC transport (solid triangles) from the OFES run forced with QuikSCAT winds.

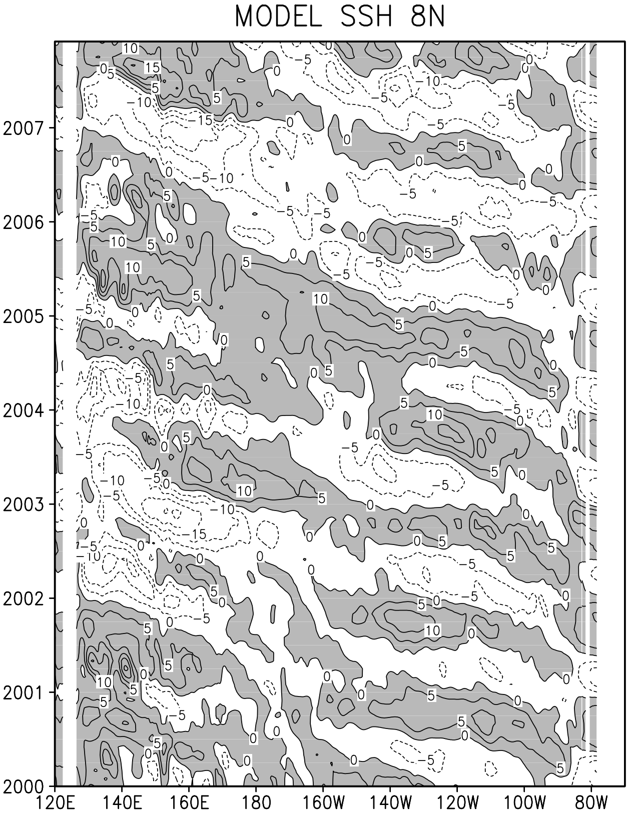

Fig. 9. Longitude-time plot of monthly sea surface height anomaly at 8°N derived from the OFES run. Contour interval is 5 cm. Positive anomaly is hatched.

the 2006/07 winter to the 2007/08 winter greatly exceeded the intraseasonal variability. This shows that the dynamic height change seen in Fig. 4 is associated with the oceanic and atmospheric changes that occurred from the 2006/07 El Niño to the 2007/08 La Niña condition.

Wind vector fields and wind stress curl averaged from December to February (DJF) in the 2006/07 and 2007/08 winters are shown in Fig. 7, along with the difference between these periods. Wind change between these periods was large south of the equator and east of 150°E, but not large in the area observed during the MR06-05 and MR07-07 cruises. Because the change in the wind stress curl was not large west of 140°E, the change in local wind in this region did not appear to induce the observed current change described in Section 3. Rather, changes in currents in this region between the two observation periods are likely associated with remote forcing. This result is consistent with the findings of Kim *et al.* (2004), who found that Rossby wave propagation from the central Pacific largely contributes to interannual variability in this region.

It should be noted that the relationship between ENSO and the NMK system found in published model results (e.g., Kim *et al.*, 2004) is for low-pass filtered timeseries (typically 12 months), while the observations reported here represent instantaneous states of the system. Therefore, we briefly report on results from the 1/10 degree resolution Ocean General Circulation Model for the Earth Simulator (OFES), which was forced with daily winds from QuikSCAT from January 2000 to December 2007 (Sasaki *et al.*, 2006). The (southward) MC and (northward) Kuroshio transports normalized by their standard deviations, which were obtained from the OFES current averaged over the DJF months, are compared to the Nino 3.4 index in Fig. 8. For reference, the mean (standard deviation) of the DJF values of the model KC and MC transports are 18 (6.8) Sv and 20 (8.8) Sv, respectively. (Note that because the model run ended at the end of 2007, the model DJF average for 2008 is simply the average over December 2007.) The correlation between the DJF MC transport and Nino 3.4 index is 0.79, which is 95% significant. The high value is primarily because of the large signal from 2006 to 2008, but the model MC transport is also large during the 2002/03 El Niño. The relationship between the model Kuroshio transport and Nino 3.4 index is less clear (the correlation coefficient is –0.26). However, the trend in the values of the DJF averaged transports of both the MC and Kuroshio between the end of 2006 and end of 2007 is in accordance with the change from El Niño to La Niña conditions reported in previous studies, i.e., a decrease in MC and an increase in Kuroshio transports shown by Kim *et al.*, (2004). Although it should be noted that both the model MC and Kuroshio transports exhibit intraseasonal variability, which during 2006 and 2007 was comparable to the lower frequency variations, the model results do highlight the need for continuous monitoring of the NMK system to establish seasonal to interannual variability.

It is also helpful to use the OFES results when discussing the mechanism of ocean variability in this region. We plot Fig. 9, which is a longitude-time diagram of monthly sea surface height anomaly at 8°N derived from the OFES in order to check observed dynamic height change from 2006 to 2008. Local negative anomalies appear west of 130°E every winter after 2002. These anomalies are probably associated with the Mindanao Dome (Masumoto and Yamagata, 1991; Tozuka *et al.*, 2002) because of positive wind stress curl in this region during winter (Fig. 7). Except for these local negative anomalies, negative anomalies are propagated westward from around the date line every year. Negative anomalies were particularly large in autumns of 2002 and 2006 years, which coincide with the ENSO years. However, no such negative anomaly was seen in autumn 2007. These results support our suggestion that dynamic height change from 2006 to 2008 was due to a remote effect originating near the date line.

In summary, the changes in the NMK system between the 2006/07 El Niño and the 2007/08 La Niña, particularly the weakening of the NEC and MC from December 2006 to January 2008, have been clearly shown. These changes were associated with the increase in dynamic height around 8°N, 130°E from December 2006 to January 2008. Remote effects caused by Rossby wave propagation from the east rather than local wind variability in this region appear to have contributed to this change. These results are not in conflict with the results of some numerical simulations.

However, our results were derived from two cruises only; we can therefore say little about the effect of higher frequency (intraseasonal) variability on the NMK system. For example, estimation of the bifurcation latitude of the NEC seems to be largely affected by the ocean eddies between 130°E and the Philippine coast. Although an evaluation of intraseasonal variability in the region is beyond the scope of this paper, we suggest that further hydrographic and time series observations should be conducted.

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