Wind-induced Upwelling in the Western Equatorial Pacific Ocean Observed by Multi-satellite Sensors

香西克俊

Advances in Space Research (submitted)

WIND-INDUCED UPWELLING IN THE WESTERN EQUATORIAL PACIFIC OCEAN OBSERVED BY MULTI-SATELLITE SENSORS

K. Kozai[1], K. Ishida[2], T. Shiozaki[3], and Y. Okada[4]

[1]*Kobe University of Mercantile Marine, 5-1-1, Fukaeminami, Higashinada, Kobe, 658-0022 JAPAN*
[2]*Toba National College of Maritime Technology, 1-1, Ikegami, Toba, Mie, 517-8501 JAPAN*
[3]*Osaka Prefecture University, 1-1, Gakuen, Sakai, Osaka, 599-8531 JAPAN*
[4]*Kinki University, Kowakae 3-4-1, Higashiosaka, 577-8502 JAPAN*

ABSTRACT

R/V MIRAI (MR01-K05 Leg3) of Japan Marine Science and Technology Center (JAMSTEC) was stationed at the point of 2 degrees North and 138 degrees East in the western equatorial Pacific Ocean from Nov.9 to Dec.9, 2001. During this air-sea interaction research cruise SeaWiFS and NOAA/AVHRR local area coverage (LAC) scenes were received by the station onboard R/V MIRAI and the products derived from these satellites are verified against oceanographic observations including the parameter of sea surface temperature, salinity, chlorophyll-a and current velocity profile to the depth of 300 meters. Level 3 wind vector products derived from QuickSCAT onboard SeaWinds are also collected and validated against in situ wind vectors. The sea surface temperature decreases from 30 to 29.3 degrees after the week-long prevailing northwest monsoon wind with the maximum gust more than 20 m/s, while the observed surface salinity and chlorophyll-a concentration increase from 34.1 to 34.37 and from 0.05 to 0.14 mg/m^3 respectively. The increase of chlorophyll-a and the decrease of sea surface temperature in this region are also shown in the multi-date SeaWiFS chlorophyll-a concentration products and Multi-Channel Sea Surface Temperature (MCSST) products from NOAA/AVHRR. Wind vector patterns corresponding to the gust more than 20m/s are also observed by QuickSCAT. During the period of the week-long northwest monsoon wind the current velocity of upper 70 meters reaches about 70cm/sec in the southeastward direction while the current velocity at the depth from 80 to 120 meters indicates 50cm/sec in the northwestward direction. The current of upper 70 meters corresponds to the Northwest Monsoon Current (NMC) and the intrusion of NMC enhanced by the strong northwest monsoon winds (westerly wind bursts) causes a reversal in the sub-surface current (New Guinea Coastal Undercurrent (NGCUC)) which creates a temporal upwelling in this region.

INTRODUCTION

Equatorial upwelling in the Pacific Ocean is known to occur east of the date line (Wyrtki, 1981). However based on the moored current measurements the estimates of equatorial upwelling in the western equatorial Pacific Ocean is reported (Halpern et al., 1989, Helber and Weisberg, 2001). Furthermore the presence of upwelling produced by the predominantly easterly winds in the western equatorial Pacific Ocean is indicated (Richards and Pollard, 1991). Although the importance of monsoonal wind forcing on the surface circulation has been discussed (Lindstrom et al.,1987), the wind-induced upwelling in the western equatorial Pacific Ocean is little observed and described because of its intermittent characteristics in temporal and spatial scales. The purpose of this study is to not only describe the upwelling event observed by SeaWiFS, NOAA/AVHRR, QuickSCAT and in situ samplings during the research cruise of R/V MIRAI (MR01-K05 Leg3) but also investigate the conditions of upwelling in temporal and spatial scales for contributing to better understanding of air-sea interaction in the western equatorial Pacific Ocean.

DATA AND METHOD

Figure 1 shows the study area with the stationary observation at 2 degrees North, 138 degrees East from Nov.9 to Dec.9, 2001. During this period the ship was moving around the stationary point except the CTD (Conductivity-Temperature-Depth) profiler observations four times a day. Details of the cruise log and summary of observations are listed in the R/V MIRAI Cruise Report (MR01-K05 Leg-3/4) (JAMSTEC, 2001). Methods of in situ atmospheric and oceanographic observation including the parameter of sea surface temperature, salinity, chlorophyll-a concentration and current velocity profile are summarized as follows. The surface meteorological parameters such as wind speeds and directions are observed during the cruise by the R/V MIRAI meteorological observation system. An anemometer is located at the foremast 24 meters above sea surface and the 10-minute averaged true wind speeds and directions are recorded. Near-surface water at the depth of 4.5 meters is continuously pumped up at the rate of 200 liter per minute from the intake to the sea surface monitoring laboratory for measuring temperature and salinity. Surface seawater samples are taken four times a day and the concentration of chlorophyll-a is determined onboard. CTD (Conductivity-Temperature-Depth) profiler observations are carried out four times a day to the depth of 500 meters. The specifications of CTD profiler are listed in Table 1. Current velocity profiles are measured by the shipboard Acoustic Doppler Current Profiler (ADCP) from Nov.9 to Dec.9, 2001. The zonal (east-west) and meridional (north-south) velocity components of each depth cell are observed every 5 minutes. Major parameters for the measurement configuration of ADCP are listed in Table 2.

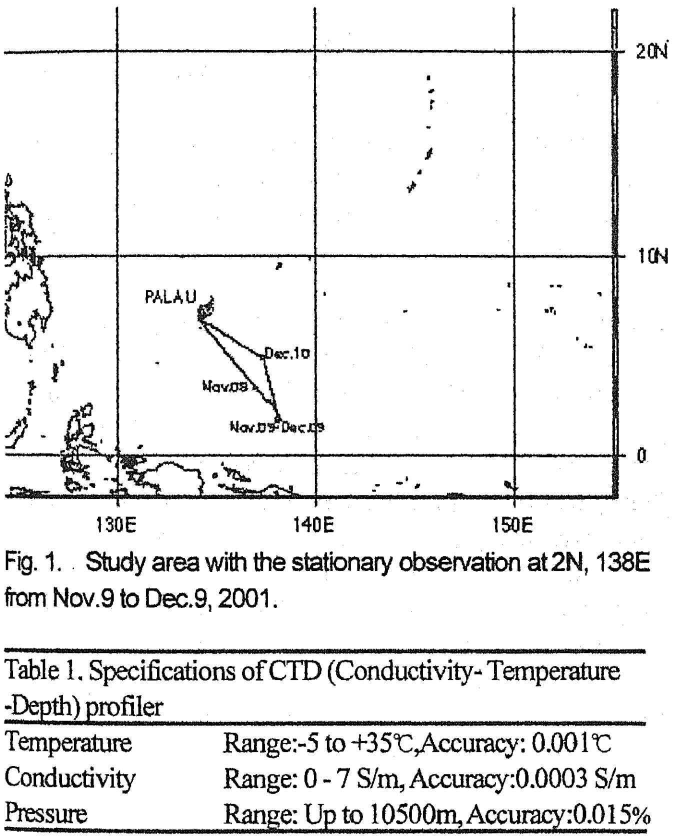

Fig. 1. Study area with the stationary observation at 2N, 138E from Nov.9 to Dec.9, 2001.

Table 1. Specifications of CTD (Conductivity- Temperature -Depth) profiler

Temperature	Range:-5 to +35℃, Accuracy: 0.001℃
Conductivity	Range: 0 - 7 S/m, Accuracy:0.0003 S/m
Pressure	Range: Up to 10500m, Accuracy:0.015%

Table 2. Measurement configurations of shipboard ADCP

Frequency	75kH
Average	every 300 sec
Depth cell length	1600cm
Number of depth cells	40
First depth cell position	30.9m
Last depth cell position	654.9m
Ping per ADCP raw data	32

Table 3. Specifications of SeaWiFS

Band (center wavelength(nm))	412, 443, 490, 510, 555, 670, 765,865
Equator Crossing	Local Noon(±20min), descending
Orbit type	Sun Synchronous at 705km
Spatial resolution	1.13km(LAC), 4.5km(GAC)
Swath width	2801km(LAC), 1502km(GAC)
Scan Plane Tilt	+20° ,0° ,-20°

SeaWiFS is an abbreviation of Sea-viewing Wide Field-of-view Sensor onboard the SeaStar launched in 1998. The sensor has eight bands in the visible and near infrared wavelengths and the tilt mechanism to avoid sun glitter as shown in Table 3. During the research cruise from Nov.14 to Dec.10 SeaWiFS LAC (Local Area Coverage) scenes are received by the station onboard R/V MIRAI once a day under the authorization of NASA SeaWiFS project as the temporary real-time agreement. All SeaWiFS raw data are decrypted by using the OGP software provided by NASA GSFC. Higher level products such as chlorophyll-a concentration are generated by using SeaDAS 4.3 software.

RESULTS AND DISCUSSIONS

Throughout the period of research cruise there are two typical weather conditions. One is characterized by the strong northwest monsoon winds (or westerly wind bursts) during the periods from Nov.18 to 24 and from Dec.1 to 9. The westerly wind burst is one of the characteristic wind variability in the tropics with a period of 40-50 days (Madden-Julian Oscillation, (Madden and Julian, 1971, 1972)). The other is characterized by the strong insolation with weak monsoon winds during the periods from Nov.12 to 17 and from Nov.25 to 30. Since the SeaWiFS LAC scenes acquired during the former periods show the high cloud coverage, the SeaWiFS LAC scenes available for the analysis are limited to those acquired during the latter periods. From now on the observation period is divided into three periods, namely the period of (Nov.18-24), before (Nov.12 to 17) and after the strong northwest monsoon winds (or westerly wind bursts) (Nov.25-30).

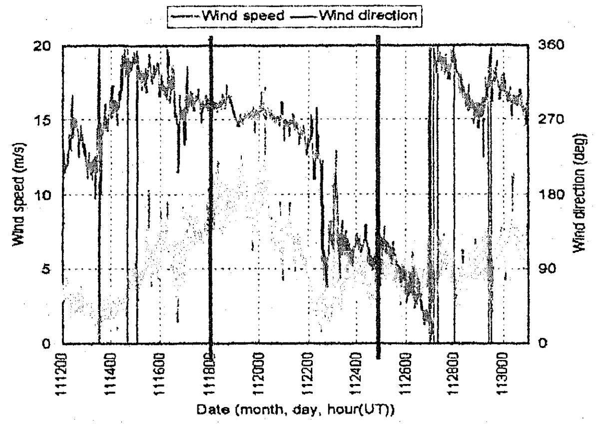

Fig.2. Temporal variability of wind speeds and directions before (Nov.12 to 17), during (Nov.18 to 24) and after(Nov.25 to 30) the westerly wind burst in Nov. 20.

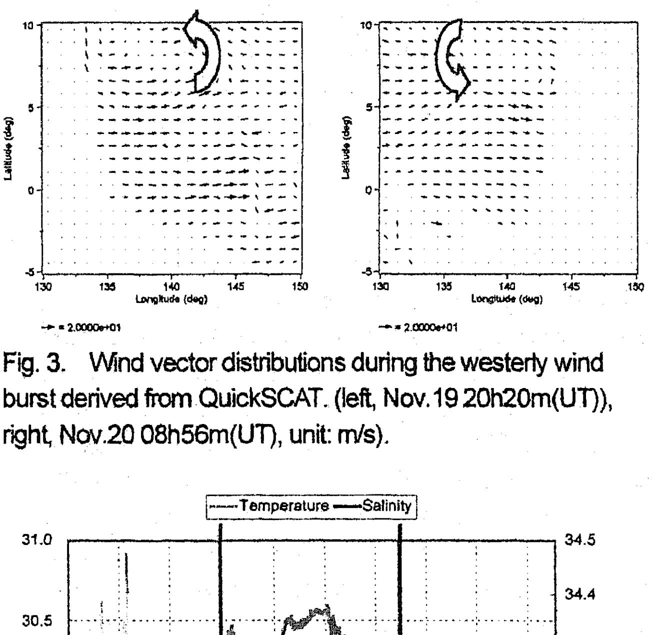

Fig. 3. Wind vector distributions during the westerly wind burst derived from QuickSCAT. (left, Nov.19 20h20m(UT)), right, Nov.20 08h56m(UT), unit: m/s).

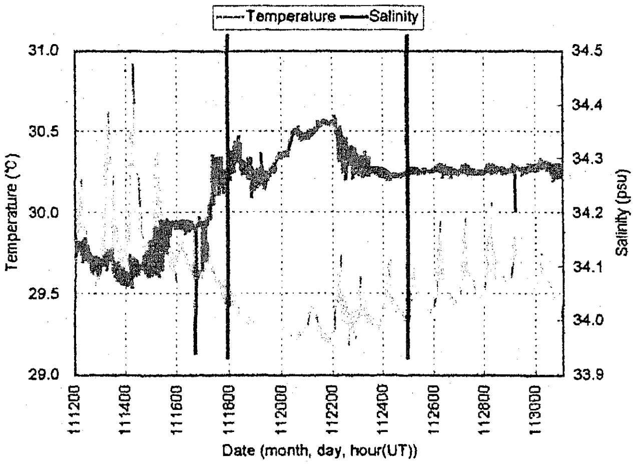

Fig. 4. Temporal variability of temperature and salinity before (Nov.12 to 17), during (Nov.18 to 24) and after (Nov.25 to 30) the westerly wind burst in Nov.20.

Variability of wind vector

Figure 2 shows the temporal variability of wind speeds and directions before (Nov.12 to 17), during (Nov.18 to 24) and after (Nov.25 to 30) the westerly wind burst. During the period from Nov.18 to 24 this period is characterized by the westerly wind burst reaching more than 20 m/sec of instantaneous wind speed at Nov. 20. After the westerly wind burst the wind directions are mostly east until Nov.27 and changing to the west afterwards. In order to describe spatial distribution of wind vector in the study area wind vectors derived from QuickSCAT are used for the analysis. Figure 3 illustrates the wind vector distribution at two different dates during the westerly wind burst. North of the stationary point of 2 degrees North and 138 degrees East the low pressure system (counter-clockwise circulation indicated as the solid arrows in Figure 3) can be seen between 5 and 10 degrees North and the center of low pressure system seems to be moving toward east. It is the low pressure system that causes the instantaneous wind speeds more than 20 m/sec at the stationary point.

Variability of temperature, salinity and velocity profile

Figure 4 shows the temporal variability of sea surface temperature and salinity before (Nov.12 to 17), during (Nov.18 to 24) and after (Nov.25 to 30) the westerly wind burst in Nov.20. A sharp decrease of salinity in Nov.16 and 29 may be attributable to showers observed by the shipboard rain gauge. During the period of the westerly wind burst sea surface temperatures decrease from 29.5 to 29.3℃ while salinity increases from 34.24 to 34.37 at Nov.22. Decrease of sea surface temperature around the stationary point is also supported by the MCSST (Multi-Channel Sea Surface Temperature) products illustrated in Figure 5. Before the westerly wind burst the sea surface temperature around the stationary point is about 30 ℃ while the sea surface temperature after the burst is about 29.5℃.

As far as the temporal variability of temperature overlaid with ADCP data are concerned, three distinctive layered current structures are illustrated in Figure 6. The first one from the surface to the depth of 50 m corresponds to the Northwest Monsoon Current (NMC) (Masuzawa, 1968) which can be characterized by the weak flow (less than 30 cm/sec) toward southeast directions and the temperature range from 29.2 to 29.8 degree Celsius. The second one from the depth of 80 m to 120 m corresponds to the New Guinea Coastal Undercurrent (NGCUC) (Lindstrom et al., 1987). Although the NGCUC is originally defined as the subsurface

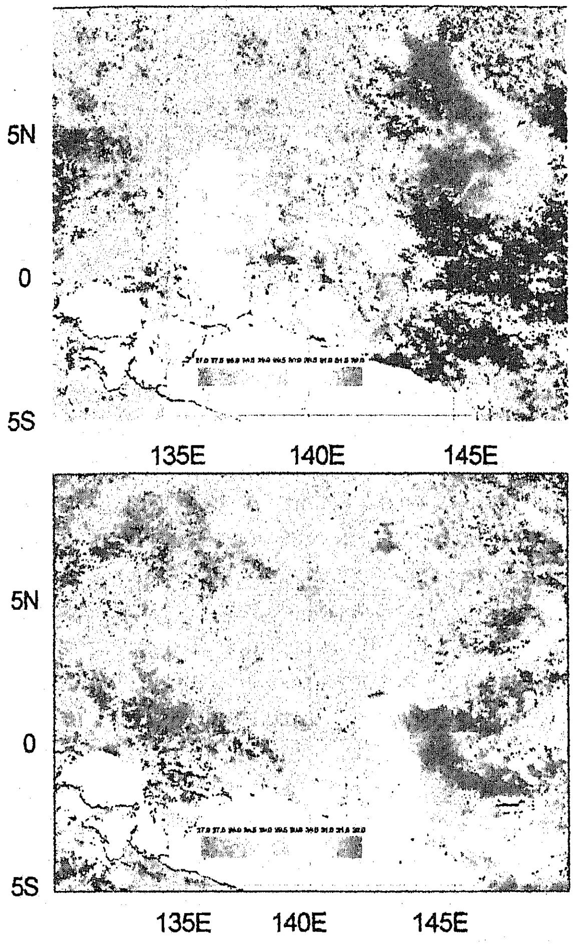

Fig. 5. Daytime MCSST composites derived from NOAA/AVHRR before (left, Nov.12-17) and after (right, Nov.25-30) the strong westerly monsoon wind (westerly wind burst).

equatorward velocity maximum centered at the depth of 200m adjacent to the coast at 2° S, it is indicated that the Northwest Monsoon Current overlies the northwestward flow of the NGCUC (Fine et al., 1994). The temperature is ranging from 25 to 29 degrees Celsius. The third one from the depth of 200m to 250m corresponds to the Equatorial Undercurrent (EUC) which can be characterized by the strong southeastward flow reaching about 70cm/sec and the temperature range from 13 to 20 degrees Celsius.

The temporal distributions of temperature overlaid with ADCP data also illustrate the characteristic responses to the westerly wind burst. Figure 6 indicate that the Northwest Monsoon Current (NMC) reaches 70cm/sec at the surface and extends to the depth of 70 m from Nov.20 to 21. The temperature contour of 29.2 degrees Celsius is sharply uprising. The accelerated NMC caused by the westerly wind burst is called the Pacific Equatorial Monsoon Jet (PEMJ) (Lindstrom et al., 1987) which is the strong equatorial eastward jet with the recorded velocity more than 110 cm/sec (Delcroix et al., 1992). At the same time the northwestward flowing New Guinea Coastal Undercurrent (NGCUC) at the depth from 80m to 120m is seem to be decelerated and partly deviated clockwise because of the enhanced NMC or the PEMJ from Nov.20 to 21. After the westerly wind burst the Northwest Monsoon Current (NMC) at the surface becomes very weak. On the other hand the New Guinea Coastal Undercurrent (NGCUC) at the depth from 80m to 120 m shows the stable westward flow of about 50cm/sec and the Equatorial Undercurrent (EUC) at the depth from 200m to 250m is strengthened especially after Nov.28. Since the northwest monsoon wind

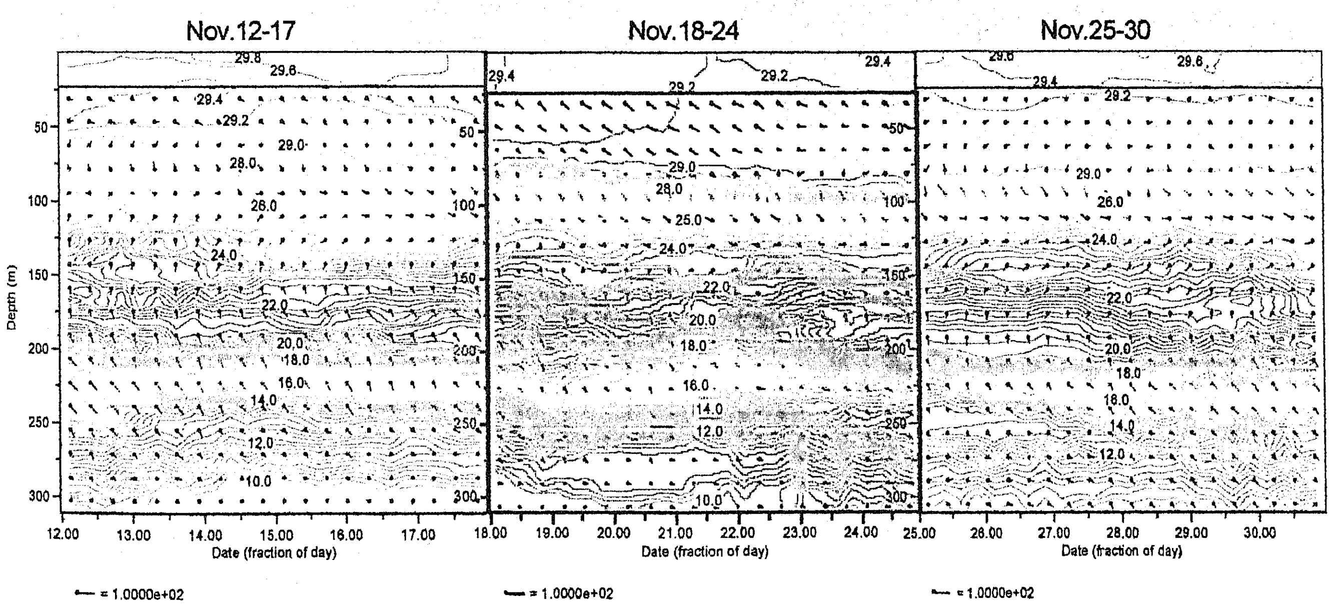

Fig. 6. Temporal variability of temperature profile overlaid with velocity vectors from Nov.12 to 30. (Units of temperature and velocity are degree Celsius and cm/sec respectively.)

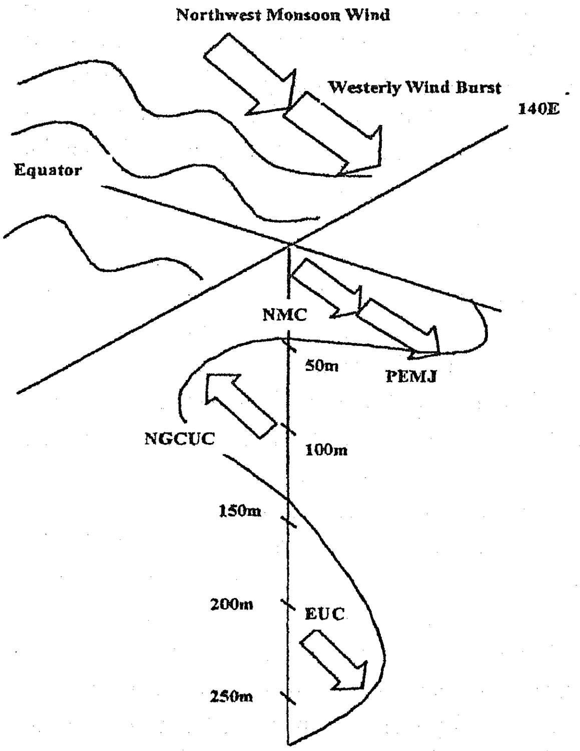

Fig. 7. Layered current structure with the Pacific Equatorial Monsoon Jet (PEMJ) triggered by the westerly wind burst.

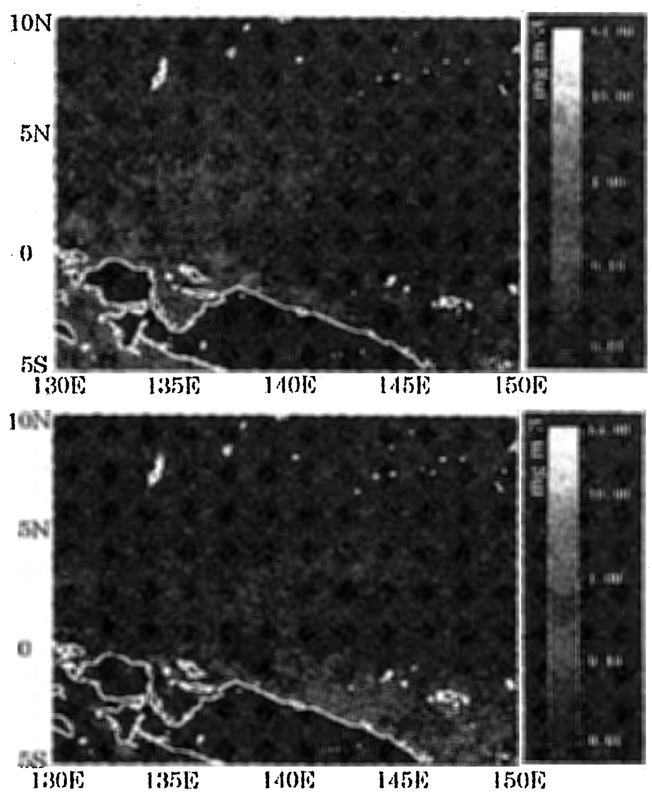

Fig. 8. Chlorophyll-a composites derived from SeaWiFS before (upper, Nov.12-17) and after (lower, Nov.25-30) the westerly wind burst.

and the corresponding NMC are weak, the cause of the strengthened EUC is unknown. However, after comparing with the velocity vectors of the NGCUC during the previous period it is found out that the total transport of the NGCUC is getting increased toward the latter half of this period and the part of NGCUC may contribute to the enhancement of the EUC. Three distinctive layered current structures with the Pacific Equatorial Monsoon Jet caused by westerly wind bursts are illustrated in Figure 7.

Variability of chlorophyll-a

Figure 8 shows the SeaWiFS-derived chlorophyll-a concentration composites before and after the westerly wind burst. Around the stationary observation point (2N, 138E) the concentration is below 0.1 mg/m^3 from Nov.12 to 17. On the other hand high concentration areas are found in the northwest of the stationary point (3N, 135E) and the northern coast of New Guinea Island. After the westerly wind burst (Nov.25 to 30) the chlorophyll–a concentration around the stationary observation point indicates the values around 0.1 mg/m^3 which are agreed well with the in situ concentration values shown in Figure 9. The high concentration area extends to 4 degrees north and the northern coast of New Guinea Island. However, the low concentration areas are found east of 140 degrees meridian, which may indicate the temporal and spatial extent of the upwelling in this region.

SUMMARY

The results of the study above are summarized as follows.

(1) During the R/V MIRAI research cruise wind-induced upwelling is expressed as the response of the western equatorial Pacific Ocean to the strong northwest monsoon winds (westerly wind bursts) revealed by in situ and QuickSCAT wind vector distribution.

(2) The characteristics response of the upper oceanographic structure to the westerly wind bursts is the Pacific Equatorial Monsoon Jet (PEMJ) reaching 70cm/sec at the surface and extends to the depth of 70 meters from Nov.20-21.

(3) The current of upper 70 meters corresponds to the Northwest Monsoon Current (NMC) and the intrusion of NMC enhanced by the westerly wind bursts causes a reversal in the sub-surface current (New Guinea Coastal Undercurrent (NGCUC)) which creates a temporal upwelling in this region.

(4) The temporal upwelling event is revealed by the sharp increase of in situ chlorophyll-a concentration, salinity and the decrease of sea surface temperature. Increase of chlorophyll-a and the decrease of sea surface temperature are also supported by the multi-date SeaWiFS and MCSST composites respectively.

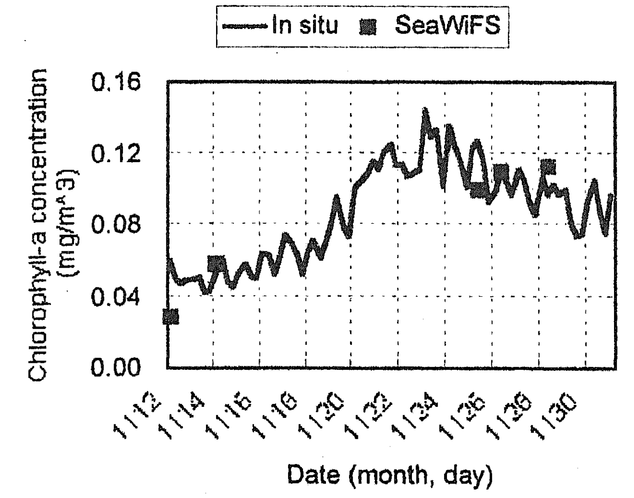

Fig. 9. Comparison of chlorophyll-a concentration between in situ and SeaWiFS product. (SeaWiFS values are indicated as average of 20x20 km.)

ACKNOWLEDGEMENTS

The authors would like to acknowledge Captain Akamine and the crews of R/V MIRAI during the research cruise MR01-K05 Leg3. The authors wish to acknowledge Dr. Asanuma of NASDA/EORC for SeaWiFS data acquisition, Mr.Hanyu and his colleagues of Global Ocean Development Inc. for assisting various shipboard observations including SeaWiFS and ADCP data. The authors also wish to acknowledge Mr.Komai and his colleagues of Marine Works Japan Ltd. for their skillful in situ sampling and analysis of chlorophyll-a. All SeaWiFS LAC scenes are received by the station onboard R/V MIRAI under the authorization of NASA SeaWiFS project as the temporary real-time agreement. All SeaWiFS raw data are decrypted by using the OGP software provided by NASA GSFC. Higher level products such as chlorophyll-a concentration are generated by using the SeaDAS 4.3 software. QuickSCAT level 3 daily, gridded ocean wind vectors are provided by JPL Physical Oceanography Distributed Active Archive Center (PO.DAAC).

REFERENCES

Delcroix, T., G.Eldin, M.Radenac, J.Toole and E.Firing, Variation of the Western Equatorial Pacific Ocean 1986-1988, *J. Geophys. Res.*, **97**, C4, 5423-5445, 1992.

Fine, R.A., R. Lukas, F. M. Bingham, M.J. Warner and R.H. Gammon, The western equatorial Pacific: A water mass crossroads, *J. Geophys. Res.*, **99**, C12, 25063-25080, 1994.

Halpern, D., R.A. Knox, D.S. Luther, S.G.H. Philander, Estimates of Equatorial Upwelling Between 140° and 110° W During 1984, *J. Geophys. Res.*, **94**, C6, 8018-8020, 1989.

Helber, R.W. and R.H. Weisberg, Equatorial upwelling in the western Pacific warm pool, *J.Geophys.Res.*, **106**,C5, 8989-9003, 2001.

JAMSTEC, R/V MIRAI Cruise Report (MR01-K05 Leg-3/4), various paging, 2001.

Lindstrom, E., R. Lukas, R. Fine, E. Firing, S. Godfrey, G. Meyers and M.Tsuchiya, The Western Equatorial Pacific Ocean Circulation Study, *Nature*, **330**, 533-537, 1987.

Madden, R.A. and P.R. Julian, Detection of a 40-50 Day Oscillation in the Zonal Wind in the Tropical Pacific, *J. Atmos. Sci.*, **28**, 702-708, 1971.

Madden, R.A. and P.R. Julian, Description of Global-Scale Circulation Cells in the Tropics with a 40-50 Day Period, *J. Atmos. Sci.*, **29**, 1109-1123, 1972.

Masuzawa, J., Second cruise for CSK, Ryofu Maru, January to March 1968, *Oceanogr. Mag.*, **20**, 173-185, 1968.

Richards, K.J. and R.T. Pollard, Structure of the upper ocean in the western equatorial Pacific, *Nature*, **350**, 48-50, 1991.

Wyrtki, K., An Estimate of Equatorial Upwelling in the Pacific, *J. Phys. Oceanogr.*, **11**, 1205-1214, 1981.

E-mail address of K. Kozai kouzai@cc.kshosen.ac.jp