THE INTRASEASONAL VARIABILITY OF SURFACE WIND AND UPPER LAYER THERMAL STRUCTURE IN THE WESTERN TROPICAL PACIFIC WARM POOL REGION DURING THE WINTER OF 1992～1993

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ABSTRACT

In this paper, the hydrographical and meteorological data observed by the R/Vs "Xiang Yang Hong No. 5", "Experiment No. 3" and "Ke Xue No. 1" during TOGA-COARE IOP are used to analyze the variability of surface wind and upper layer thermal structure, and to reveal the periods of intraseasonal oscillation of surface wind components and certain layers of sea temperature from November 6, 1992 to February 18, 1993 in the western tropical Pacific warm pool region. It is shown that the variation of the sea surface temperature (SST) was inversely correlated to that of surface wind components. It is also indicated from spectral analysis that the significant periods of intraseasonal oscillation of daily mean zonal wind (MZW) were 30- to 60- day and 8- to 9- day long, and that of mean meridional wind (MMW) was 6- to 7- day long. The fluctuation of daily mean sea temperature (MST) in certain layers from surface to the 250 m layer also had the 30- to 60- day low frequency oscillation except for the 150 m layer, and the fluctuations of the daily MST in 100, 150, 200 and 250 m layers had the same 3-day period, their coherence and phase differences were over 0.90 and between 319° and 353° respectively, which implies the fluctuations of daily MST from 100 to 250 m layers were in phase with each other in the same 3-day period. The analysis of *in situ* observations revealed a physical evidence of the westerly wind bursts (WWBs) which trigger off the eastward movement of warm water through intraseasonal oscillation and induce the onset of El Niño event.

Key words: TOGA-COARE IOP, intraseasonal oscillation, westerly wind bursts, spectral analysis

I. INTRODUCTION

The western tropical Pacific is a key region for global climate variability on intraseasonal and interannual time scales, and it is also the region of strong coupling between the ocean and the atmosphere. The variabilities on intraseasonal time scale in the atmosphere and the ocean are evident over the warm pool of the western tropical Pacific (Kawamura, 1989).

The study of the 30- to 60-day atmospheric oscillation has received much attention since the 1970's. The results show that the variability of atmospheric osillation is related to the variation of zonal atmospheric circulation, deep cumulus convective activity and the development and eastward shift of large scale ascent convergent air current. It also affects the climate anomaly of air circulation on spatial scales ranging from mid- and high latitudes to global area and the condition of droughts and floods in Asia. This intraseasonal oscillation of the atmosphere could induce the variability of air-sea interaction over the warm pool region of western tropical Pacific. The comprehensive oceanographic and atmospheric observations were made by three research vessels of R/Vs "Xiang Yang Hong No. 5", "Experiment No. 3" and "Ke Xue No. 1" at the intensive flux array (IFA) during the intensive observation period (IOP) of TOGA-COARE. By using the instruments of Neil Brown Mark III conductivity-temperature-depth (CTD) profiler, Sea Bird SeaLogger CTD profiler and Omega sounding, a long time series of high quality *in situ* hydrographic and meteorological observations were obtained to further understand the effect of 30- to 60-day atmospheric oscillation on upper ocean thermal structure and the eastward movement of warm water in the warm pool region of the western tropical Pacific (TOGA Operation Plan, 1992). Fortunately, during IOP, the western Pacific warm pool region was in the time of the WWBs prior to the 1992-1993 El Niño event (TOGA-COARE Scientific Report, in press). The objective of this paper is to discuss the variabilities of the SST and upper ocean thermal structure and their intraseasonal oscillation during strong westerlies episodes. The wind spectral analysis further proved that the WWB and its 30- to 60-day intraseasonal oscillation is closely related to the onset of El Niño events.

Ⅱ. DATA AND PROCESSING

Meteorological data: The surface wind speed, wind direction and SST derived the stations at 2°S, 155°E and 2°S, 158°E are mainly utilized in this paper. Because the tendencies of surface wind variations obtained in two stations were coincident, the data from synoptic charts and the station at 2°S, 158°E could be used to supply the time series lacking at the (2°S, 155°S) station so as to compose a 105-day long successive wind time series, and the lack of SST data at 2°S, 155°E station is estimated by averaging SST difference between the two stations.

Hydrographic CTD data: hydrographic observational data at the 2°S, 155°E station were obtained with a Neil Brown Marine Systems Mark III profiler once every 6 hours, a total of 4 times per day. Observational time series include three legs: leg 1 was from November 6 to 29, 1992, leg 2 from December 16, 1992 to January 8, 1993 and leg 3 from January 24 to February 18, 1993; hydrographic data were collected at 2°S, 158°E station using a wire-lowered Sea Bird Electronics SeaLogger CTD profiler, once every 3 hours, a total of 8 times per day, surveying time series contains three legs: leg 1 was from November 10 to December 11, 1992, leg 2 from December 19, 1992 to January 22, 1993 and leg 3 from January 31 to February 18, 1993; hydrographic data at station 4°S, 156°E were collected in the same may as those at station 2°S, 158°E, i. e. , using the same instrument, the same observational times per day and the same time series in legs 1 and 2 but leg 3 was from February 1 to 19, 1993. During calculations of the period of daily MST fluctuations in certain layers of the upper ocean, the daily MST in certain layers of 2°S, 155°E station are estimated at first, the missing time series will then be supplied by estimating the daily MST in certain layers of 2°S, 158°E station and applying linear interpolation to compose the 105- day long successive time series.

Ⅲ. TIME SERIES OF DAILY MEAN SST AND SURFACE WIND

Fig. 1 shows the time series of daily MZW (u m / s) and MMW (v m / s) and SST (°C) (MSST). Dashed lines represent daily MZW, MMW and MSST at 2°S, 155°E station and solid lines represent those at station 2°S, 158°E. According to the data processing above, spectral analyses are made using the 105- day time series of daily MZW, MMW and MSST (as shown in Fig. 2) from November 6, 1992 to February 18, 1993.

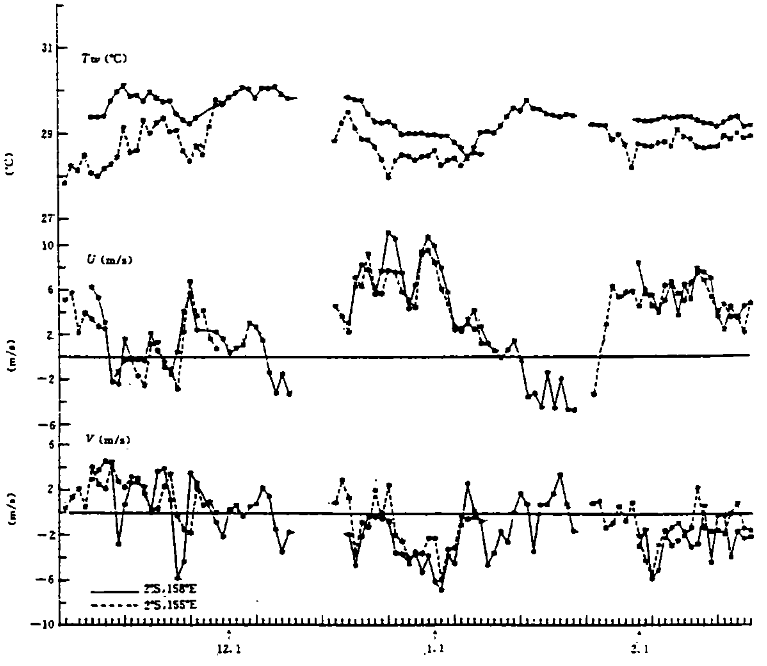

Fig. 1. Time series of daily mean zonal, meridional surface winds, SST at stations 2°S, 155°E and 2°S, 158°E.

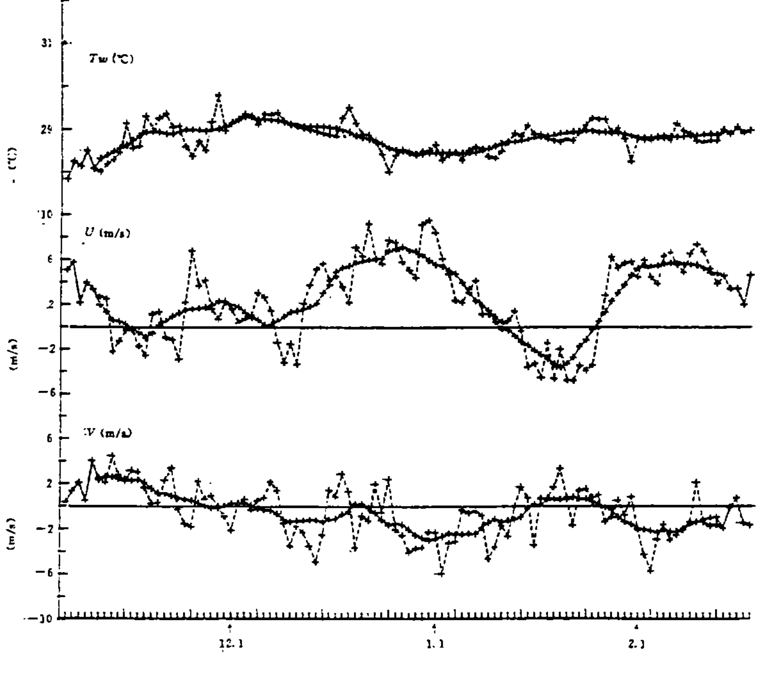

Fig. 2. Time series of daily mean zonal and meridional winds, SST and their 11-day running means.

1. *Variations of daily mean surface wind and SST*

Daily MZW with typical speeds equal to and more than 5 m/s and a persistent time period of more than 5 days will be referred to as a WWB episode in this paper (TOGA-COARE Scientfic Report, in press, Mcphaden, 1992). It is shown from variation of daily MZW in Fig. 2 that during the whole observational period, there were two WWBs episodes besides the anomalous 1～5 m/s easterlies persisting for 13 days January 14 to 26, 1993, i. e. , the strong westerlies persisted for about 14 days from December 20, 1992 to January 2, 1993 (the speed of daily MZW was from 5 to 9 m/s) and that persisted for about 16 days from January 28 to February 12, 1993 (the speed of daily MZW was from 5 to 7 m/s). Comparing the time series for daily MZW and the percentage of high cloudiness (PHC) (Figure ignored), the strong westerly were likewise positively related to PHC, which proves that strong westerly episodes are closely associated with deep atmospheric convective activity (Zhang, 1993).

It can be seen from the variation of daily MMW that during the whole surveying period, there were two northerly episodes with daily means more than 2 m/s and durtions of 18 days and 8 days besides the southerlies persisting from November 6 to 22, 1992, i. e. northerlies persisted in about 18 days with the speed of 2～6 m/s from December 26, 1992 to January 12, 1993 (during which wind speed was less than 1 m/s from January 5 to 8) and that persisted in about 8 days with the speed of 2～6 m/s from February 1 to 8, 1993. It is also shown from the measured surface zonal and meridional winds that the two westerly episodes were just coincident with the two northerly episodes, which means two corresponding WWBs were associated with air current crossing the equator from the northern hemisphere, and from the analyses of daily synoptic charts and *in situ* aerological sounding, it can be concluded that the main reason for the triggering of equatorial WWBs is due to the convergence of the air current crossing the equator with westerly air current north (or northwest) of the South Pacific Convergence Zone (SPCZ) (Figure ignored). The time interval of the initial WWBs between the two episodes was 47 days, which was consistent with 30- to 60-day intraseasonal oscillation of the tropical atmosphere (Lau, 1989).

The variation of SST is directly related to immigration of warm water produced by advection which is induced by the strong westerlies with a speed of 5～10 m/s (Delcroix et al. , 1993). It is shown from Fig. 2 that the SST appeared to respond well to zonal and meridional winds, that is, the SST decreased with the strengthening of westerlies and northerlies, and increased when westerlies and northerlies weakened. Fig. 1 shows that daily MSST at 2°S, 155°E station obviously decreased after the strong westerlies persisted for 14 days with a speed of 5～9 m/s during the first WWB, the minimum of daily MSST appeared five days after WWB on December 25, 1992 (28°C); and daily MSST remained lower 2 or 3 days after westerlies weakened below 5 m/s, the average daily MSST from January 2 to 5, 1993 was 28. 3°C; the minimum of daily MSST at 2°S, 158°E occurred on January 6, 1993 (28. 4°C), and the average of daily MSST was 28. 6°C from 4 to 7 January 1993. During the second WWB, the minimum of daily MSST at 2°S, 155°E station appeared two days after WWB (28. 2°C) on January 31. Strong westerlies lasted about 16 days (January 28～February 12, 1993), and daily MSST maintained relatively low in late stage of this episode, the average of daily MSST from February 10 to 13 was 28. 6°C, and that from February 11 to 14 was 29. 2°C at station 2°S, 158°E, which implies the response of the SST to zonal wind at 2°S, 158°E station lagged behind that at station 2°S, 155°E.

2. *Periodic analysis of surface wind*

In order to discuss the characteristics of the surface wind intraseasonal climate oscillation over the warm pool of the western tropical Pacific during the winter of 1992~1993, the time series of 11- day running means for daily MZW and MMW are conducted. Solid curves in Fig. 2 represent 11- day running means of daily MZW and MMW time series. It can be clearly seen from Fig. 2 that daily MZW had a long-term low-frequency oscillation. The fine spectrum of daily MZW is estimated with the processing of Hanning smooth coeffcient during the power spectral analysis of daily MZW. Fig. 3-1a shows the fine spectrum of daily MZW with a long-term period indicating that daily MZW had a significant period 30- to 60- day, and had a 8- to 9- day significant oscillation as well after subtraction of the long-term tendency from time series of daily MZW.

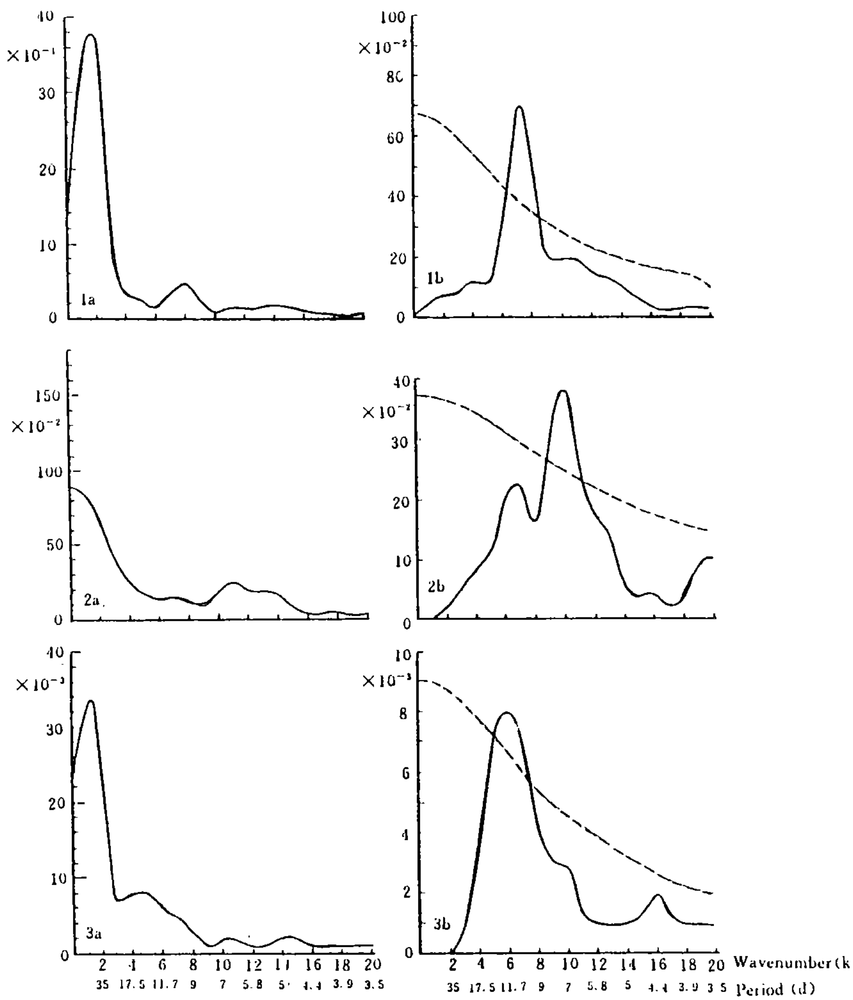

Fig. 3. Power spectra of daily mean zonal and meridional winds and SST, 1a, b, 2a, b and 3a, b represent daily MZW, MMW and MSST respectively; a denotes the spectrum with long-term period, b denotes the spectrum after subtraction of long-term tendency.

The dashed curve denotes confidence level $\alpha=0.05$, which stands for the upper limit of "red noise" spectral density, the significant 8- to 9- day periods have passed the significant test by confidence level $\alpha=0.05$. Fig. 3-2a shows the fine spectrum of daily MMW and that daily MMW had about a 6- and a 10-day periods and the significant 6- to 7- day periods if the tendency of 11-day running mean was subtracted (Fig. 3-2b).

3. *Periodic analysis of daily mean SST*

It is shown from spectral analysis of daily MSST that daily MSST had 30- to 60-day low-frequency oscillation (Fig. 3-3a), and also had the significant 11-day periods (Fig. 3-3b). The significant period of daily MSST was 54-day that was estimated by maximum entropy method (MEM) (Figure ignored). A Parzen band-pass filter is used to make a cross spectrum analysis of the response of daily MSST to MZW with the result that both the daily MZW and MSST had 30- to 60-day low-frequency oscillations, and the phase difference between the two was 188°, and had a coherence greater than 0.5, which further confirmed a remarkable inverse correlation between the daily MZW and MSST as discussed by McPhaden (McPhaden, 1991).

IV. TIME-DEPENDENT VARIATION OF THE UPPER OCEAN IN THE WARM POOL REGION OF THE WESTERN TROPICAL PACIFIC

There are *in situ* observational data in two WWBs episodes obtained during TOGA-COARE IOP in the warm pool region of the western tropical Pacific, which provided valuable data for the study of the variability of ocean condition in the warm pool region of the western tropical Pacific.

1. *The variability of temperature in the upper ocean*

As the latitudinal variation of the ocean is less than the longitudinal variation, the relatively long succeeding 105-day time series of daily MST in the upper layer is conducted using the daily MST at 2°S, 158°E to supply the missing daily MST of 2 °S, 155° E. From the variations of daily MST in certain layers (Fig. 4), it can be seen that the daily MSTs at the 10, 50, 100, 150, 200 and 250 m layers before WWBs (from November 6 to December 17, 1992) were respectively higher than those after WWBs (from December 18, 1992 to January 31, 1993), in which the variations of daily MSTs at the 10, 50 and 250 m were small, the daily MSTs before WWBs were only higher than those after WWB by 0.2～0.4°C in these three levels, but the daily MSTs at the 100, 150 and 200 m layer before WWBs were respectively higher than those after WWB by about 1.5° C, which may be related to the variability of the Equatorial Undercurrent (EUC). And the fluctuations of the daily MST considerably intensified after the WWB, and the maximum deviations of the daily MSTs from 50 to 200 m layers after WWBs were each greater than those before the WWB, especially those of 100 to 200 m layers, which indicated fully that the variabilities of the subsurface sea temperature in the tropical western Pacific are more sensitive to the response to El Niño events than those of the surface sea temperature (Zou et al., 1991).

2. *Characteristics of thermocline and heat content in the upper ocean*

Table 1 shows the average depth of certain isotherms (m) and daily mean heat content ($10^8 J/m^2$) of the three stations 2°S, 155°E, 4°S, 156°E and 2°S, 158°E. The isothermal depths of 28°C, 20°C and 13°C represent respectively the upper layer, central

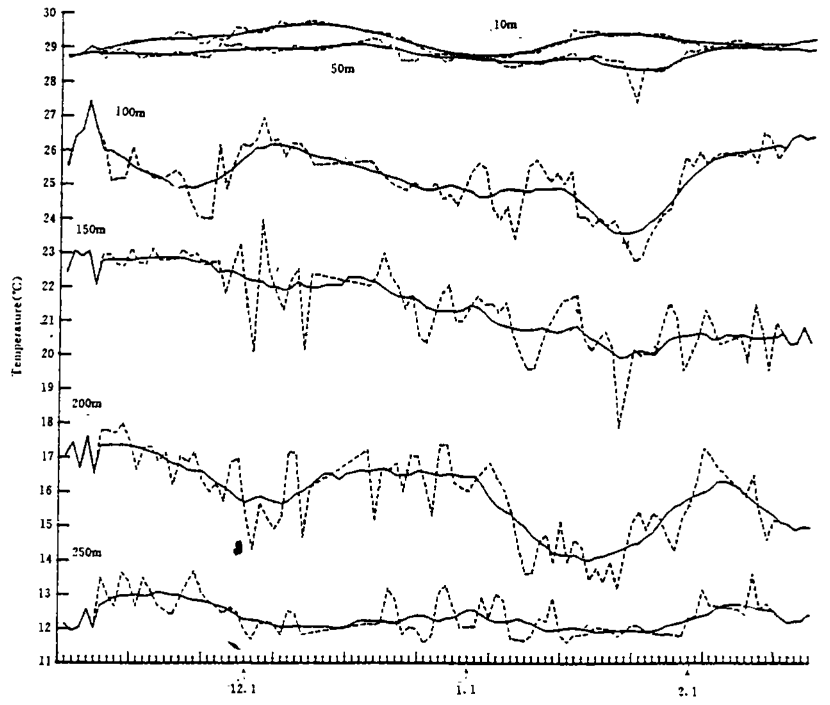

Fig. 4. Time series of daily MSTs at 10, 100, 150, 200 and 250 m layers and their 11- day running means.

part and lower layer of the thermocline as shown in Table 1. It can be seen from Table 1 that the depths of the upper homogeneous layer at 2°S, 155°E and 4°S, 156°E were

Table 1. Average depth of certain isotherms (m) and heat content (0～150 m) ($10^8 J/m^2$) at 2°S, 155°E, 4°S, 156°E and 2°S, 158°E stations.

Station	Time	Mean isotherm depth (28°C) (m)	Mean isotherm depth (20°C) (m)	Mean isotherm depth (13°C) (m)	0-150m heat content ($10^8 J/m^2$)
2°S,155°E	Nov. 6-29,1992	75.3	178.7	246.0	638.9
	Dec. 16-31.	67.7	169.1	236.7	631.2
	Jan. 1-8,1993	72.6	162.8	240.3	624.7
	Jan. 24-31.	58.0	154.4	218.0	613.4
	Feb. 1-19	75.2	155.7	241.3	634.4
4°S,156°E	Nov. 10-30. 1992	73.5	184.0	246.4	650.0
	Dec. 1-11.	80.4	179.0	243.4	656.6
	Dec. 19-31	66.3	175.6	240.5	647.6
	Jan. 1-8,1993	52.6	169.0	225.9	622.3
	Jan. 9-22	39.8	157.9	227.4	614.0
	Feb. 1-19.	66.7	172.1	235.0	639.8
2°S,158°E	Nov. 10-30,1992	78.2	175.9	232.5	648.0
	Dec. 19-31,	78.5	167.8	224.1	649.1
	Jan. 1-8,1993	88.0	161.9	214.8	642.0
	Jan. 9-22,	68.6	154.6	210.4	624.1
	Feb. 1-17	80.9	175.0	228.6	636.1

thick before WWB, in which the depth of 28°C warm water was 80.4 m at 4°S, 156°E in the first 10 days of December 1992; under strong westerlies, the 28°C warm water migrated eastward, so the average depths of 28°C warm water at 2°S, 155°E and 4°S, 156°E were 66 and 68 m respectively; however, the depth of 28°C warm water at station 2°S, 158°E did not shoal in the last 10 days of December, and the average depth descended up to 88 m in the first 10 days of January of 1993, then gradually rose. The 28°C warm water appeared to evidently lose at the three stations in the mid- and late January of 1993; at the same time, the thermocline of station 2°S, 155°E obviously shoaled, and the average depth of the 20°C isotherm was 154 m, which was shallower than that in November (average depth was 179 m) by 25 m, and the average depth of lower layer of the thermocline rose gradually from November, 1992 (246.0 m) to the last 10 days of January (218 m) of 1993, whereas the average heat content from surface to the 150 m evidently decreased in the mid- and late January of 1993, but the average heat content at 2°S, 158°E was still higher than that at 2°S, 155°E and 4°S, 156°E at that time. It is noteworthy that during WWB, the variabilities of the average thermocline and heat content were remarkable at 4°S, 156°E, the average depths of the upper homogeneous layer, central part and lower layer of the thermocline were shallower than that before WWB by 40.6, 26.1 and 19.0 m respectively, and the average heat content from surface to 150 m was less than that before WWB by 42.6×10^{8}J/m^{2}. The reason for that difference may be associated with zonal wind and surface current velocity, which were greater at 4°S, 156°E than at the other two stations after WWB (Shi, 1993).

3. *Spectral analysis of daily MST*

In order to understand the periodical oscillation of daily MST in certain layers in the centre of the warm pool region during IOP, the daily MSTs at certain layers of 10, 50, 100, 150, 200 and 250 m are estimated. Considering that the latitudinal variation of the ocean is usually less than the longitudinal one, the missing daily MST of 2°S, 155°E are supplied with the daily MSTs estimated from 2°S, 158°E, then the auto- and cross-spectra of 105- day time series of the daily MST are calculated with power spectrum and a comparison with that estimated with the maximum entropy method, setting the time lag at 35 days.

Fig. 5 shows the curves of the energy spectrum density of daily MST in certain layers and that the fine spectra for each layer of the daily MSTs are estimated by using the Hanning smooth coefficient method. The results show that daily MSTs in 10, 100 and 250 m layers all possessed long 30- to 60- day periods and that in the 150 m layer had biweekly periods (14 days). It can also be seen that the 150 and 200 m layers had the same about 3.5- and 4.4- day periods (Fig. 5a). The results of power spectrum density of daily MST estimated with a Parzen band-pass filter show that the daily MSTs in 10, 50, 200 and 250 m layers had low-frequency variations except for the 150 m layer, the dominant periods were between 30- and 60- day long, the periods for the 100 m layer were between 20- and 30- day in duration (Fig. 5b). The significant periods of the daily MSTs in 10, 200 and 250 m layers estimated with the maximum entropy method were 50, 41 and 39 days respectively (Figure ignored); and it is also shown that the daily MST in the 150 m layer also had biweekly periods and that in the 150 and 200 m layers had the same 3.5- and 4.5- day periods, which are the same as that estimated with Hanning coefficients. The results from cross-spectral analysis show that the daily MSTs in certain layers from 100 to 250 m layers (interval depth is 50 m) varied at the same fre-

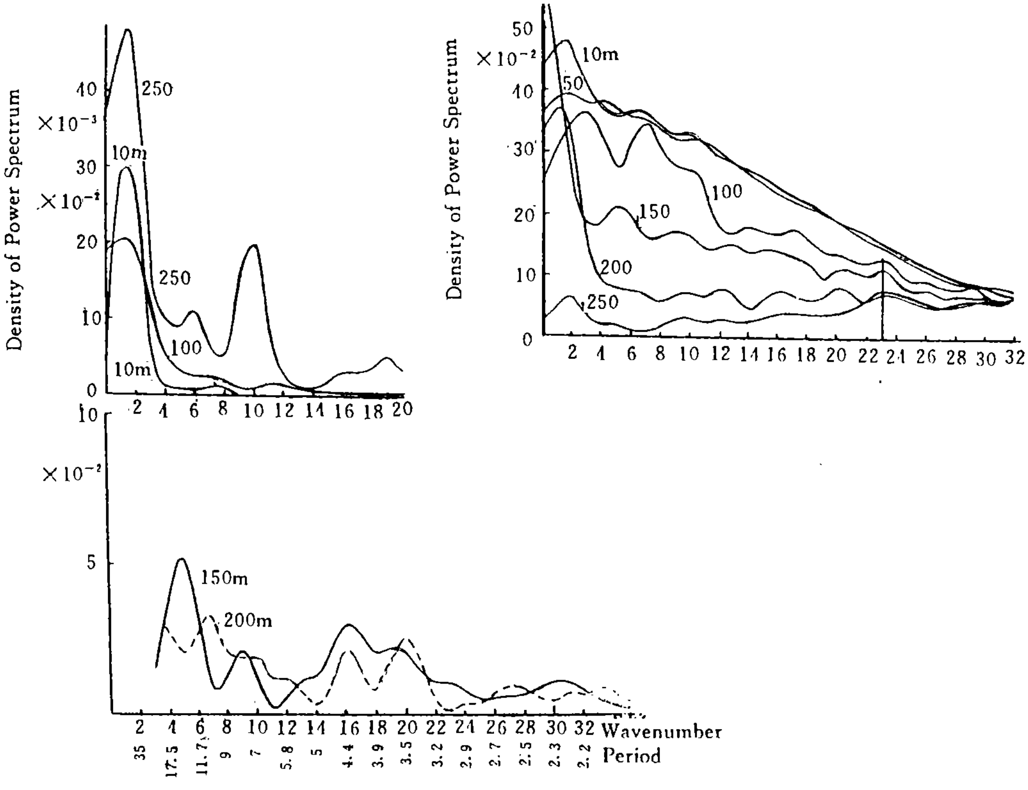

Fig. 5. Power spectra of daily MST in certain layers.

quency of 3 days, the values of energy spectrum density for four layers were 0. 130, 0. 117, 0. 076 and 0. 078 respectively, and they were closely coherent at this frequency (coherence values are all over 0. 9) (Fig. 6), the phase-differences between 100 and 150 m, 150 and 200 m, and 100 and 200 m layers were 353°, 342° and 335° respectively, and those between 100 and 250 m, 150 and 250 m, and 200 and 250 m layers were 319°, 324° and 342° respectively, which indicated that the fluctuations of the daily MSTs in 100, 150, 200 and 250 m layers had the same oscillation periods of 3 days, and they were basically in phase with each other.

V. CONCLUSIONS

In this paper, the surface wind, the SST and upper ocean thermal structure in the warm pool region of the western tropical Pacific are discussed by *in situ* observational time series analysis. The following conclusions are obtained:

a. During the surveying period, the response of the SST to the surface wind was remarkable, that is, the SST decreased during strong westerlies and northerlies, and the SST increases tended to occur during weak westerlies and northerlies. The strong westerlies persisted for about 14 days (December 20, 1992~January 2, 1993) during the first WWB episode, and lasted about 16 days (January 28~February 12, 1993) during the second WWB episode. The minimum daily mean SST at 2°S, 155°E occurred five days af-

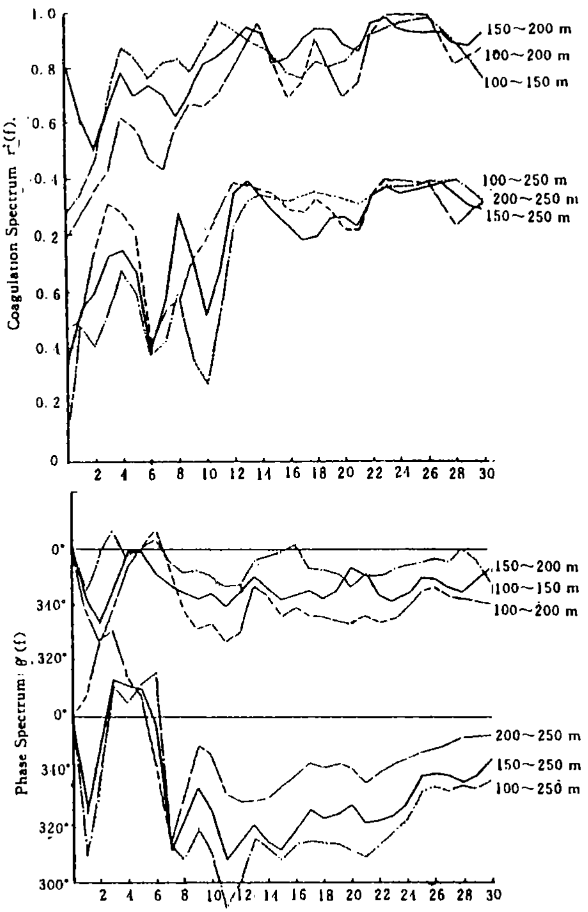

Fig. 6. Coherence and phase difference of the daily MST in certain layers.

ter the first WWB (28. 0°C), and on the second day after the second WWB (28. 2°C). The response of the daily MSST at 2°S, 158°E to daily MZW lagged behind that at 2°S, 155°E station.

b. The equatorial WWBs induced the eastward movement of the warm water, the shoaling of thermocline layer and the decrease of upper 0~150 m heat content in the warm pool region of the western tropical Pacific. The strong westerlies beginning from late December 1992 and lasting 2 weeks caused the 28°C warm water to turn thin and even disappear and the upper 0~150 m heat content to decrease significantly during the mid- and late January of 1993, the range of the variation being evident at station 4°S, 156°E.

c. The results of spectral analysis show that the zonal surface wind had low-frequency oscillations with about 30- to 60-day periods, and also had dominant 8-~9-day periods, while the meridional surface wind had the notable 6-~7- day periods. The analysis in this paper further confirms the fact of close relationship between the onset of El Niño events and the 30- to 60-day climate oscillations of the zonal wind over the centre of the warm pool region.

d. The results of spectral analysis of daily MST show that the daily MSTs of the surface, 10, 100, 200 and 250 m layers possessed the long 30- to 60- day periods, the fluctuations of daily MSTs of the 100, 150, 200 and 250 m layers had the same 3-day periods, they were closely coherent with each other, the coherence values were all above 0.9, and the fluctuations of the daily MSTs of 100, 150, 200 and 250 m layers with a 3-day periods were in phase with each other.

The analysis presented here is preliminary, for it is just an individual example of *in situ* observational time series analysis during the TOGA-COARE IOP, as we have not yet obtained successive long time series for spectral analysis and study of WWBs. The mechanism of WWBs needs to be further investigated.

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