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Inertial oscillations in the Kuroshio west of Okinawa

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Abstract: Inertial oscillations generated in the upper layer of the Kuroshio have been investigated by using moored ADCP data together with wind data from a JMA buoy robot at an adjacent site. The ADCP data were obtained at the central region of the Kuroshio west of Okinawa during one year from 1989/12 to 1990/11. The kinetic energy of the inertial current and the Kuroshio was separated from the total current field by a simple method which uses progressive vector diagrams. During a typhoon period, a strong inertial oscillation was generated not only in the surface Ekman layer but also in the underlying region of the Kuroshio. Strong inertial oscillations were also accompanied by significant reduction of the Kuroshio energy at the surface layer throughout the year.

1. Introduction

Inertial oscillations have often been observed in the oceans (e.g., WEBSTER 1968; SAKOU and NESHYBA, 1972; KUNDU, 1976; SALAT *et al.*, 1992). Inertial oscillations in the surface layer are generated mainly by winds (POLLARD, 1970; KUNDU, 1976). The wind-generated inertial oscillations transfer kinetic energy downward and cause the deepening of the mixed layer (SHAY *et al.*, 1992; TROWBRIDGE, 1992). The sea-surface wind stresses and the heat fluxes across the surface play an essential role in the dynamics of the upper ocean (GILL, 1982; QIU and KELLY, 1993). It is known that the conditions in which inertial oscillations are effectively generated by winds are (i) the clockwise rotation of the wind direction within an inertial period in the Northern Hemisphere or the rapid weakening of a strong wind which has been blowing for a few hours up to half an inertial period (POLLARD, 1970; PRICE, 1983), and (ii) the sudden shift of the direction of a strong wind (POLLARD and MILLARD, 1970). According to POLLARD and MILLARD (1970), a strong wind blowing in a fixed direction for an inertial period rather suppresses inertial oscillations because there is a period at which the wind stress and the inertial current work in the opposite direction. Mechanisms of the generation of inertial oscillations are not so simple. The detailed processes of the vertical transfer of the energy by inertial oscillations still remain as one of the most important subjects to be elucidated because of the difficulty of current observation under severe surface conditions. The effect of typhoons on the upper ocean also attracts great concern of oceanographers (HONG and YOON, 1992; TAIRA *et al.*, 1993).

In this paper, we analyze one-year term moored ADCP (acoustic Doppler current profiler) data obtained in the Kuroshio west of Okinawa together with the wind data from a buoy robot of the JMA (Japan Meteorological Agency). Special attention is paid to the inertial oscillation generated in the Kuroshio by typhoons. In the following, the date is expressed in a format of year/month/day.

2. Observation and method

A moored ADCP observation was carried out at the station M2 indicated in Fig. 1 during a period of 1989/12 to 1990/11 (MIZUNO *et al.*, 1991). The station M2 is located at the central region of the Kuroshio flowing to the northeast between Okinawa and the continental shelf in the East China Sea. The water depth is about 1500 m. An ADCP was mounted upward on the top of the mooring line. The first mooring

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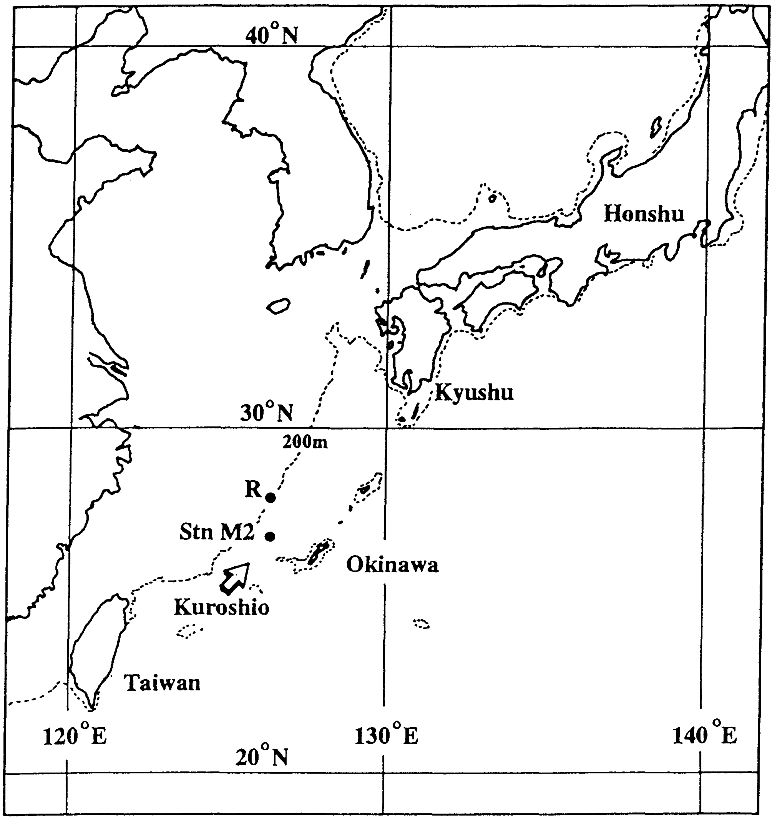


Fig. 1. Location map of the observation site. The positions of the ADCP mooring and the buoy robot of JMA are marked M2 and R, respectively.

Tabe. 1. Characteristics of the ADCP observation.

	Observation period	ADCP depth	Sampling interval	Depth resolution
First mooring	1989/12–1990/7	430 m	30 min	8 m
Second mooring	1990/7–1990/11	398 m	30 min	8 m

system was recovered immediately after resetting the second system in 1990/7 for the maintenance of the mooring system and the ADCP battery exchange. Characteristics of the first and second moorings are presented in Table 1. The location of the JMA buoy robot is also marked R in Fig. 1, where the wind at 8 m height above the sea surface was measured every 3 hours. The inertial period (frequency) at the station M2 is 26.3 h (3.81×10^{-2} ch^{-1}).

We shall make use of the progressive vector diagram to extract the inertial current from the original ADCP data. When the inertial current is superimposed on the northeastward flowing Kuroshio, we obtain a progressive vector diagram as shown typically in Fig. 2. When T_I denotes the inertial period and S the distance between two neighbobring kinks along the path on the diagram with a time interval T_I, the mean velocity of the Kuroshio during the period T_I is

$$v_K = S/T_I. \qquad (1)$$

The perturbed velocity v_I is obtained by subtracting v_K from the total velocity field v,

$$v_I = v - v_K. \qquad (2)$$

The v_I may be a measure of the inertial current. It can be calculated in the same way whether or not the neighboring points on the diagram with

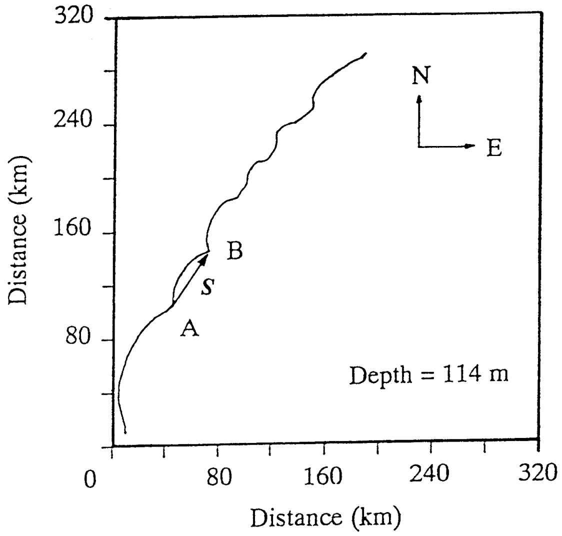


Fig. 2. Progressive vector diagram for the total velocity v obtained at 114 m depth in the observation period when the typhoon T9015 attacked the observation site.

the interval T_I are on the kinks. The four principal constituents K_1, O_1, M_2 and S_2 of tidal currents were determined through the harmonic analysis which uses the one-year data. These constituents were removed from the total velocity v prior to the calculation of v_K and v_I.

3. Results and discussion

We shall examine the monthly viariability of the inertial current. The mean direction of the Kuroshio current at station M2 is estimated as 40° clockwise from the north (NAKAJIMA *et al.*, 1992). The power spectra for the velocity component (V) in this direction including the tidal current are shown on the monthly basis for the 114 m depth data in Fig. 3. The spectral peaks corresponding to the inertial current and the semidiurnal tidal current are marked I and S, respectively. The semidiurnal current includes the M_2 and S_2 constituents. The spectral peak for the semidiurnal tidal current is clearly seen in the figure. In 1989/12, 1990/1 and 1990/5–6, inertial current with spectral level comparable to that for the semidiurnal tidal current was generated. The spectral peaks for inertial current became much higher than those for the semidiurnal tidal current in 1990/7–9. The observed periods for inertial oscillation were shorter or longer than the theoretical period. This might be caused by the Doppler effect due to the Kuroshio current or the effect of the stratification (GILL, 1982). The progressive vector diagrams at 114 m depth for the total velocity v including the tidal current are shown on the monthly basis in Fig. 4. A sequence of prominent kinks were seen on the paths for 1990/1 and 1990/8–9. These months are included in the period when the steep spectral peaks for the inertial current appear in Fig.3. The total length of the path on the diagram was remarkably decreased in 1990/8–10, showing the slack of the Kuroshio at 114 m depth.

Strongest inertial oscillation was generated when the typhoon T9015 attacked the observation site on 1990/8/29. The data for the total horizontal velocities v obtained during 8/25 to 9/9 are shown with the depth-time plot in Fig.5. The wind vectors are also shown in a series of arrows at the top of each depth profile. The wind vectors rotated clockwise during 8/29 to 9/3, evidencing that the typhoon passed the western side of the observation site. A pronounced inertial oscillation was initiated on 8/30 by this typhoon and continued until 9/5.

The method to extract the inertial current from the total current as expressed in Eqs. (1) and (2) was applied to the data during 8/28 to 9/6 when the typhoon T9015 attacked the observation site. The v_K and v_I for this period are shown with the vector plots in Figs. 6(a) and (b), respectively. For comparison, the wind vectors are also drawn at the top of the figure. A strong inertial oscillation was generated at depths of 114 to 170 m immediately after the wind with speeds greater than 15 ms^{-1} changed rapidly its direction on 8/30. This oscillation propagated downward with time. The generation process of the inertial oscillation at depths of 114 to 170 m is consistent with that proposed by POLLARD and MILLARD (1970). In the course of the generation of inertial oscillation v_K was remarkably reduced at 114 to 186 m depths.

The 3-day mean kinetic energies for the total current including the Kuroshio and the inertial oscillation are shown for various depths in Fig.7 together with those for the wind plotted against time. The E_{T3} and E_{W3} denote the 3-day mean kinetic energies for the total current and the wind,

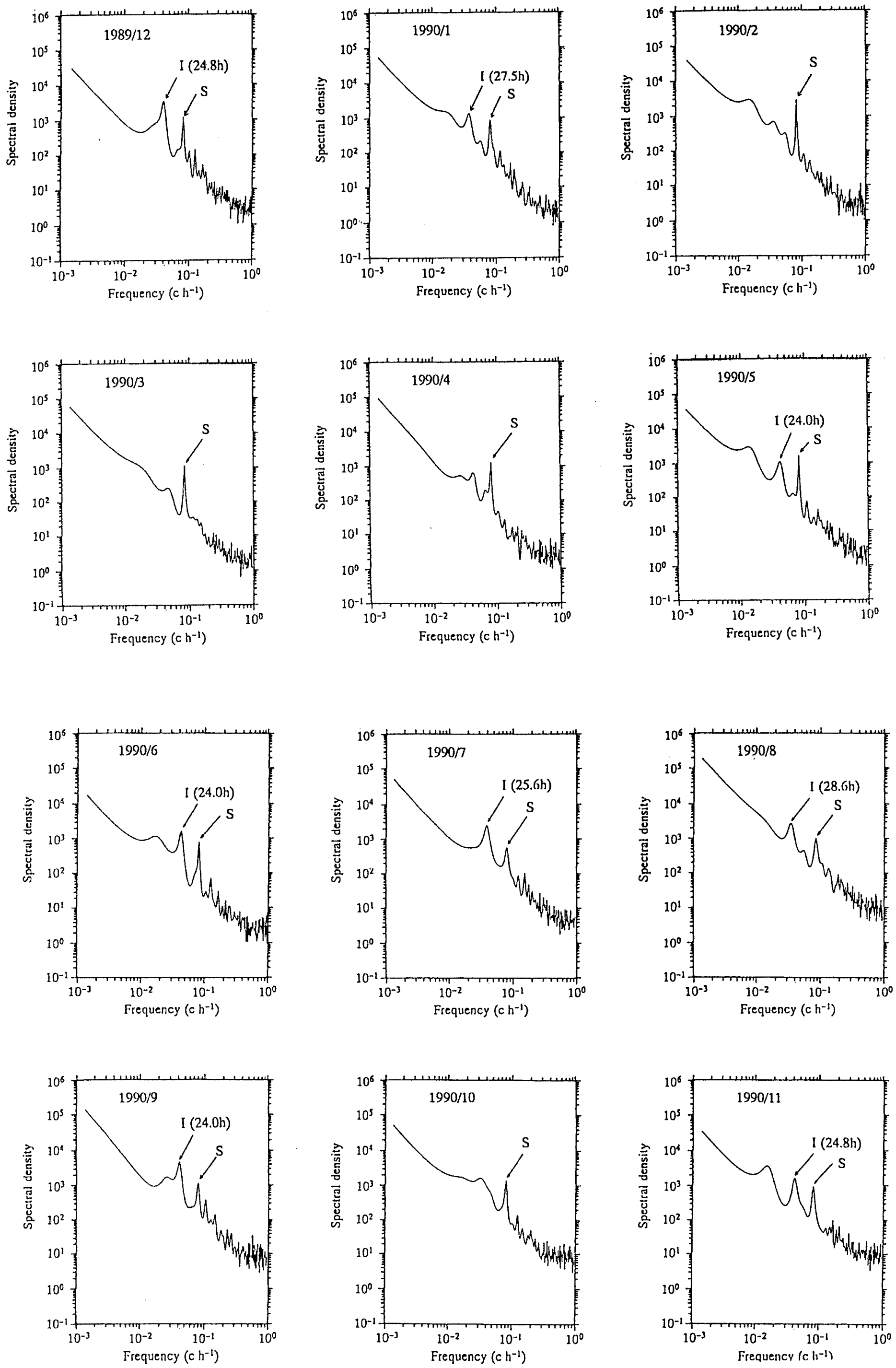


Fig. 3. Power spectra for the velocity component (V) along the mean current direction of the Kuroshio by using the data at 114 m depth. Units of spectral density: $3.6 \times 10^3 cm^2 s^{-1}$. The spectral peaks for the inertial current and the semidiurnal tidal current are marked I and S, respectively. The period of the inertial current at the peak is indicated in parentheses beside mark I.

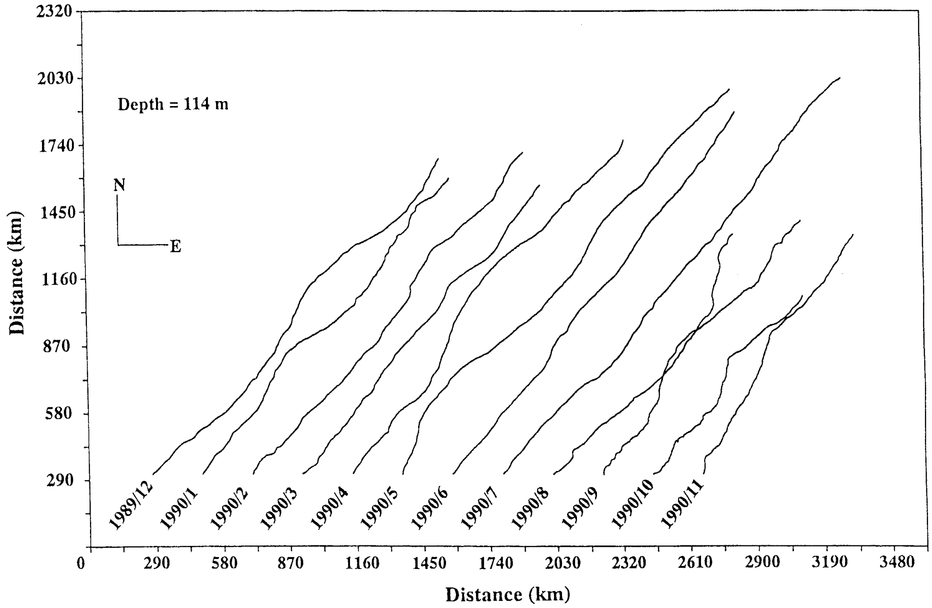


Fig. 4. Progressive vector diagrams for the total velocity v drawn on the monthly basis (114 m depth).

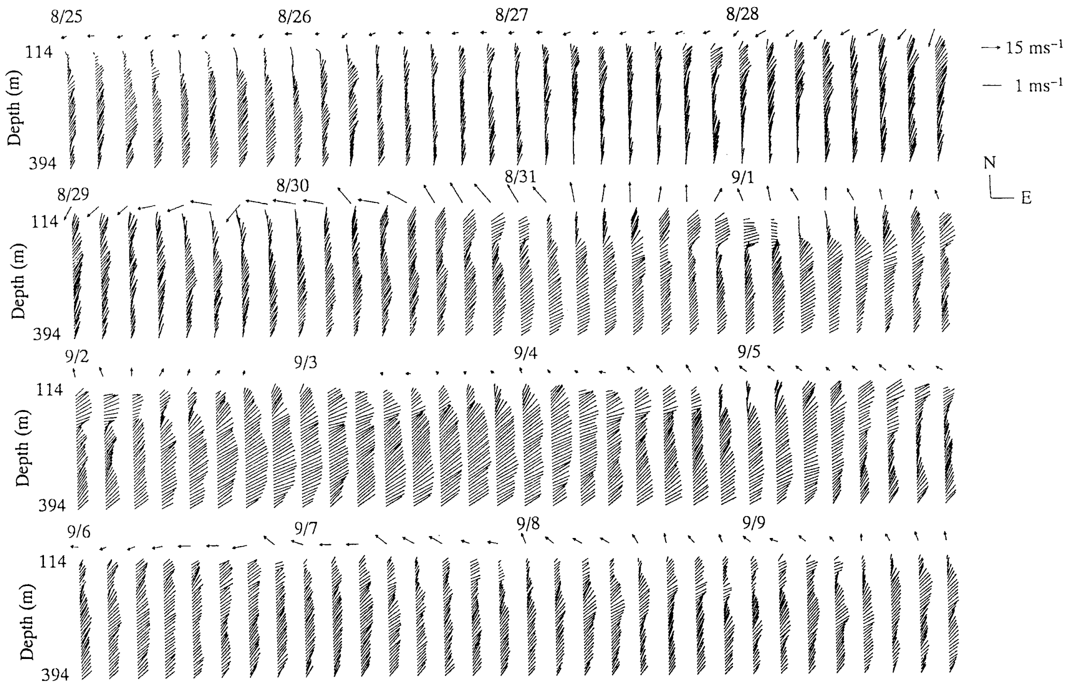
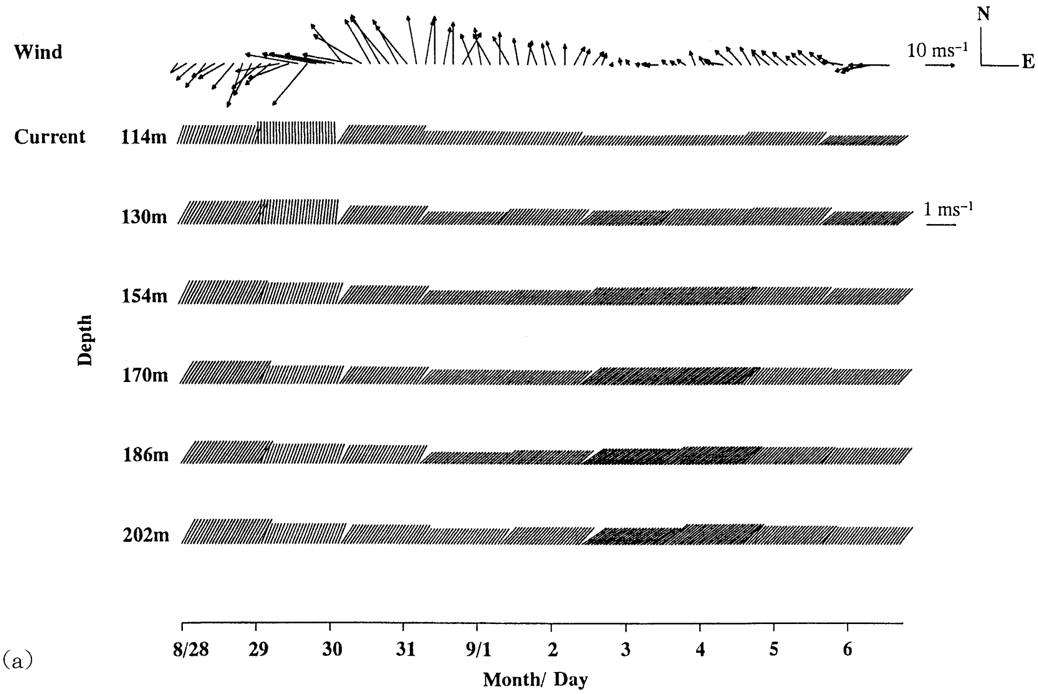
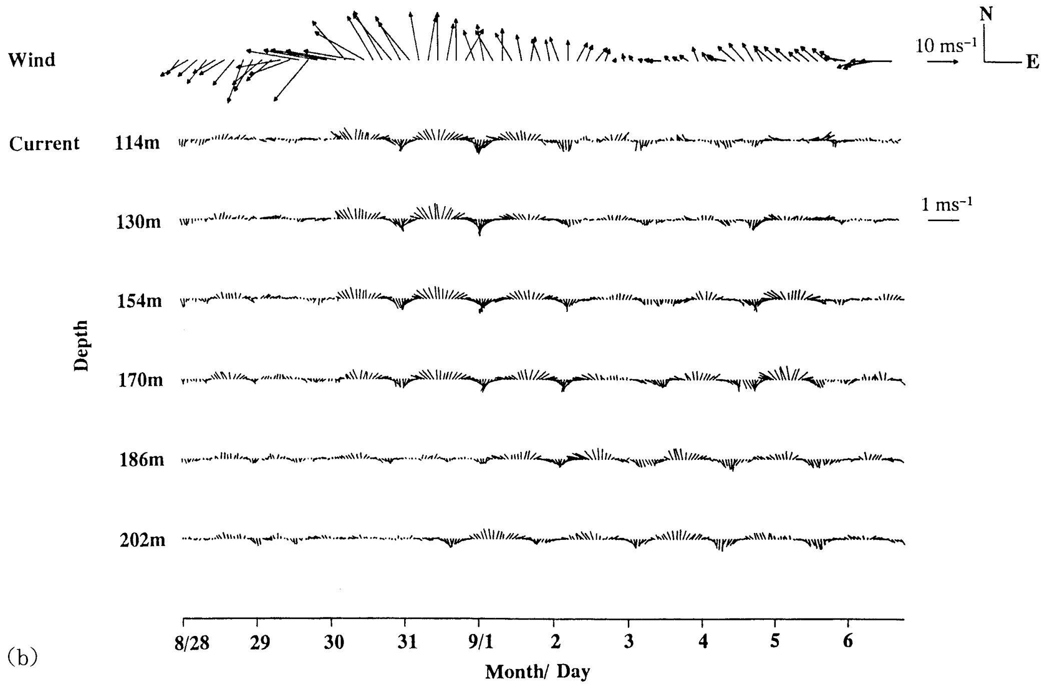


Fig. 5. Velocities at depths of 114 to 394 m when the typhoon T9015 attacked the observation site. The depth interval is 8 m. The wind vectors are also drawn above each current profile.



(a)



(b)

Fig. 6. The Kuroshio current (a) and the inertial current (b) during 8/28 to 9/6 when the typhoon T9015 attacked the observation site. The wind vectors are also drawn at the uppermost part of the figure. The four principal constituents K_1, O_1, M_2 and S_2 of the tidal current are removed, although the percentage of the tidal current in the total current is very small.

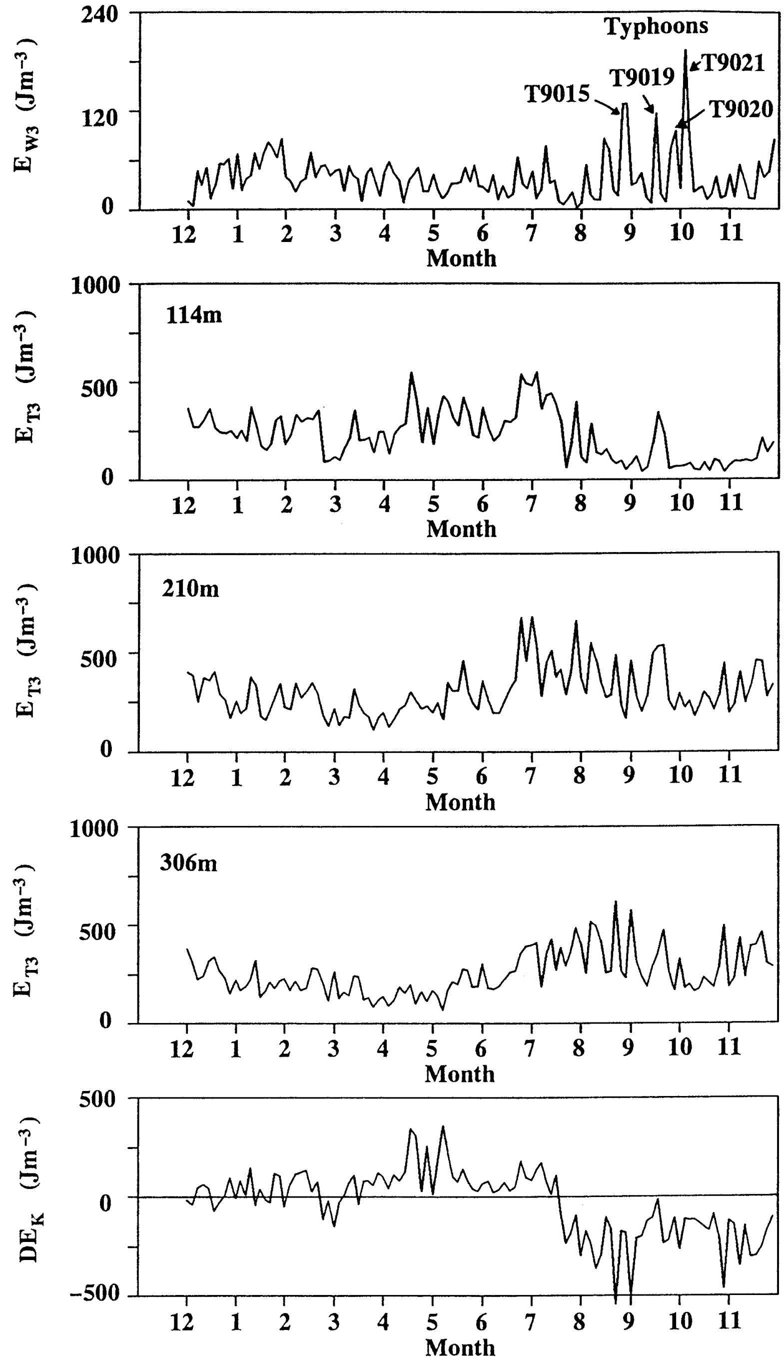


Fig. 7. Comparison of fluctuations of the 3-day mean kinetic energies of the current and wind; E_{T3} for the total current and E_{W3} for the wind.

respectively. We shall estimate the difference (DE_K) between the total kinetic energies in the surface and intermediate waters of the Kuroshio, by subtracting E_{T3} at 306 m depth from E_{T3} at 114 m depth. DE_K became negative in 1990/8–11, showing the reduction of kinetic

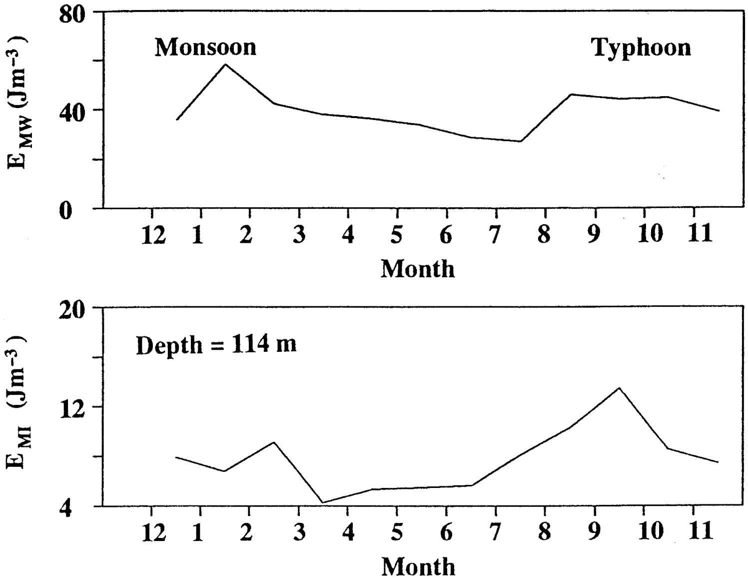


Fig. 8. Variation of the monthly mean kinetic energy of the wind and the inertial current at 114 m depth; E_{MW} for the wind and E_{MI} for the inertial current.

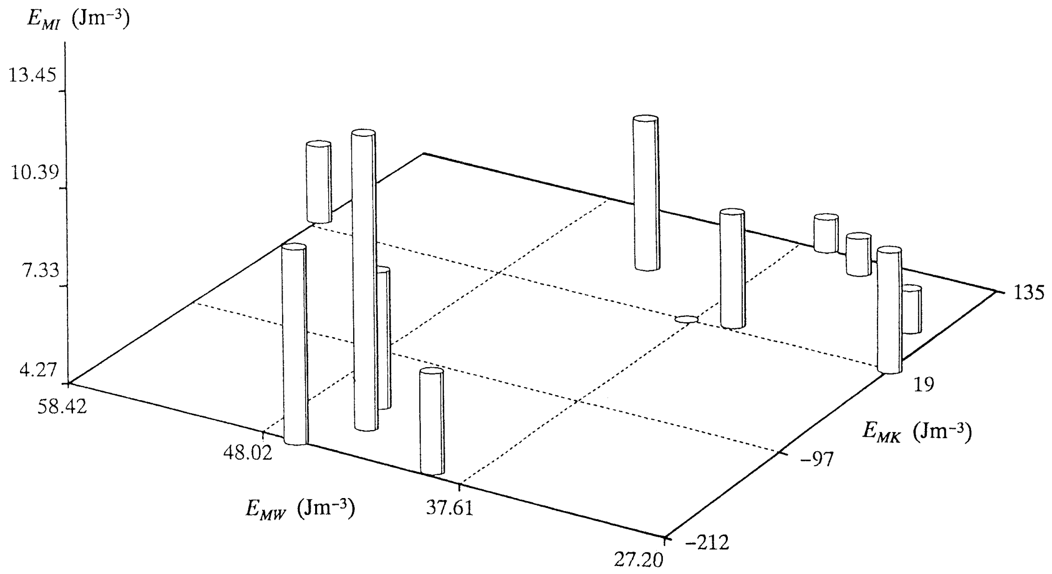


Fig. 9. Variation of the monthly mean kinetic energy for the inertial oscillation (E_{MI}) shown on the plane (E_{MW}, E_{MK}).

energy at the surface layer of the Kuroshio. This energy reduction was well correlated with the period when the severe winds caused by the typhoons T9015, T9019, T9020 and T9021 attacked successively the observation site.

The time plot of the monthly mean kinetic energies for the wind and the inertial current (E_{MW} and E_{MI}, respectively) is shown in Fig.8. E_{MI} was calculated from Eq.(2) by using the data at 114 m. E_{MW} had the largest value at the period of winter monsoon. In contrast, E_{MI} was greater in the typhoon period than in the monsoon period. It is understood that the conditions for effectively generating the strong inertial current were satisfied more frequently in the typhoon period rather than in the monsoon period. The monthly variation of E_{MI} is shown on the (E_{MW}, E_{MK}) plane in Fig.9, where E_{MK} is the monthly mean difference between the kinetic energies of the Kuroshio at depths of 114 m and 394 m. It should be noted that strong inertial currents were accompanied by significant reduction of the Kuroshio energy at the surface layer throughout the year.

4. Conclusions

The analysis of the one-year term ADCP data obtained in the Kuroshio west of Okinawa and combined with the wind data provides us the following results on the inertial oscillation:

(1) A simple method is proposed which can extract the inertial current and the Kuroshio current from the observed data by using progressive vector diagrams.

(2) The strong inertial oscillation generated by the typhoon T9015 occurred not only in the surface layer but also in the underlying Kuroshio region.

(3) The inertial oscillations were more effectively generated in the typhoon period than in the monsoon period.

(4) Strong inertial currents were accompanied by significant reduction of the Kuroshio energy at the surface layer throughout the year.

Acknowledgements

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