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Diurnal and semidiurnal current fluctuations at abyssal depths southeast of Okinawa

Kenzo TAKANO[*1], Yaochu YUAN[*2], Kazuo KAWATATE[*3], Shiro IMAWAKI[*3], Jilan SU[*2], Ziqin PAN[*2], Hiroshi ICHIKAWA[*4] and Shin-ichiro UMATANI[*3]

Abstract: Direct current measurements were carried out on a continental slope southeast of Okinawa from November 1991 to September 1992. Diurnal and semidiurnal current fluctuations measured by three current meters at abyssal depths and near bottom are studied. A harmonic analysis shows that the four major tidal constituents, in particular, the M_2 and K_1 are dominant during the observation period; the major axis lengths are 1.0 - 2.3 and 1.2 - 1.6 cm/s, respectively. Temporal variations of the tidal constituents suggest that there may be a topographic effect on the features of tidal current fluctuations. A rotary spectral analysis shows that the energy contained within diurnal periods of negative rotational components is much larger than that within those of positive ones. The inequality between the positive and negative components is also shown by a dynamic spectral analysis using current vector time series modified by subtracting the four major constituents of the tidal current fluctuations from the original data; it is probably due to the existence of local inertial oscillations. The suggested inertial oscillations are variable with time. The analysis also shows that the semidiurnal current fluctuations are basically composed of the semidiurnal tidal constituents.

1. Introduction

The Ryukyu Ridge is a part of the western boundary of the North Pacific subtropical gyre. Okinawa Island is located in the middle of the ridge. It has been thought that the western boundary current (WBC), the Kuroshio, of the North Pacific subtropical gyre flows in the East China Sea located northwest of the Ryukyu Ridge. However, recent studies suggest that a part of the WBC may flow east of the Ryukyu Ridge (YUAN *et al.*, 1991; SEKINE and KUTSUWADA, 1994 ; TAKANO *et al.*, in preparation, hereafter TP). To estimate the transport of the WBC accurately, it is necessary to observe current velocities directly. Recently CHAEN *et al.* (1993) carried out direct current measurements at abyssal depths and near the bottom southeast of the Ryukyu Ridge, and found fairly steady bottom-intensified southwestward flows. We carried out direct current measurements southeast of Okinawa at abyssal depths from November 1991 to September 1992. The results show that there are current variabilities with periods ranged from a few hours to several months at abyssal depths on the continental slope. In this paper we analyze the diurnal and semidiurnal current fluctuations basically related to tidal and inertial oscillations, and show the characteristics of the fluctuations with the tidal and near-inertial periods. This is a preliminary analysis toward future studies of tides and inertial oscillations at abyssal depths on a continental slope. Longer period variabilities with two to sixty-four days periods are studied by YUAN *et al.* (1994). TP will discuss seasonal and interseasonal variations of the abyssal flows.

2. Observation

The locations of mooring stations OA, OB and OC are shown in Fig.1a with bottom topography. The vertical arrangement of the current meters is shown in Fig.1b. Seven current meters were deployed in November 1991 and recovered in September 1992 on board the R/V Shijian

*1 Institute of Biological Sciences, University of Tsukuba, Tsukuba, 305 Japan
*2 Second Institute of Oceanography, State Oceanic Administration, Hangzhou, 310012 China
*3 Research Institute for Applied Mechanics, Kyushu University, Kasuga, 816 Japan
*4 Faculty of Fisheries, Kagoshima University, Kagoshima, 890 Japan

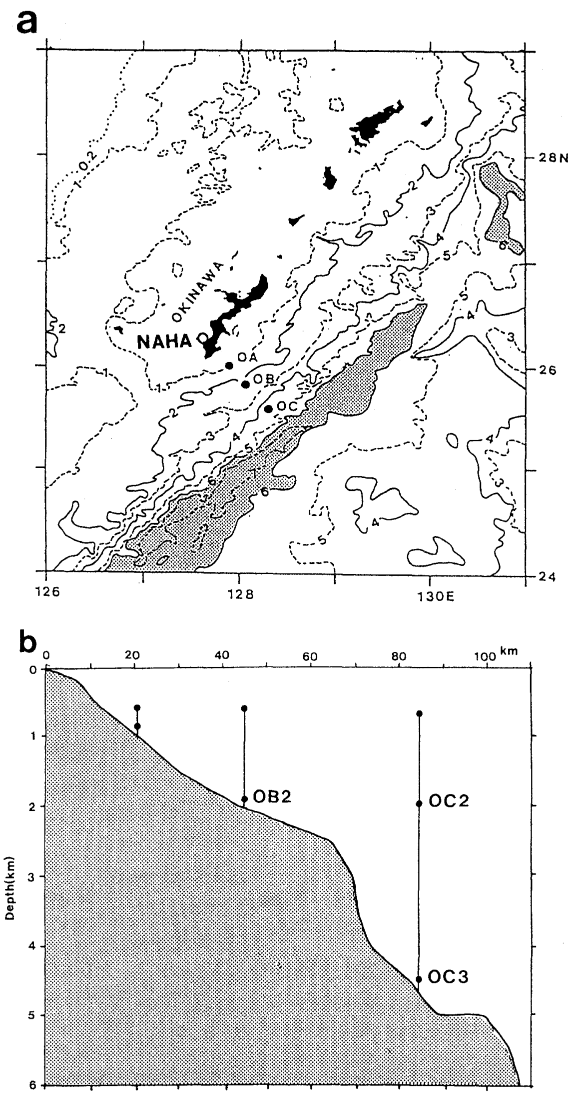

Fig.1. (a). Map showing mooring locations OA, OB and OC. Depths are shown in km; shading indicates depths greater than 6 km. (b) Vertical arrangement of current meters. Data obtained at OB2, OC2 and OC3 are analyzed.

(State Oceanic Administration, China). In this paper we analyze the year-long data obtained from three current meters at stations OB and OC; mechanical problems prevented the other current meters from giving quality records for over one month. The data sampling interval was one hour. The details of the current measurements related to this paper are shown in Table 1. Local inertial periods at stations OB and OC are 27.6 hours and 27.8 hours, respectively. Further information of the experiment is given in TP.

Hereafter OB2 refers to the current meter deployed at a depth of 1890m at station OB, and OC2 and OC3 at depths of 2000m and 4500m, respectively, at station OC.

3. Rotary spectra of current fluctuations

In order to determine the characteristics of the current fluctuation, we calculate positive (counterclockwise) and negative (clockwise) components of rotary power spectra (GONELLA, 1972) by use of the FFT (Fast Fourier Transform) method. In Fig. 2, left (right) panels indicate positive (negative) components of the rotary spectra, and upper, middle and lower panels show results for OB2, OC2 and OC3, respectively.

In each panel we find significant diurnal and semidiurnal spectral peaks. There are clear differences between the positive and negative components, in particular around the diurnal periods. The heights of the semidiurnal peaks in the positive and negative components are almost equal to each other. In contrast, those of the diurnal peaks are much higher in the negative components than in the positive ones. Further, the widths of the diurnal peaks are much wider than those in the positive ones, and hence the energy contained in the diurnal fluctuations of the negative components is much larger than that of the positive ones.

Table 1. Details of current measurements.

Station	Location	Water depth (m)	Meter depth (m)	Start date	End date	Record length (days)
OB	25° 48′ N 128° 03′ E	2020	1890	Nov. 4, 1991	Sep.9, 1992	310
OC	25° 34′ N 128° 20′ E	4630	2000 4500	Nov.13, 1991 Nov.13, 1991	Sep.9, 1992 Sep.9, 1992	301 301

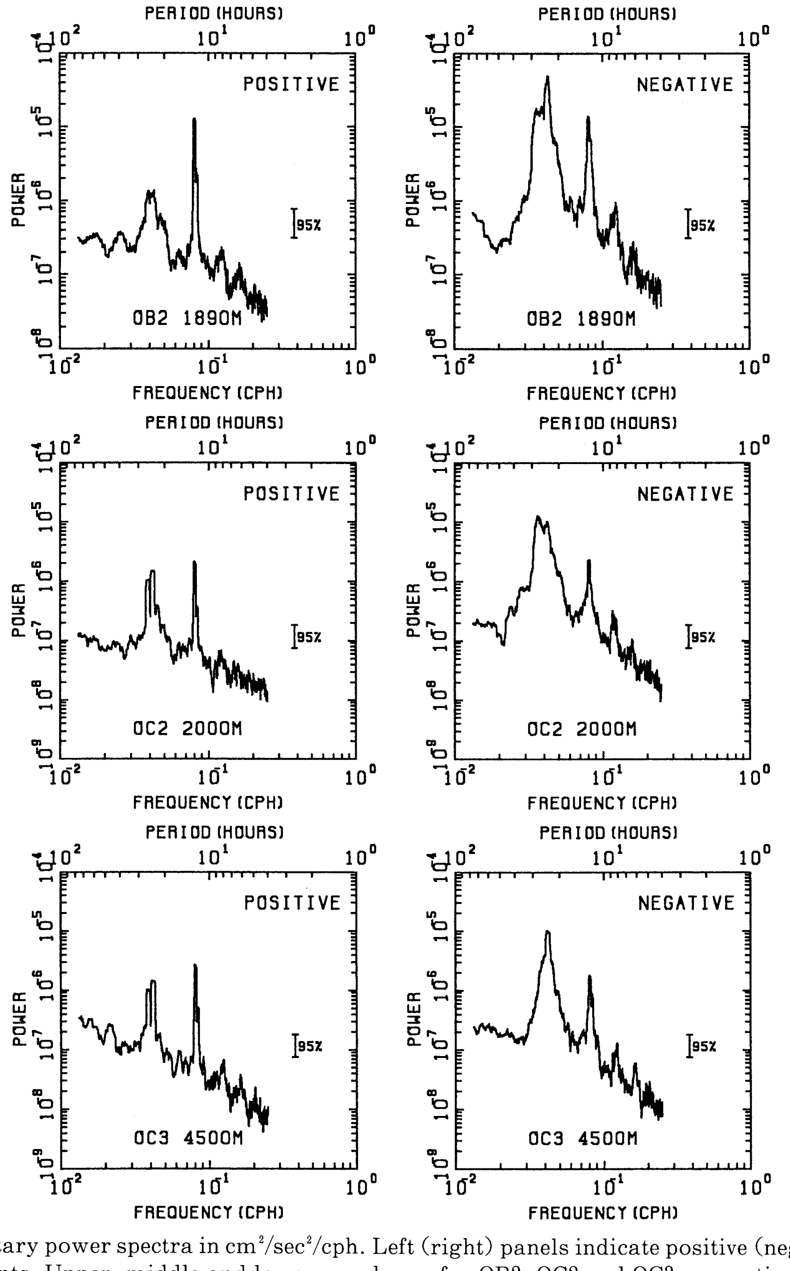

Fig. 2. Rotary power spectra in $cm^2/sec^2/cph$. Left (right) panels indicate positive (negative) components. Upper, middle and lower panels are for OB2, OC2 and OC3, respectively.

The spectral shapes of OC2 and OC3 have some similarities, in particular in the positive components. We find that two peaks around the diurnal period in the positive components are significantly separated from each other and their heights are almost equal to the heights of the semidiurnal peaks in the positive components. These features are different from those for OB2.

4. Harmonic analysis

In order to investigate the tidal fluctuations contained in the observed current vectors, we evaluate the harmonic constants of the eight

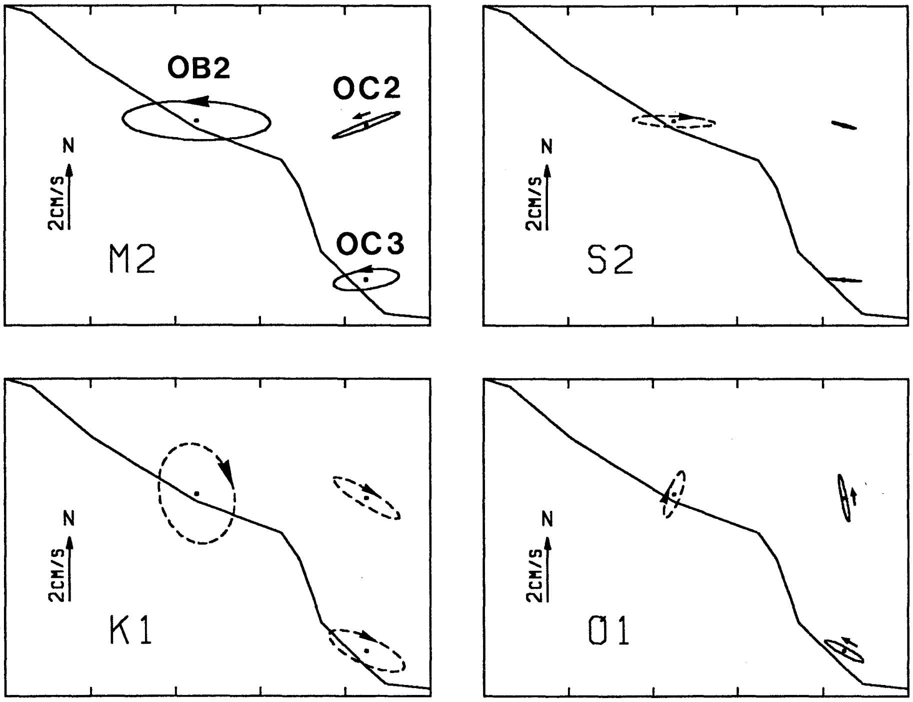

Fig. 3. Tidal ellipses of the four major constituents (M_2, S_2, K_1 and O_1) for OB2, OC2 and OC3 shown by dots (cf. Fig.1b). Upward indicates northward for the ellipses. The bottom is shown by a solid line.

major tidal constituents (M_2, S_2, K_1, O_1, N_2, K_2, P_1 and S_1) throughout the observation periods by use of the least square method. Figure 3 shows the tidal ellipses of the four major constituents (M_2, S_2, K_1 and O_1); amplitudes of the other constituents are small compared to these four major constituents. The ellipses are drawn at the corresponding individual current meter locations and depths (cf. Fig. 1b). Note that the ellipses represent horizontal current vectors with upward north. A solid (broken) ellipse means that current vectors of the tidal constituent turn counterclockwise (clockwise).

For semidiurnal tides (M_2 and S_2) and diurnal tides (K_1 and O_1), the amplitudes of the M_2 and K_1 are larger than those of the other constituents at each station. The M_2, K_1 and S_2 are stronger at OB2 than at OC. The rotational direction of the M_2 is positive and that of the K_1 is negative at each station. Between OC2 and OC3, there is no significant difference in either the ratio of the minor to major axis lengths or the length of each axis. The major axis direction of the M_2 and K_1 at OC2 and OC3 are almost the same.

Table 2. Phases (in degrees) of the four major constituents at OB2 and OC3 referred to OC2.

C.M.	M_2	S_2	K_1	O_1
OB2	-122	+30	-1	+171
OC3	+18	+27	+2	+39

The ratios of minor to major axis amplitudes are less than 0.32 except for the K_1 at OB2 (0.73). These small ratios suggest that the differences of the energy between the positive and negative components are not large. The rotary spectral analysis in the preceding section shows inequality in the energy contained within diurnal periods between the positive and negative components. The difference in the energy partition into these two components may be due to local inertial oscillations; this will be discussed later.

The phases of the four major constituents relative to OC2 are shown in Table 2. The OC3 is ahead of the four major constituents. The

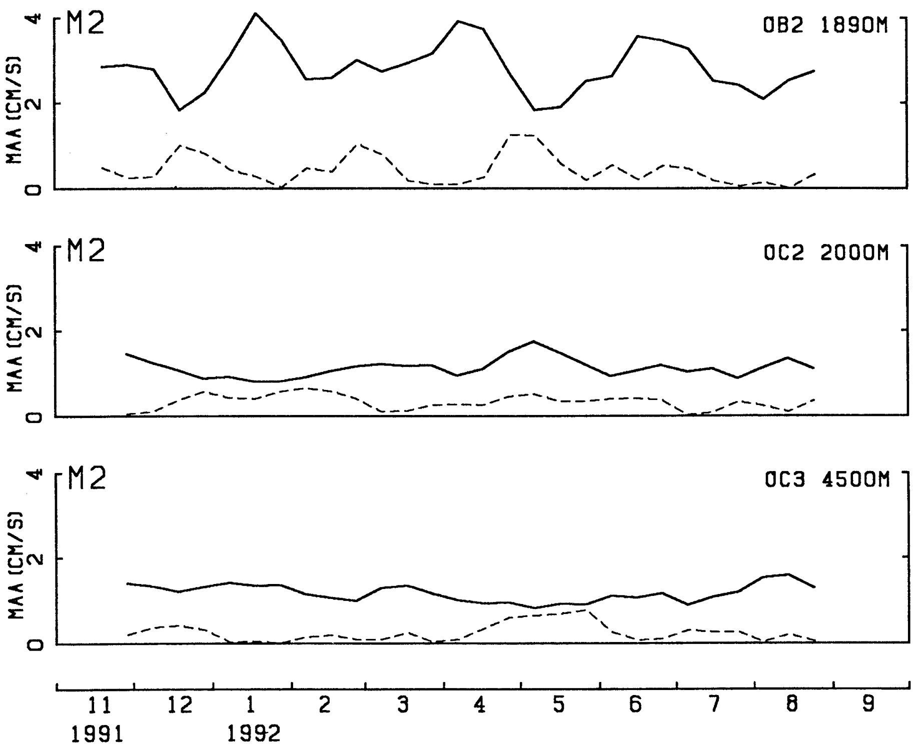

Fig. 4. Temporal variations of major (solid line) and minor (broken line) axis amplitudes for the M_2 constituent, analyzed every 10 days using 29.5 days long data. Upper, middle and lower panels are for OB2, OC2 and OC3, respectively.

phase differences might be caused by the locations of OC2 and OC3; OC2 was far above the bottom, while OC3 was close to the bottom. It might indicate the existence of internal tidal currents which are vertically out of phase (MATSUYAMA and TERAMOTO, 1985). However, we note the relatively small phase differences between OC2 and OC3 for the dominant constituents M_2 and K_1; the phases at OC3 proceed only about 40 minutes for the M_2 and about 10 minutes for the K_1. These phase differences are smaller than the temporal resolution of the present data sampling (60 minutes).

The results of barotropic tidal models suggest that the station OB is located behind the station OC for the M_2 and is almost on the same phase for the K_1, S_2 and O_1 (ODAMAKI, 1989; KO, 1993). The phase differences of the K_1 agree with the model results, but it is generally hard to explain the difference in tidal phase between the two neighboring points OB and OC with barotropic tidal models. To investigate further, we have to consider the effects of bottom topography, internal tides and others on the characteristics of the tidal currents at abyssal depths.

5. Temporal variations of tidal fluctuations

The above harmonic analysis gives us the tidal aspects of the current fluctuations throughout the observation period of about 10 months. The current meter records also indicate the existence of distinct interseasonal variations. Those interseasonal variations might affect tidal fluctuations, in particular when the tidal fluctuations include internal components induced by combined effects of the stratification and bottom topography.

Figures 4 and 5 show temporal changes of the major and minor axis amplitudes of the M_2 and K_1 constituents, respectively. They are calculated with harmonic analyses of 29.5 days long data for the four major constituents; a data length of 29.5 days is selected for avoiding the effect of the intensification of tidal currents in

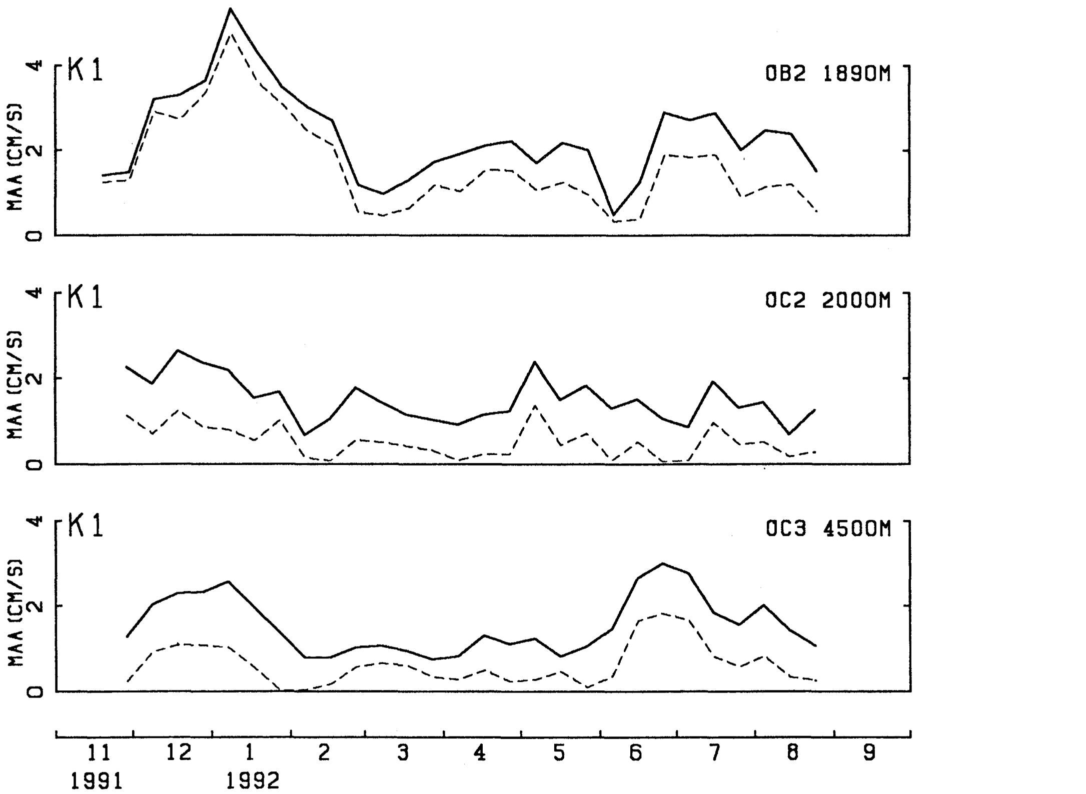

Fig. 5. Same as Fig. 4 except for the K_1 constituent.

spring tides due to some unknown reasons (TAKEOKA and MURAO, 1993). The calculations are continued with shifting the analysis period by 10 days throughout the observation period; e.g., at OB the first data set (29.5 days long) begins on Nov. 4 and the second one on Nov. 14.

The major axis amplitudes of the M_2 are much less variable at OC2 and OC3 than at OB2. This is also the case of the K_1, though its amplitudes at OC2 and OC3 are more variable than those for the M_2. At OB2 and OC3, the major and minor axis amplitudes of the K_1 become large in January and June or thereabouts, but there is no correlated increase and decrease in those of the M_2. It should be noted that both of OB2 and OC3 are located close to the bottom, which might account for some features of the observed tidal currents. It is also interesting that the minor and major axis amplitudes of the K_1 vary in almost the same manner for each current meter.

6. Discussion and summary

Diurnal and semidiurnal current fluctuations at abyssal depths southeast of Okinawa are studied. The rotary spectral analysis shows strong diurnal and semidiurnal current fluctuations (Fig. 2). The detected peaks are identified as the four major tidal constituents of which dominant are the M_2 and K_1 constituents. The tidal ellipses of the M_2 and K_1 constituents at OC2 and OC3 are similar in magnitude and major axis direction. At OB2, the magnitudes are larger than at OC2 and OC3 and the major axis directions are different from those at OC2 and OC3 (Fig. 3).

Temporal variations of the M_2 and K_1 (Figs. 4 and 5) show that throughout the observation period at OC2 and OC3, the M_2 amplitude is little variable but the K_1 amplitude is fairly variable. This suggests that the M_2 tide at OC2 and OC3 is mainly external, because each tidal current amplitude should be invariant in time if it is the barotropic tide (AOTA and MATSUYAMA, 1987).

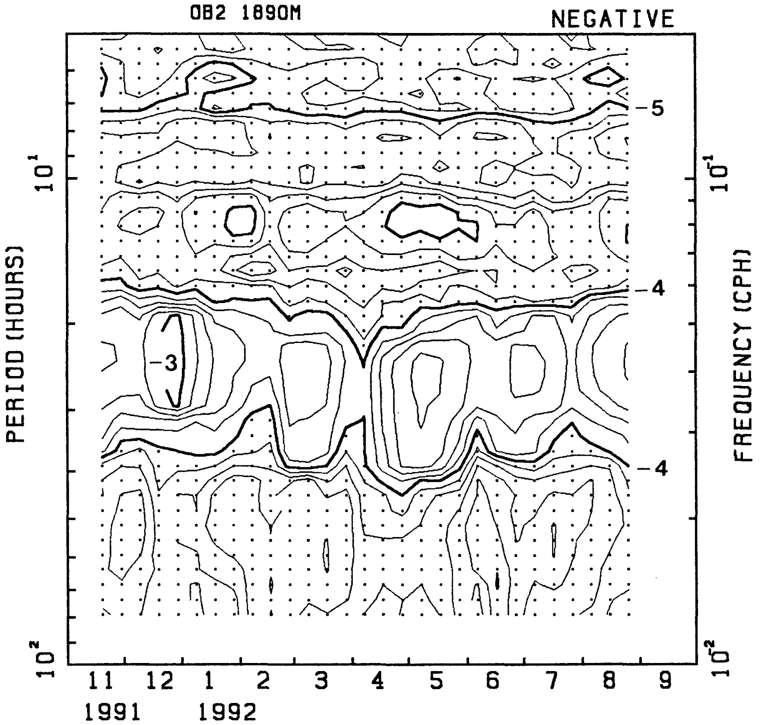

Fig. 6. Power density of the negative component of dynamic rotary spectrum at OB2 after subtracting the four major tidal constituents from the raw data. Numerals indicate logarithm of the power density ($cm^2/sec^2/cph$) to base 10. Contour inverval is 0.2. Shading indicates values less than −4.

In contrast, the major axis amplitudes at OB2 are more variable. The M_2 and K_1 constituents at OB2 might be mostly due to bottom-intensified internal tides, although it is difficult to confirm it because the vertical structure of currents is not measured.

As mentioned previously, the energy contained within diurnal periods of the negative rotary components is much larger than that of the positive components. The rotational direction of the K_1 constituent is negative, but its magnitude is not enough to account for the difference in the energy partition into the two components. This suggests that there may be non-tidal fluctuations having mainly negative components, which are probably local inertial oscillations. To investigate it in detail, we calculate dynamic spectra from current vector time series which are made by subtracting the four major tidal constituents from the original time series. Then, the harmonic constants are calculated every 10 days using 29.5 days long data.

Power density of negative components of dynamic rotary spectrum at OB2 is shown in Fig. 6 and positive components in Fig.7. A distinct high power zone is only found within near the diurnal periods (20–35 hours) in the negative components. This feature is also found at OC2 and OC3. Since the local inertial period is about 28 hours, these high energy zones are considered to be due to the inertial oscillations. Individual inertial oscillations are not persistent, and hence the estimated power is probably due to the mixture of inertial oscillations with different phases and amplitudes. The mixture does not give rise to a sharp peak at the local inertial period. This may be the reason why the peaks near the diurnal periods in Fig.6 are broad and spread over 20 to 35 hours in period. The strength of the high power zone varies in a few months. This temporal variability might be related with the variations of oceanic and/or atmospheric environments, which will be discussed in another article. Figures 6 and 7 also show that there is

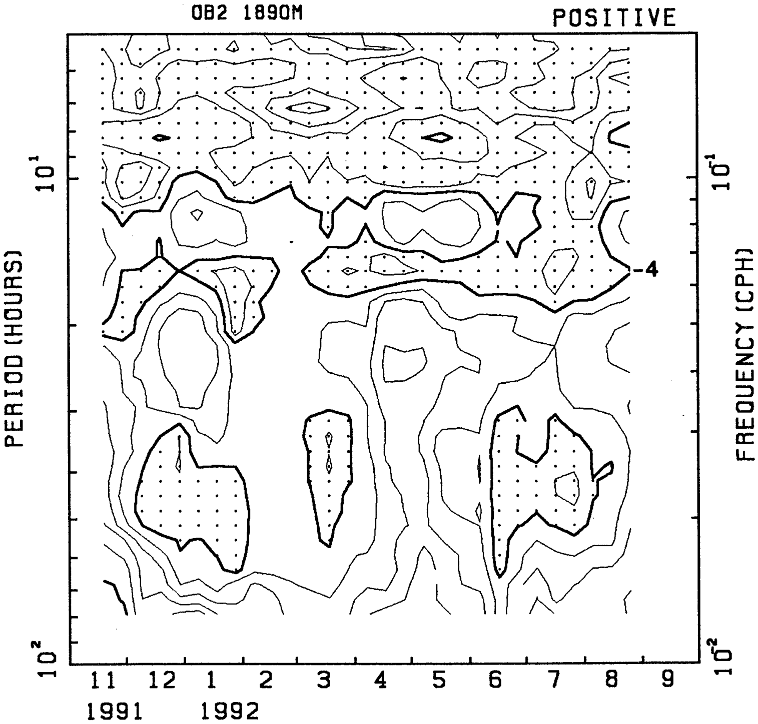

Fig. 7. Same as Fig. 6 except for the positive component.

no significant high power zone around semidiurnal periods in the two components, which indicates that the semidiurnal current fluctuations found in the original data are basically composed of tidal constituents.

Sources of the inertial oscillations cannot be identified in this study. We compare the dynamic rotary spectrum (Fig. 6) with the wind variability observed at Naha located in southwestern Okinawa. However, we cannot find any significant correlations between them. The inertial oscillations in this area might be composed of oscillations propagated from some area. FU (1981) suggested that propagating internal waves with near-inertial frequency coming to an area might induce inertial oscillations at the latitude of that area. In addition, we also have to consider the effects of the advection, bottom topography and so on. To investigate the sources of inertial oscillations, more detailed observational data covering broader area are required.

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References

AOTA, M. and M. MATSUYAMA (1987): Tidal current fluctuations in the Soya Current. J. Oceanogr., **43**, 276–282.

CHAEN, M., M. FUKASAWA, A. MAEDA, M. SAKURAI and M. TAKEMATSU (1993): Abyssal boundary current along the northwestern perimeter of the Philippine Basin. pp. 51–67. *In* T. TERAMOTO (ed.): Deep ocean circulation, physical and chemical aspects. Elsevier Sci. Publ.

FU, L.-L. (1981): Observations and models of inertial waves in the deep ocean. Rev. Geophys. and Space Physics, **19**, 141–170.

GONELLA, J. (1972): A rotary-component method for analyzing meteorological and oceanographic vector time series. Deep-Sea Res., **19**, 833–846.

KO, J.-S. (1993): Modeling of tides in the east Asian marginal seas. Master thesis, Sung Kyun Kwan Univ., Korea, 142 pp.

MATSUYAMA, M. and T. TERAMOTO (1985): Observations of internal tides in Uchiura Bay. J. Oceanogr., **41**, 39–48.

ODAMAKI, M. (1989): Co-oscillating and independent tides of the Japan Sea. J. Oceanogr., **45**, 217–132.

SEKINE, S. and K. KUTUWADA (1994): Seasonal variation in volume transport of the Kuroshio south of Japan. J. Phys. Oceangr, **24**, 261–272.

TAKEOKA, H. and H. MURAO (1993): Tidal currents influenced by topographic eddies in Uchiumi Bay. J. Oceanogr., **49**, 491–501.

YUAN, Y., M. ENDOH and H. ISHIZAKI (1991): The study of the Kuroshio in the East China Sea and the currents east of the Ryukyu Islands. Acta Oceanologica Sinica, **10**, 373–391.

YUAN, Y., Z. PAN, J. SU, S. UMATANI, S. IMAWAKI, K. KAWATATE and K. TAKANO (1994): Spectra of the deep currents southeast of Okinawa Island. La mer, **32**, 245–250.