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Characteristics of Tidal Currents Observed at Five Mooring Stations in Sagami Bay

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Abstract : Tidal currents in Sagami Bay were investigated by the long–term records of current and temperature obtained in the surface and deep layers at five mooring stations during the period from July to November, 1996. The time series and power spectra of the current and temperature records showed the predominance of the semidiurnal period fluctuations at all stations. The semidiurnal current was high correlation to the temperature at the same depth at all stations. The semidiurnal current amplitudes observed at the station in the inner region of the bay were dependent on the depth, and was very larger than tidal current amplitudes to be due to the surface mode estimated by the numerical experiments. These results indicate the observed tidal current to be due to the internal tides mostly. The predominance of the semidiurnal internal tide supports the key idea that the internal tides observed in Sagami Bay are mostly generated at the northern part of the Izu Ridge (OHWAKI *et al.* 1994, KITADE and MATSUYAMA 1997). The current and temperature data obtained at three depths (10m, 35m and 60m depths)near the northwest coast show that the tidal current amplitude with the semidiurnal period had a maximum at 10m depth and gradually decreased with depth. Its current amplitudes were variable with the change of the stratification. The phase relation between the current and temperature with the semidiurnal period indicates the internal wave propagation in the upper layer along the coast to be right the hand. These results are consistent to the results obtained by both the temperature measurements along the coast and the numerical experiment (KITADE and MATSUYAMA, 1997).

Keywords : *tidal current, internal tides, inertial period, internal Kelvin wave, internal inertia gravity wave, vertical structure of the tidal current*

1. Introduction

Sagami Bay is located in the central Japan, facing to the Pacific Ocean and its length from the mouth to head is about 55km and the width is about 60km (Fig.1). The Oshima island is located at the bay mouth and divides into two channels, *i.e.*, the Oshima West Channel and East Channel. The Sagami Trough extends to the northwest region of the bay head through the Oshima East Channel, and the shallow water region is only found off the northeast coast of the bay head. The Kuroshio flows south of Sagami Bay and part of the Kuroshio water usually inflows through the Oshima West Channel and flows out through the Oshima East Channel (TAIRA and TERAMOTO, 1986). The anticlockwise current circulation in the bay is formed by this current and the strength of the circulation is closely related to the location of the Kuroshio path (IWATA and MATSUYAMA 1989, KAWABE and YONENO 1987).

Tidal phenomena in Sagami Bay have been observed by some methods, and the observational results have represented some interesting features. TERAMOTO (1971) observed the surface current by GEK on the ship and the volume transport by the Electronic Potential

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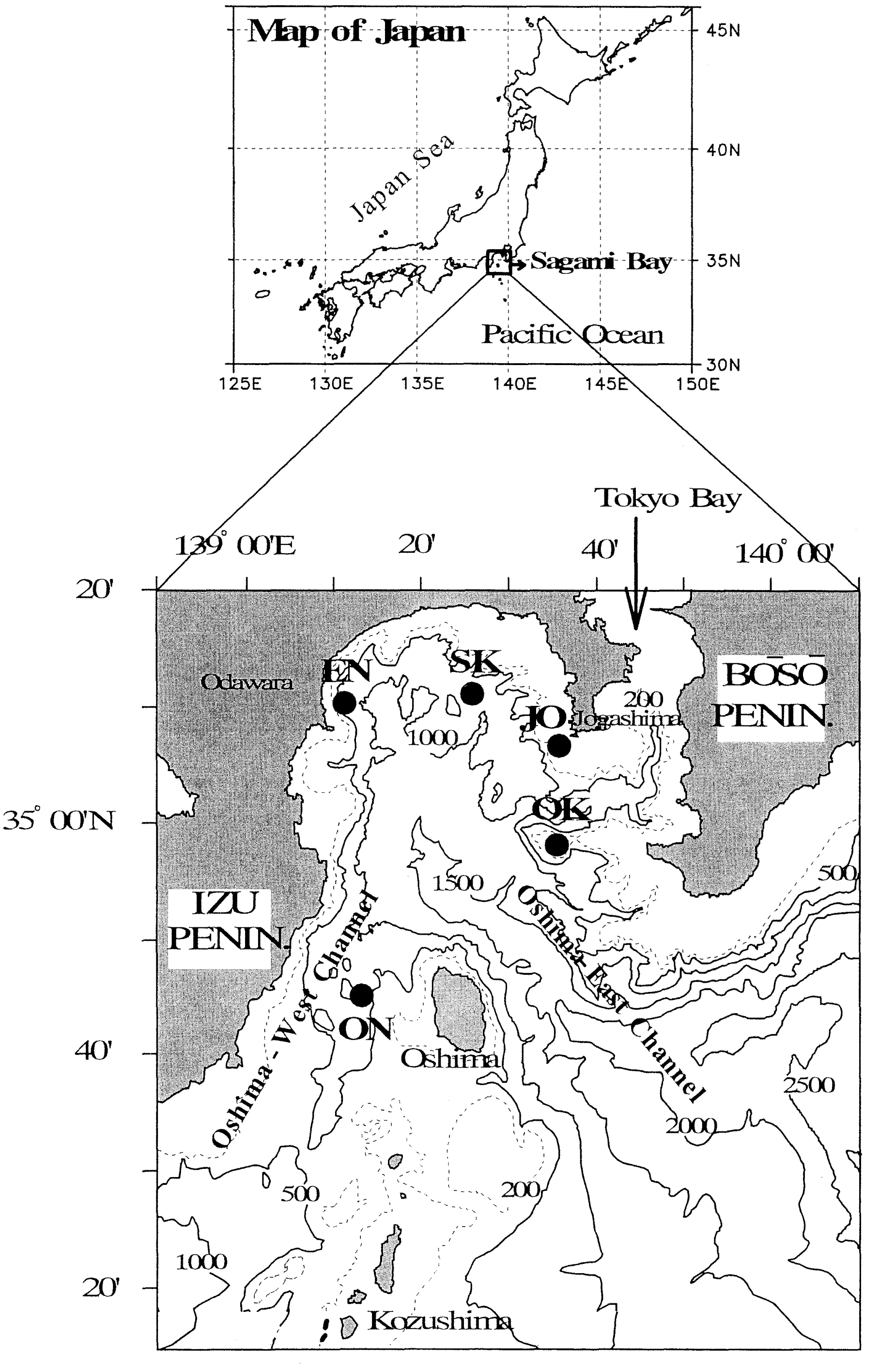

Fig. 1. Locations of current measurement Numerals on the bottom contour are in meter.

Measurements through the Oshima West Channel. He reported the strong current with semidiurnal period in spite of the small volume transport across the channel. KONAGA *et al* . (1979)carried out the current measurement at the mooring buoy near Oshima Island in the same channel and found the strong tidal currents and the predominance of the semidiurnal period, especially M2 constituent. However, the characteristics of these tidal currents were not sufficiently explained by them. MATSUYAMA and IWATA(1985)made the current and temperature measurements at 30m and 60m depths on the shelf off Jogashima (JO shown in Fig.1)and reported the existence of internal tides on the shelf. MATSUYAMA *et al* . (1988)also showed the existence of the internal tides from the temperature measurements by the thermistor chain near the northwest coast of the bay (near EN in Fig.1). OHWAKI *et al* . (1991)showed that the tidal current due to the surface tides is smaller than 1cms^{-1} in the main part of the bay, estimated by the numerical experiments. They also indicated the observed tidal current in the upper layer at the five mooring stations of the inner region of the bay to be much larger than the tidal current due to the surface mode. Then they documented the observed tidal current to be mainly due to the internal tides in the upper layer of the inner region of the bay. KITADE *et al.* (1993) and KITADE and MATSUYAMA (1997) clarified the predominance and behavior of the semidiurnal internal tide by the temperature measurements at seven mooring stations in the upper layer of the inner region of the bay and the numerical experiments by using a two-layer model.

The current measurements of the previous studies were made only in the upper layer of the bay, and the temperature measurements were made at some depths, which were shallower than 60m depth (MATSUYAMA *et al* . 1988, KITADE and MATSUYAMA 1997). Therefore the existence and characteristics of the internal tides were clarified to be mostly due to analysis of the temperature measurements in the upper layer near the coast. The current measurements in multiple layers are required to investigate vertical structure with the tidal current at the mooring stations in not only the shallow shelf region but also deep waters to confirm the previous studies and to verify the predominance of semidiurnal internal tide in the deep water.

The data set obtained from the mooring stations during the period from the summer to fall of 1996, was used to study the tidal current variations and verify the predominance of the semidiurnal internal tide.

2. Tidal current due to the surface tides in Sagami Bay

It is very difficult to extract the tidal current due to the surface tides from the observational current data for including the internal tidal current in the records and for the large water depth in Sagami Bay. Then OHWAKI *et al.* (1991)estimated the tidal current amplitudes and phase for M2 and K1 constituents of the surface tides in Sagami Bay and Suruga Bay by the numerical modeling. Figure 2 shows the horizontal distributions of the length of major axis of the tidal ellipses for both constituents. In Sagami Bay, the length of the major axis of both constituents is very small in the inner region of the bay. The numerical calculation was carried out with square grids of 2km spacing, so it is not so sufficient to clarify the local phenomena of the surface tides in the complicated bottom topography region, *i.e.*, the small bank such as Okinoyama Bank nearby the mouth of Tokyo Bay. But, the characteristics of the surface tides in the most part of the bay are considered to be grasped from the numerical experiments. In this numerical model results, the current amplitude due to the surface tides in Sagami Bay is very weak, below 1 cms^{-1}, except around Oshima Island for both M2 and K1 constituents, while the current amplitude for M2 constituent is over 10 cms^{-1} in the Oshima West Channel. These results will be useful for the analysis of the current data in this study.

3. Current Measurements and Data

The observations were made during the period from July to November, 1996. The mooring stations, as shown in Fig.1, were located in the Oshima West-Channel (ON), on small bank of Okinoyama facing to the mouth of Tokyo Bay (OK), at the eastern coast off

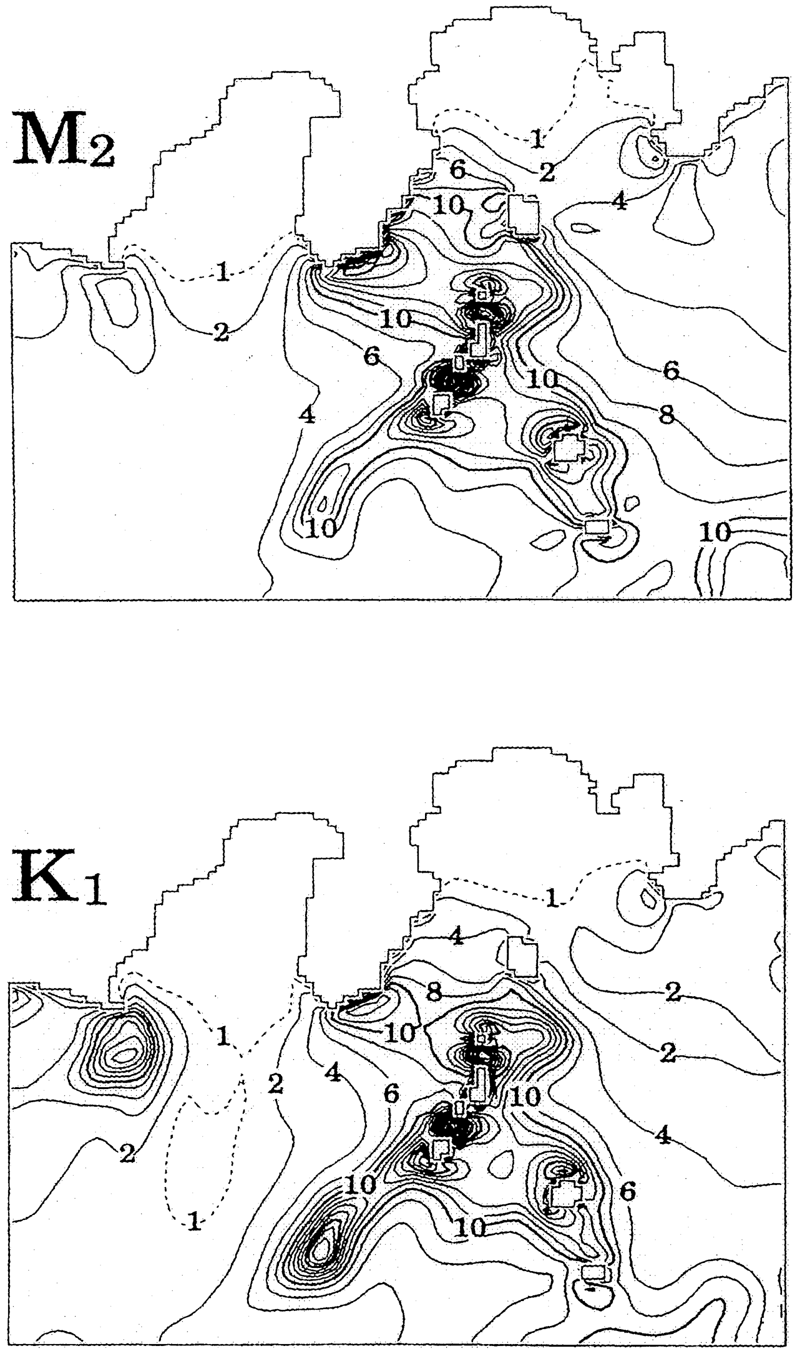

Fig. 2. Tidal current amplitudes for the M2 and K1 constituents for the surface tides estimated by numerical experiments. Contour numerals are in cms^{-1} (after OHWAKI, *et al.*, 1991)

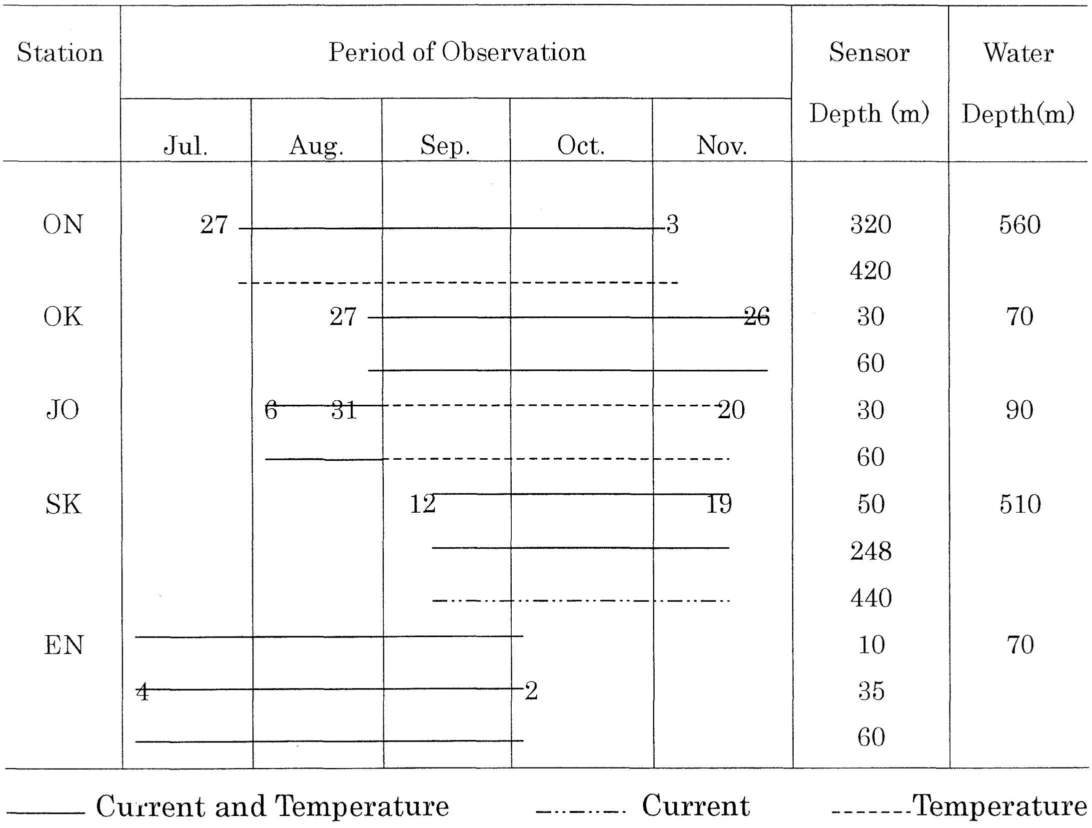

Fig. 3. Mooring information at five stations in Sagami Bay.

Jyogashima (JO), near the center of the bay (SK)and at the northwestern coast off Odawara (EN). The mooring periods and sensor depths for each station are represented in Fig.3. Both ON and SK were located in the deep water, while other three stations were located in the shallow and/or coastal regions. The sampling interval was 30 minutes for ON, OK, JO, SK and 10 minutes for EN. Each record length was different among the stations, so that the starting time and the record length at each station are shown in Fig. 3.

4. Results

Current and Temperature Fluctuations

Although the observation periods were different among the stations, as shown in Fig.3, the observations at the same time were made in the latter half of September, 1996 except JO. Then, for comparison to each other, we show the time series of the current and temperature fluctuations at four mooring stations at the same time during the period from September 15 to September 29 (Figs. 4 and 5). We can find the predominance of tidal period fluctuations in both the current and temperature records at all stations. The temperature at 60m depth abruptly increased at OK, JO and EN on September 22, so that the temperature difference between 30m and 60m depths at these stations became small, *i.e.*, the change of the vertical stratification in the upper layer (Fig.5). As the results, the temperature variations with the tidal periods at 60m depth at OK and JO were slightly small in the latter half of the record in comparison with those in the former half.

The tidal currents in the deep layer of Sagami Bay have rarely reported from the long–term measurements except the study of TAIRA and TERAMOTO (1985). Even they focused on

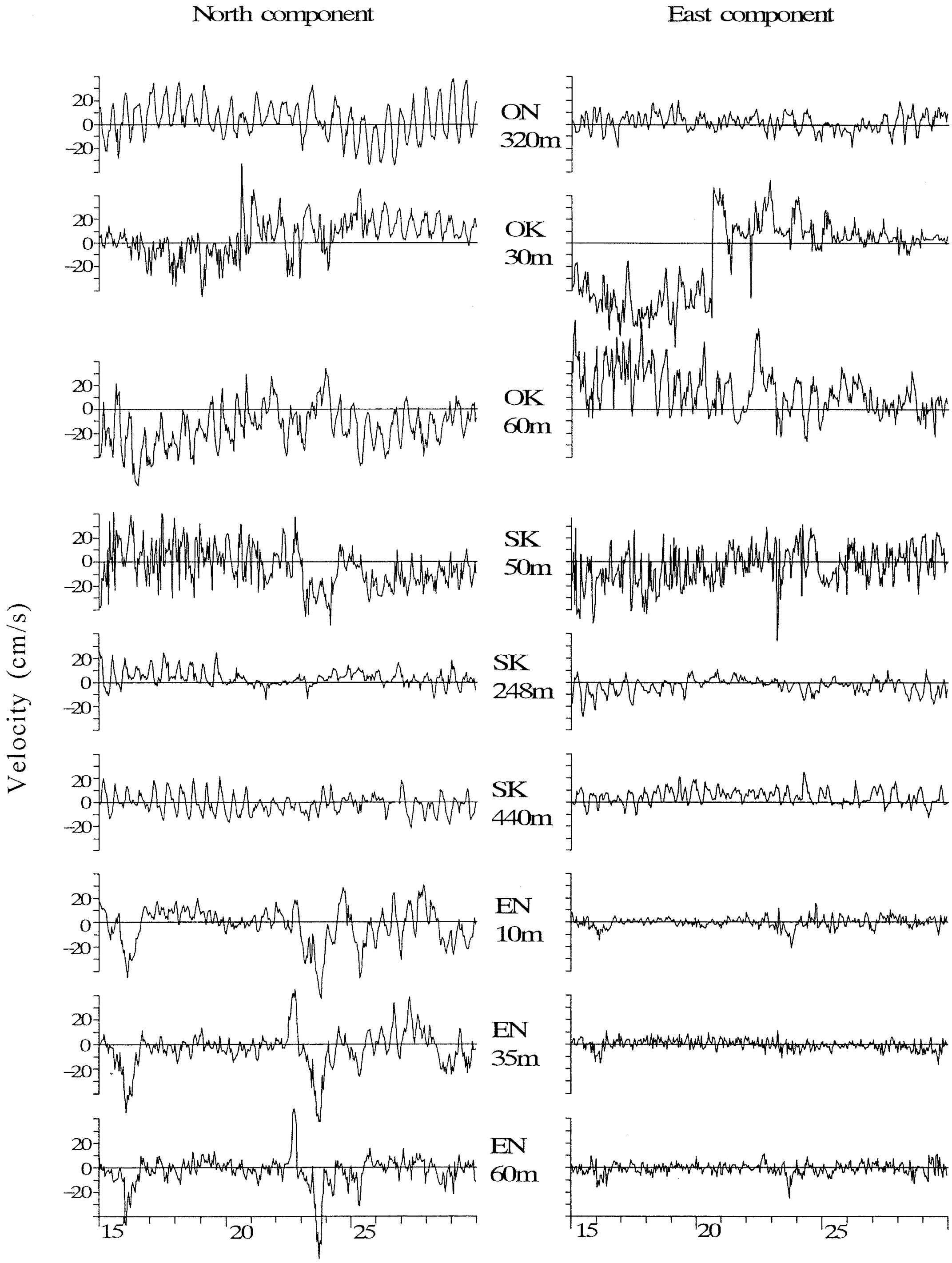

Fig. 4. Time variations of the east and north components of current at four stations during the period from September 5 to September 29, 1996.

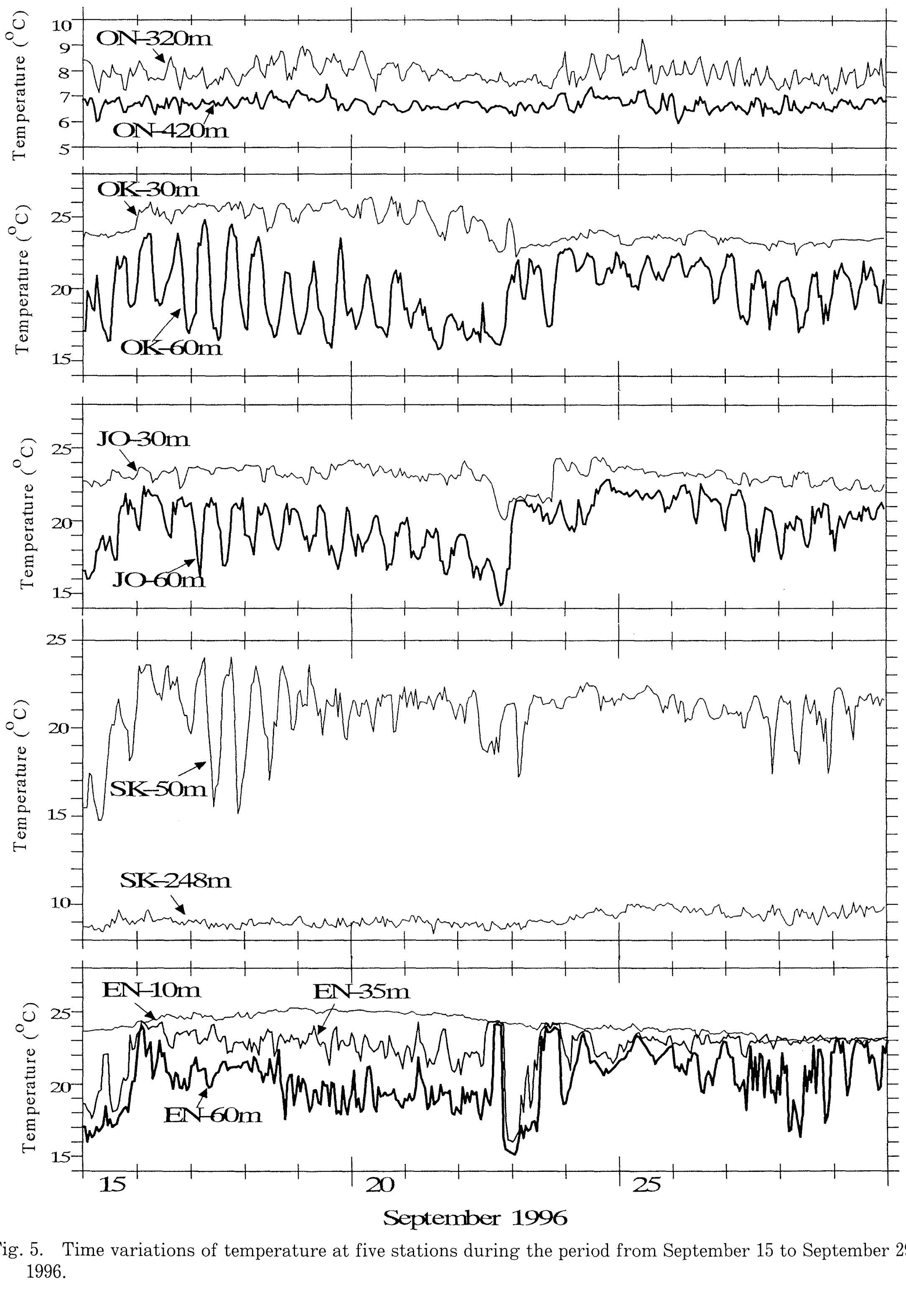

Fig. 5. Time variations of temperature at five stations during the period from September 15 to September 29, 1996.

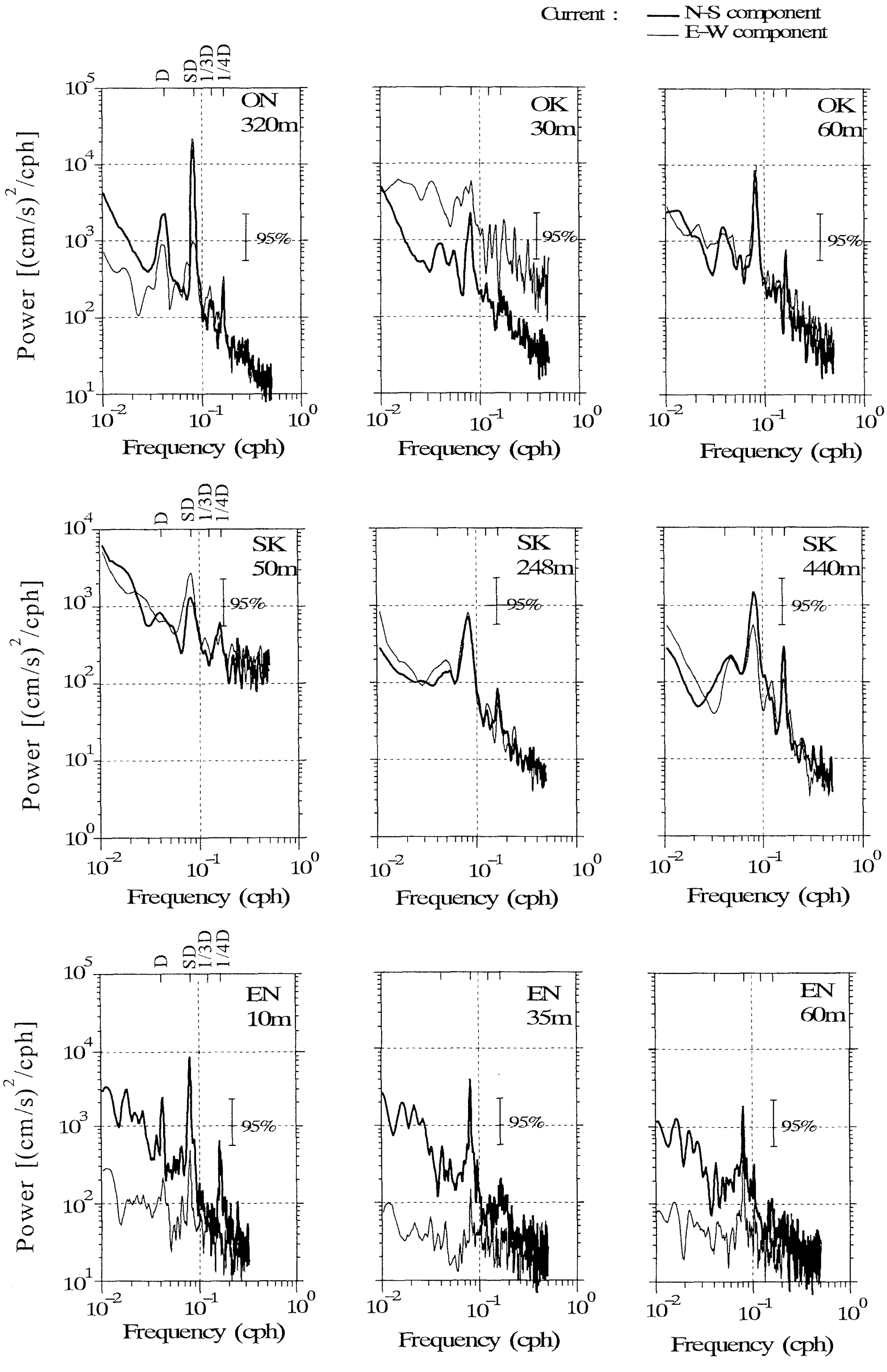

Fig. 6. Power spectra of the current at ON, OK, SK and EN for each period of observation.

the bottom current in the Sagami Trough. Therefore, the current data observed in the deep layer at ON and SK are expected to supply the information of tidal current characteristics. The current data at ON were obtained at 320m depth, but were not obtained for the meter trouble at 440m depth unfortunately. The tidal current at 320m depth at ON was usually over 10 cms^{-1} and the north component of the current dominated over the east component, so the orientation of the tidal current ellipse was almost north–south direction, *i.e.*, the along-channel direction. The temperature records were obtained both at 320m and 420m depths in the same period as the current records. The temperature in the deep layer at ON also shows the remarkable tidal fluctuations, and the high frequency fluctuations also existed at 320m depth during the period from September 24 to 30, 1996.

At SK, located near the center of the bay, the current data were obtained at three depths, *i.e.*, at 50m, 248m and 440m depths and the tidal current amplitude at 50m depth was larger than those at 248m and 440m depths. The current amplitudes were not so different between 248m and 440m depths, and their variations closely resemble each other in this observational period. The temperature fluctuations with the tidal periods at 50 m depth were found through the record, and at times had very large amplitude, while they were very smaller at 248m depth than at 50m depth. The depth dependence of the current amplitude and partial intensification of the temperature fluctuations with the tidal periods suggest the predominance of the internal tides at SK.

The tidal current fluctuations at the station on the bank (Okinoyama Bank)near the bay mouth, OK, had the large amplitude. The current fluctuations included both the several-day period and high frequency period fluctuations together with tidal periods, so the more detailed analysis is required to grasp the characteristics of the tidal current fluctuations. The temperature fluctuations with tidal periods had the large amplitude at 60m depth, while they were not so clear at 30m depth. At JO (Fig.1), as shown in Fig. 3, the current data were not useful for the current meter trouble except those in August, but the temperature data were obtained at both 30m and 60m depths. The temperature records with the tidal periods at 60m depth resemble those at the same depth at OK, but the amplitude at JO was clearly smaller than OK. The amplitude difference of the temperature at the same depth between both stations was expected to be difference of the internal tidal amplitude because the basic stratification was little difference between both stations.

The current and temperature fluctuations at the northwestern part of the bay head, EN, were also shown in Figs. 4 and 5, respectively. The tidal current fluctuations were the significant phenomena at the three depths, and the north component of the current was dominant over the east one. The north component of the current almost agrees with the alongshore direction at EN, so the results indicate the predominance of the alongshore component. The tidal amplitude of the north component of the current gradually decreased from the upper layer (10m depth)to lower layer (60m), that is, the current included the characteristic of baroclinic mode. In addition, the temperatures at both 35m and 60m depths also fluctuated with the tidal periods, so that both temperature records also suggested the existence of the internal tides. The tidal period fluctuations were rarely found in the temperature record at 10m depth at a glance, because the temperature sensor at 10m depth was already set in the surface mixed layer with a weak stratification in the latter half in September.

Statistical Properties

Power spectra were calculated for the current and temperature records at four stations, ON, OK, EN and SK to detect the predominant periods in more detail. Figure 6 shows the power spectra for both east and north components of current at four stations. The current data were obtained at the two or three depths at these stations except at ON. The significant peaks are found at the semidiurnal period in all records, while the peaks of the diurnal period existed at 320m depth at ON, and at 10m depth at EN. The weak peaks at the inertial period (about 20.9 hour)are found at 248m and 440m

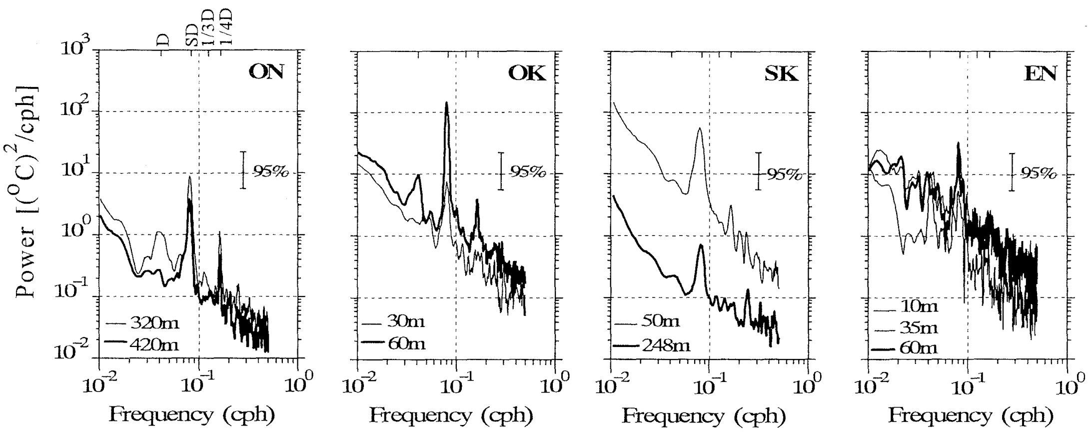

Fig. 7. Power spectra of the temperature at ON, OK, SK and EN for each period of observation.

depths at SK. The phenomenon is expected to be relation to the near-inertial motion. The peak at 1/4 day period existed in all spectra, and was especially remarkable at 320m depth at ON, at 60m depth at OK, at 440m depth at SK and 10m depth at EN.

The current records were obtained at each station in the different observation period, but the records at the different depth at the same station were obtained for the same time. Therefore, it is useful for the comparison of the kinetic energy among the records at the same station. At EN, the energy level of the north component of current with the semidiurnal period gradually decreased with the depth increase from 10m to 60m depths. The peaks at diurnal period and 1/4 day period existed at 10m depth, while it is not found at the two deeper depths at EN. For the semidiurnal period at SK, the east component of current dominated over the north component at 50m depth, but vice versa at 440m depth, and both components were almost equal at 248m depth. The energy level of the semidiurnal current was a minimum at 248m depth among the three observation depths. The results suggest the complexity of the vertical distribution of the semidiurnal current at SK.

Figure 7 shows the temperature spectra at the four stations. The semidiurnal period peak is found in all records, but the energy levels are different from each other at this period. The diurnal period peak is found only at 60m depth at OK, at 10m depth at EN and at 320m depth ON, but is not found at all three depths at SK. located near the center of the bay. The reason of no peaks at diurnal period at the station near the center of the bay is explained as follows; the diurnal internal wave have the characteristic of the internal Kelvin wave, and distance between the station and coast is longer than the internal radius of Rossby deformation (5 to 7km). In addition to it, the diurnal internal wave does not have the large amplitude in Sagami Bay (OHWAKI *et al.* 1994, and KITADE and MATSUYAMA 1997).

The power spectra of both the current and temperature fluctuations indicate the predominance of the semidiurnal period in all records. Then it implies the semidiurnal period fluctuations to be deep relation to the internal tides. The spectra in some records have the peaks at the diurnal period as well. So, it is expected to be a closely relation between the current and temperature fluctuations with not only semidiurnal but diurnal periods.

Table 1 shows the coherence between north and east components of the current and temperature for the diurnal and semidiurnal periods at the same depth at all stations. The coherence at the semidiurnal period is higher than the value of the 95 % confident limit in all case. This result indicates that the current with the semidiurnal period is a closely relation to the temperature, as expected. So the predominance of the semidiurnal internal tide is

Table 1. Coherence between current and temperature.

Station	Observation Period	Depth	Semidiurnal Constituent		Diurnal Constituent	
			east comp.	north comp.	east comp.	north comp.
ON	Jul.27 to Oct.21	320m	0.64	0.82	0.37	0.38
OK	Aug.27 to Nov.26	30m	0.21	0.66	0.43	0.43
		60m	0.79	0.84	0.35	0.35
SK	Sep.12 to Nov.13	50m	0.66	0.19	0.52	0.52
		248m	0.42	0.35	0.29	0.29
EN	July 4 to Oct.2	10m	0.43	0.35	0.52	0.52
		35m	0.62	0.61	0.37	0.37
		60m	0.80	0.78	0.38	0.38

Confidence limit of 95% is 0.39

clarified in the inner region of the bay.

The other hands, the diurnal period is high coherence at 30m depth at OK, 50m depth at SK and 10m depth at EN, so that the diurnal period shows the high coherence in the record of the upper layer only. We do not have the more data to explain the reason of the phenomenon in this paper.

5. Discussion

Predominance of the semidiurnal internal tide

OHWAKI *et al.* (1994) and KITADE and MATSUYAMA (1997) indicated most of the internal wave observed in Sagami Bay are generated at the northern part of the Izu Ridge and propagated into the bay by the numerical experiments as follows. The semidiurnal internal wave are propagated into the bay head, having the characteristic of the internal inertial gravity wave, while the diurnal one can not be propagated into the bay head for having the characteristic of the internal Kelvin wave. As a result, the semidiurnal internal tide dominates over the diurnal period. Both studies also demonstrated the predominance of the semidiurnal internal tide by the observational results in the upper layer in the inner region of the bay.

In this study, the power spectra of the current and temperature data illustrated the predominance of the semidiurnal period in not only the surface layer but also deep layer at all stations as shown in Figures 6 and 7. The predominance of the semidiurnal internal tide implies that the internal tides observed in the inner region of the bay are generated on the Izu Ridge and propagated into Sagami Bay. Our results support the key idea of the internal tides generation on Izu Ridge and propagation into Sagami and Suruga Bays indicated by O HWAKI *et al.* (1994) and KITADE and M ATSUYAMA(1997).

Characteristics of tidal current in Oshima West Channel

In order to comprehend the characteristic of the tidal current ellipse, we calculated the major and minor axis, and orientation of the current ellipse of four major constituents, *i.e.*, M2, S2, K1 and O1 for 29.5 days record at 320m depth at ON. The harmonic constants of two segments, *i.e.*, from August 27 to September 25 and from September 22 to October 21, are shown in Table 2. The M2 constituent is predominant over the other constituents, and the length of the major axis and orientation for M2 constituent were less variable between the two segments. In addition, the other three constituents are also not large different between the two segments. The tidal currents due to the surface tides (Fig. 2) are slightly smaller than the observed current amplitude. These results suggest that the tidal currents observed at 320m depth in the Oshima West Channel are not so strongly affected by the internal tides. The internal tidal currents are expected to have a large amplitude in the Oshima West Channel as indicated by TERAMOTO (1971). Unfortunately, we have no information of the detailed vertical structure of the tidal current in the bay.. We have measured the vertical structure of the tidal current near the center of the bay by the mooring ADCP to investigate the structure of the internal tides.

Table 2. Harmonic constants of tidal current ellipses at ON for 29.5 days period

Period	Depth (m)	Const.	Maj. Axis (cms^{-1})	Min. Axis (cms^{-1})	Orientation (deg.)
Aug.27 to Sep.25	320m	M2	13.2	1.1	7
		S2	5.8	0.1	13
		K1	2.7	0.1	51
Sep.22 to Oct. 21	320m	O1	2.9	0.7	31
		M2	13.1	0.9	5
		S2	7.7	0.6	24
		K1	4.4	0.6	27
		O1	3.2	0.2	34

Tidal currents near the northwest coast of the bay

We obtained the current and temperature records at three depths, *i.e.*, 10m, 35m and 60m depths at EN at the same time during about three month from early July to early October 1996. We do not yet have the data in the three layers except the above ones in this bay, so it is important to investigate the vertical structure of tidal currents. The observations were curried out during the existence of the seasonal thermocline, but the thermocline depth varied for this three months. The observation was made at the steep slope sits near the northwest coast of the bay (Fig. 1). The power spectra of the current and temperature at EN with the semidiurnal period had the significant peaks in all records (Figs.6 and 7). However, the energy level of both current and temperature was different among depths, that is, the current and temperature were the highest energy at 10m depth and 60m depth, respectively. Then we investigate the vertical structure and behavior of the semidiurnal internal wave near the coast, using the data at the three depths at EN.

Figure 8 shows the 25-hours running mean records of temperature at each depth at EN. The temperature records show the abrupt change of the vertical distribution, so that we firstly examine how the difference of the vertical density distribution affects on the characteristics of the semidiurnal internal waves. At second, we investigate the behavior of the semidiurnal internal wave near the coast. Then, we separate the records into three segments as shown in Fig.8, and calculate the harmonic constants of the tidal currents for each segment, which is the record length of 29.5 days.

Figure 9 shows the amplitude of the north and east components of current for the four major constituents, *i.e.*, M2, S2, K1, and O1 constituents. As expected, the M2 constituents are dominant over the other three constituents. We will focus on the M2 constituent. The north component of current was predominant over the east component at each depth. The current amplitude was a maximum at 10m depth in all segments as indicated in the power spectra. The north component of current was the maximum for Period II from early August to early September. Period II agrees with that of maximum value of the mean temperature difference between 10m and 60m depths. The results suggest the magnitude of the current amplitude in the upper layer to be related to the strength of the stratification.

Figure 10 shows the coherence and phase difference between the temperature at 60m depth and the north component of current at each depth. The temperature is useful as an index for expressing the vertical displacement of seasonal thermocline. The temperature at 60m depth was high coherent with the alongshore current at 10m, 35m and 60m depths, and the phase difference was about 180 degrees, that is, the northward current in the upper layer was out of phase to the subsurface temperature. This relation implies the southward current with the downward displacement of the seasonal thermocline, that is, the phase relation implies the southward propagation of the internal waves. Therefore the semidiurnal internal waves propagated to be right the land, near the northwest coast of the bay head. KITADE and MATSUYAMA (1997) indicated the behavior of the semidiurnal internal tide in Sagami Bay by the numerical experiments using a two-

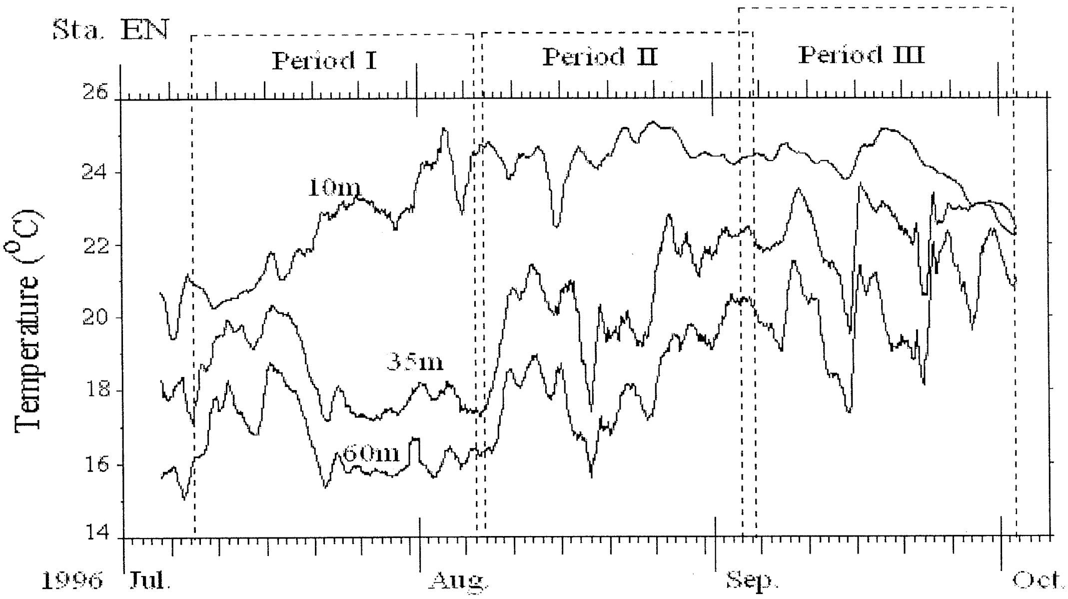

Fig. 8. Time series of 25-hour running averaged of temperature fluctuation at 10m, 35m and 60m depths at EN, during the period from July 4 to October 2, 1996. Divided in three segments : Period I : July 8 to August 6, Period II : August 7 to September 5, Period III : September 3 to October 2, 1996.

layer model. They showed the internal wave to behave an internal Poincare wave near the coast for the reflection at the coast, and for the phase of the internal wave to propagate along the coast as the above results. We can summarize that the behavior of the semidiurnal internal wave observed at EN agree with those of the numerical experiments using the layer model.

The coherence for the diurnal period was high between the north component of current at 10m depth and temperature at 60m depth, and the phase difference was about 180 degrees. As the same as the semidiurnal period, the diurnal period fluctuation also propagated the southward along the coast to be right the land in the upper layer. The diurnal period is over inertial period at this latitude, so the phenomenon behaved as the internal Kelvin wave at EN.

6. Summary

Tidal currents in Sagami Bay were investigated by the long term records of current and temperature obtained at five mooring stations during the period from July to November, 1996. The current data were obtained both in the surface and deep layers at the same time. The time series of the temperature and current records at all stations showed the remarkable fluctuations with tidal periods and power spectra of these records clearly expressed the peaks at tidal periods, especially semidiurnal period. The semidiurnal period fluctuation was predominant over the diurnal one in the current records at all records. The semidiurnal current was high correlation to the current in the all observation depths, while the high correlation between the current and temperature for the diurnal period was limited in the upper layer. The semidiurnal current amplitude depended on the depth. The tidal current amplitudes for the M2 constituent are very larger than ones of the tidal current due to the surface tides (less than $1cms^{-1}$) estimated by the numerical experiments in the inner region of the bay (OHWAKI *et al* ., 1991). Therefore the observed tidal current is considered to be mainly due to the internal tides.

The current and temperature data obtained at three depths (10m, 35m and 60m depths) at EN shows that the tidal current amplitude with semidiurnal and diurnal periods had a

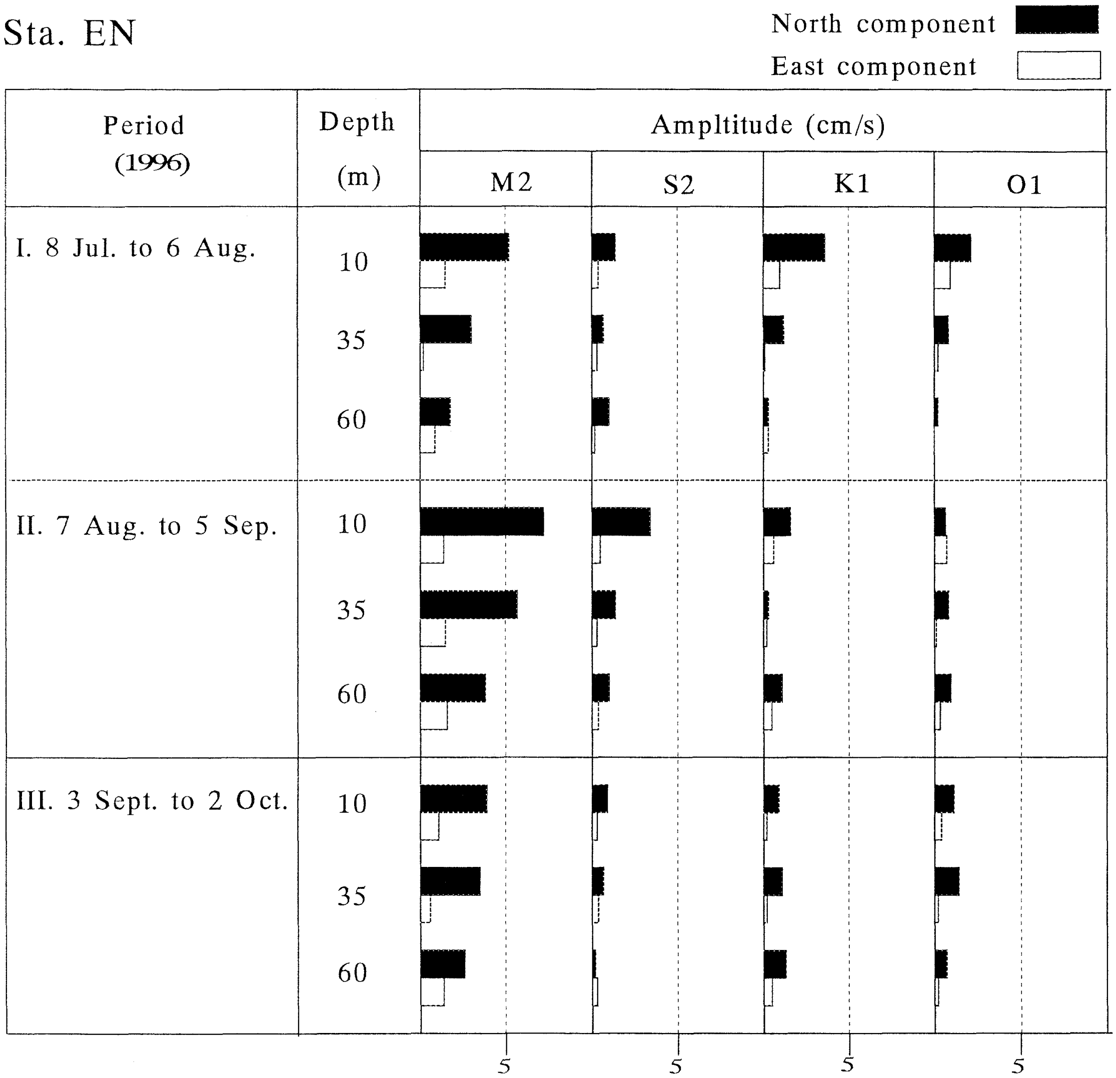

Fig. 9. Amplitude of the north and east components of current for four major constituents at EN for three segments.

maximum at 10m depth and gradually decreased with depth, while the maximum amplitudes for temperature fluctuations appeared at 60m depth. The seasonal thermocline existed slightly under at 60m depth, so that the current fluctuations show high correlation with the temperature fluctuations at 60m depth. The phase relation between the current in the upper layer and temperature in the subsurface layer indicates the internal wave propagation in the upper layer along the coast to be right a hand. These results are consistent with the results obtained by the temperature measurements along the coast and the numerical experiment with a two-layer model (KITADE and MATSUYAMA, 1997). At EN, the diurnal period fluctuations also indicated to be high coherence and phase lag of about 180 degrees between alongshore current at 10m depth and temperature at 60m depth. The diurnal internal wave also propagated the southward along the coast to be right the land in the upper layer, as

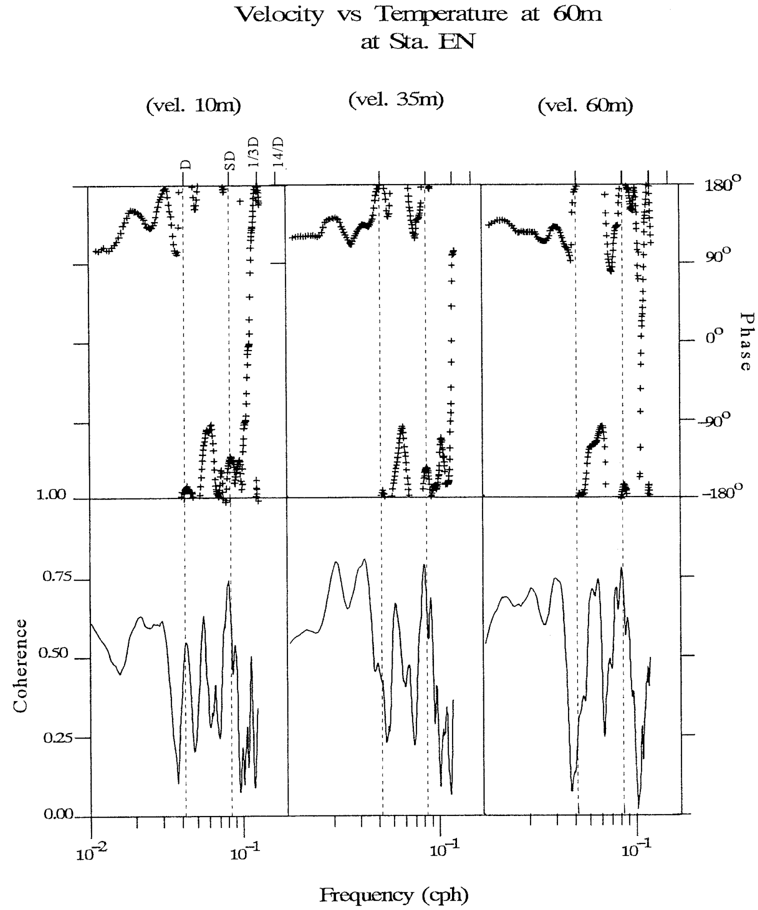

Fig. 10. Coherence and phase difference between the north component of current at 10m, 35m and 60m depths and temperature at 60m depth at EN, during the period from July 5 to October 2, 1996.

having a characteristic of the internal Kelvin wave.

TAIRA and TERAMOTO (1985) observed the currents at the depth of 7m above the sea bottom in the Sagami Trough (water depth of more than 1500m) and showed the tidal current of about 5 cms^{-1} and the energy concentration around the semidiurnal period. The strong deep current due to the internal tides were observed in the bottom layer in the Suruga Trough (MATSUYAMA *et al.* 1993). We are also interested in the bottom tidal current in relation to the internal tides such as Suruga Trough. In addition, we have examined the observations to take the vertical structure of the tidal currents at mooring stations by the ADCP measurements to investigate the detailed characteristics of the internal tides. In near future, the observation results will be offered. We will also examine the numerical experiment with the continuously stratified model both to explain the observational results and to clarify the characteristics of the internal tides in Sagami Bay.

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