La mer 49 : 1-15, 2011
Société franco-japonaise d'océanographie, Tokyo

Observed Turbulence Properties over the Continental Shelf and Slope off Jogashima, Sagami Bay

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Abstract: In order to clarify the characteristics of turbulence and mixing in Sagami Bay, direct measurements of turbulence using Turbulence Ocean Microstructure Acquisition Profiler (TurboMap) were carried out along the ridge west off Jogashima twelve times from June 2007 to October 2010. Turbulence kinetic energy dissipation rate was large near the bottom of shelf edge. In some case, large value of ε was found along a characteristic curve for semidiurnal internal tide emanated from near-critical bottom slope off Jogashima. Since the rate of loss of temperature variance χ_T was in linear relation with ε and almost all of mixing efficiency Γ_T was smaller than unity, the effect of double diffusion was considered to be small in the bay. Eddy diffusivity coefficients of density K_ρ estimated by using constant theoretical value of $\Gamma_T=0.2$, were in O $(10^{-7}$—$10^{-2})$ m^2s^{-1}. Large values of K_ρ were found near the bottom of continental shelf and slope. Monthly average values of turbulent parameter, i.e., ε and K_ρ, were examined and show no clear seasonal variation, except high in summer and low in winter. Since the averaged values of ε show good relation with the surface tidal amplitude time squared value of buoyancy frequency, the internal tides were considered to be one of major energy source of turbulence in the bay.

Keywords: *Turbulence, internal tide, mid-slope mixing, Sagami Bay*

1. Introduction

Recently, turbulent measurements are performed in various areas in the ocean for a reason that turbulence plays an important role on water mass modification. A lot of energy sources and processes are proposed and studied for the generation of ocean turbulence, which is mainly induced by shear instability, wave breaking and vertical convection motion (eg. THORPE, 2007). Turbulence associated with shear instability and wave breaking is frequently observed near the generation area of internal waves, and strong turbulence could be found along the ray path of the internal wave (eg. LIEN and GREGG, 2001). Vertical convection motion induced by cooling is also considered to be an important process for turbulence in surface mixed layer (SMYTH *et al.* 1996). OAKEY (1988) discussed the water modification of Meddy, that is, Mediterranean salty water mass observed in Atlantic Ocean, by terms of turbulent mixing and double-diffusive convection. However, the effect and importance of turbulence on water mass modification in coastal ocean are more complicated due to the existence of bottom topography, freshwater discharged from river and combined effect of various physical phenomena, such as internal wave and coastal upwelling. From the points of the exchange of various materials and fisheries environment, coastal ocean is an important area for human beings. Therefore, it is necessary to make detailed turbulent measurements for clarifying the circulation of various materials in the coastal ocean.

There are many physical processes, which affects water exchange and modification in Sagami Bay, eg. internal tides, surface water circulation associated with the Kuroshio,

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coastal upwelling and coastal-trapped waves induced by wind, and intermediate-intrusion of the Oyashio water, etc. (IWATA and MATSUYAMA, 1989; KITADE and MATSUYAMA, 1997, 2000; KITADE *et al.*, 1998; NURJAYA *et al.*, 1999; SENJYU *et al.*, 1999). These phenomena have a characteristic of baroclinic motion. Especially internal tide and coastal trapped wave are expected to have strong vertical current shear and contribute possible energy source of turbulence in Sagami Bay (Fig. 1). Sagami Bay is a typical deep bay and having narrow continental shelves. Thus the internal tides are generated at the northern part of Izu Ridge and southern part of Boso Peninsula propagated into the bay and reflected at the coast (KITADE and MATSUYAMA, 1997). From theoretical analysis by using narrow continental shelf model, KAWAMURA and KITADE (2007) indicated that the internal tides with higher vertical mode are regenerated by the reflection and/or scattering of the lowest-mode internal tide at the coast and shelf edge. By using a three-dimensional level model, KAWAMURA *et al.* (2005) reported that a beamlike structure of internal wave, which consists of higher-modes of internal waves, is induced at the shelf edge by a scattering of the first-mode internal Kelvin wave. Such a regeneration process of the higher-mode internal wave might be important for the generation of turbulence and mixing. Since the strong horizontal currents associated with internal tide has been frequently observed near the shelf edge off Jogashima, the east of Sagami Bay (eg. KITADE *et al.* 1993), there is a possibility that the scattering of internal tide is induced at the shelf edge. The scattering process of internal tide is considered to cause strong vertical shear of horizontal current.

To clarify the characteristics of turbulence and mixing in Sagami Bay, microstructure measurements were carried out twelve times over the continental shelf and slope off Jogashima from summer of 2007 until autumn of 2010. In this study, we try to present the turbulence properties and its seasonal variability and try to clarify the effects of internal wave scattering on turbulent mixing over the continental shelf and slope.

Table 1. Number of cast at each microstructure measurement station off Jogashima during summer of 2007 to autumn of 2010

Year	Date	Station					
		T1	T2	T3	T4	T5	T6
2007	June 17	1	2	2	3	3	3
	July 9	2	3	3	3	3	2
2008	May 24	1	1	1	1	1	1
	June 14	1	2	2	3	2	2
	July 6	2	2	2	2	2	2
	September 1	1	2	3	3	3	2
2009	December 2*	1	3	3	3	3	3
2010	January 19*	2	2	2	2	2	2
	July 15	1	1	1	1	1	1
	August 28	1	1	1	1	1	1
	September 13	1	1	1	1	1	1
	October 15*	2	2	2	2	2	2

* *accompanied with CTD measurements*

2. Observation and Data

Repeated direct measurements of microstructure were conducted by the TR/V Seiyo Maru (Tokyo University of Marine Science and Technology) off Jogashima, Sagami Bay, from summer 2007 to autumn 2010. During this period, the microstructure observations were carried out twelve times using Turbulence Ocean Microstructure Acquisition Profiler (TurboMAP, by JFE Advantech). Table 1 presents the date and number of cast at each station. To confirm the temperature and salinity data obtained by the TurboMAP, hydrographic observations using Integrated CTD (ICTD; Falmouth Scientific, Inc.) were occasionally performed at the same stations (Table 1). Although our observations were not conducted sequentially in one year, but they covered all season. Most of observations were carried out from early summer to autumn, the seasons when signals of internal tide are expected to be predominant from previous studies. The observation stations are located along a small ridge across the shelf, on 139°29′—139°34′E at 35°08′N, off Jogashima, Sagami Bay (Fig. 1). The length of cross-shelf transect is about 8 km which consists of six stations (T1 to T6). The distances between stations are about 1 or 1.5 minute in longitude. Measurements in one section take about 3 hours, with two or three casts at each station. All survey spanned in different surface tide condition. But in June 2007, we

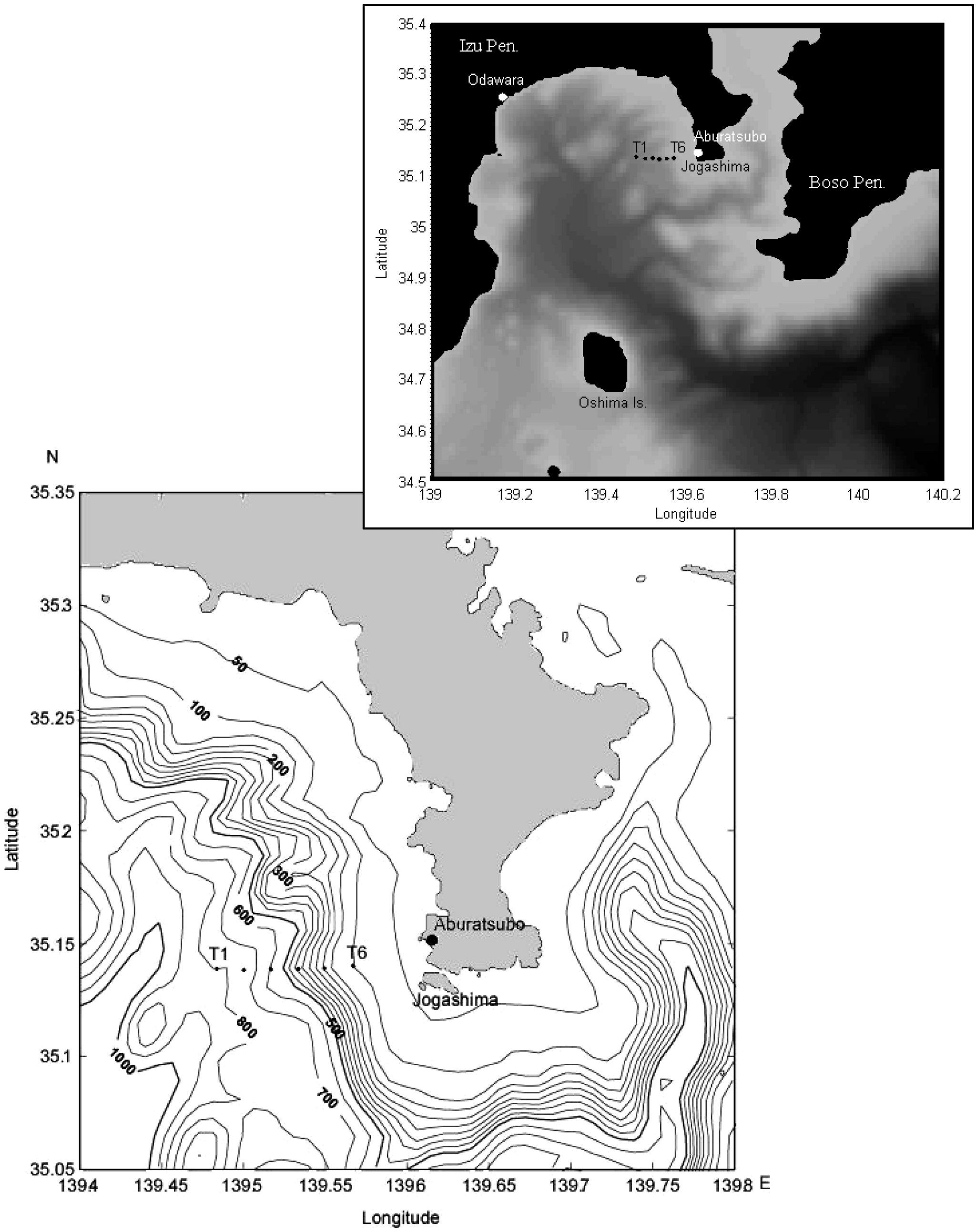


Fig. 1. The observation section (station T1-T6) off Jogashima (inset: shows the location of Sagami Bay). Bathymetric contour derived from JTOPO-30.

were conducted the observation in both flood and ebb tides. The tide condition was obtained from Aburatsubo Tidal Station, near Jogashima.

TurboMAP is a free-falling instrument and its falling speed was adjusted to 0.65 m s^{-1}. The instrument can obtain data of the rate of change of velocity, low-resolution temperature data, conductivity, pressure, three dimensional acceleration and high-resolution temperature data from sea surface to bottom (up to 500 m depth if the water depth is deeper than 500 m). The low-resolution data was obtained by platinum wire thermometer, whereas the high-resolution temperature was obtained by FP07 thermistor. The instantaneous shear du'/dz and temperature gradient dT'/dz were extracted from raw observed shear and temperature gradients data with a high-pass Butterworth filter. The pressure data were filtered with a low-pass Butterworth filter. Turbulence kinetic energy dissipation rate ε was estimated in 5m interval from the variance of vertical shear by the following equation

$$\varepsilon = \frac{15}{2}\nu\overline{\left(\frac{\partial u'}{\partial z}\right)^2} \qquad (1)$$

where ν is the kinematic viscosity ($\nu = 1.27 \times 10^{-6}$ m^2 s^{-1}). Variances of shear were estimated by integrating power spectrum of vertical shear.

In handling of temperature and salinity data obtained by the TurboMAP, we synchronized the response speed of conductivity sensor to that of temperature sensor as well as possible, and then applied a 1-m running mean to the salinity data. After handling the subsequent data processing, we processed the data in 1-m increments. In the case of trouble of conductivity data obtained by the TurboMAP, such as in October 2010, salinity data obtained by ICTD were used in the following data analysis.

3. Distribution and variation of temperature field

Before describing the distribution of turbulence and its property, it is worthwhile to inspect the distribution and seasonal variation of temperature field in Sagami Bay. Figure 2 shows the distribution of temperature obtained at each observation. Observations were carried out along a small ridge with steep bottom slope. The shape of ridge which indicated in the figure is of the shallowest region of the ridge. Since observation were carried out along the ridge extending from the continental shelf with steep bottom slope, water depth of the observation station is occasionally somewhat different from the shallowest part of the ridge. We can see the seasonal variations of temperature field, that is, the seasonal thermocline began to develop from early summer and its depth increased in autumn, and the surface mixed layer deepen in winter. Main thermocline exists at the depth of about 300m in Sagami Bay. In some cases the thermocline shows slightly down to the right, indicating northward current associated with anti-clockwise circulation that is frequently observed in Sagami Bay (Iwata and Matsuyama, 1989). The tilt of thermocline is especially large in July 2010, indicating warm water intrusion. The process of warm water intrusion will be discussed later. Wave-like variations with small horizontal scale, about 3km, are also found in the temperature distribution in upper layer. The distribution of phase and amplitude of the small scale waves implies the contribution of higher mode internal waves.

4. Characteristics of turbulence and mixing

4.1. Distribution of turbulent energy dissipation rate

Figure 3 shows the turbulence energy dissipation rate ε, which is estimated in 5m interval from the shear data obtained by the TurboMAP. The averaged values of ε were indicated in the figure where the vertical profiles of shear were obtained more than once. The ray paths of M_2 internal tide originating from near critical bottom slope, along which strong current shear is expected to be generated, were drawn in the figure. The ray slope, c, is given by $c^2 = (\omega^2 - f^2) / (N^2 - \omega^2)$, where ω is the M_2 tidal frequency (1.4×10^{-4} s^{-1}), f is the inertial frequency (8.5×10^{-5} s^{-1}), and N is the local buoyancy frequency ($N^2 = (-g/\rho)(\partial\rho/\partial z)$, where g is the gravitational acceleration and ρ is the water density) (e.g. Prinsenberg *et al.*, 1974). The internal tide is generated in where the bottom slope matches the slope of ray path for the internal tide. The two slopes match at the shelf edge, around 105—110m depth, and on the continental shelf, at 86—88m depth, suggesting that both sites are favorable for generating M_2 internal tides with strong vertical shear. Near critical bottom slope, that is, $c \approx dh/dx$ (where h is the water depth) existed on the continental shelf and shelf break from spring to fall, but only on the shelf break

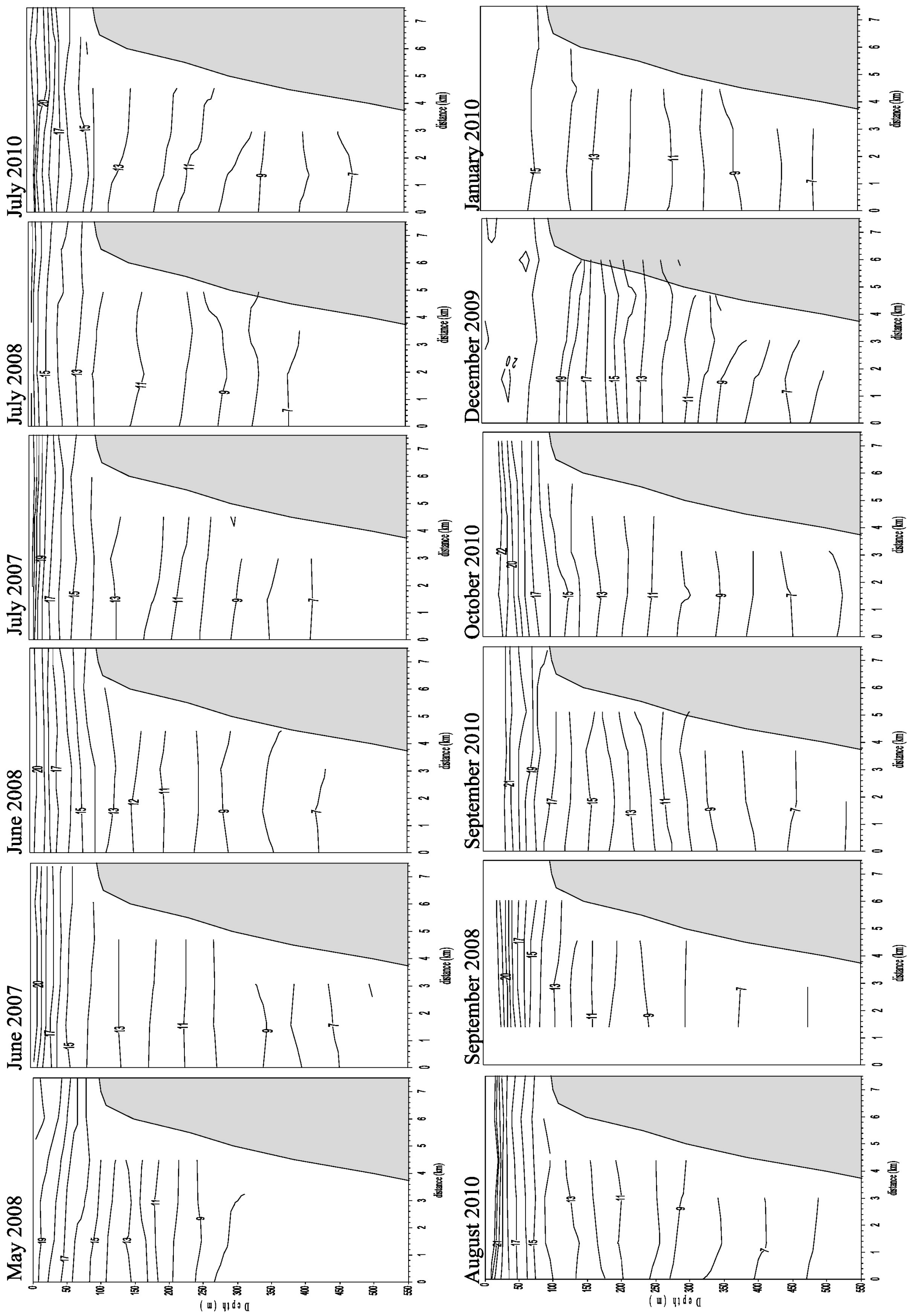


Fig. 2. The distribution of temperature off Jogashima during summer of 2007 to autumn of 2010.

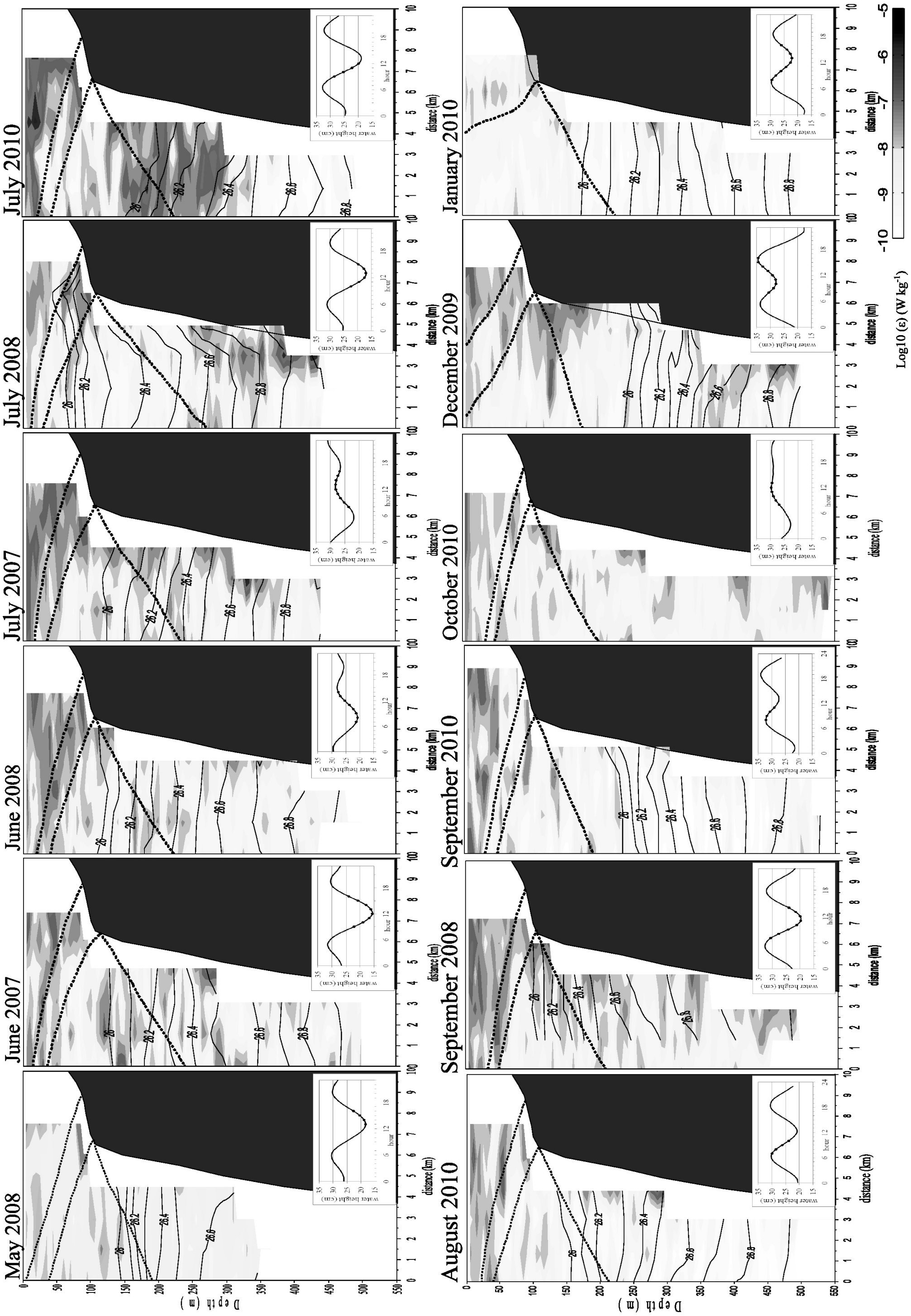


Fig. 3. Distribution of turbulence kinetic energy dissipation rate ε off Jogashima during summer of 2007 to autumn of 2010. White contour lines denote constant potential density σ_θ at interval 0.1 kg m^{-3}. Right lower panels: tidal condition at Aburatsubo during observation

in winter. There are some active turbulence layers over the continental shelf and slope off Jogashima. The strong turbulence layer, $\varepsilon = 10^{-7}$—10^{-5} W kg^{-1}, appeared in the shelf edge around 100-m depth and near the bottom of continental shelf. The other is some of turbulence patches ($\varepsilon = 10^{-8}$—10^{-7} Wkg^{-1}) which showed in a beam-like structure away from the shelf edge to offshore. Distribution of the beam-like structure agrees with ray path of M_2 internal tide in June and July of 2007, June and September of 2008. These results imply that the scattering of semidiurnal internal tide energy near the shelf and shelf break is one of the major processes on the generation of turbulence.

In interior of water column, most of ε shows typical value in open ocean, 10^{-10}—10^{-9} W kg^{-1}, but we have also observed some sporadic patches of strong turbulence ($\varepsilon \geq 10^{-8}$W kg^{-1}). The patchy turbulence is located at different depth in different month. Some of most intense turbulence layer ($\varepsilon > 10^{-6}$W kg^{-1}) also occurred occasionally in 255–440 m depth over the continental slope in June and July of 2007, July and September of 2008, August of 2010. These strong turbulence layers were 100—150 m away from bottom and become stronger in summer. Furthermore, in July of 2010, the value of ε was relatively large in 150–300 m depth of all stations. From the distribution property of ε, these two cases are expected to be caused by other process and/or energy source rather than induced by the scattering of semidiurnal internal tide.

4.2. Relation of ε and χ_T

The rate of dissipation of thermal variance χ_T can be estimated from the data of FPO7 on TurboMAP and is expected to be large at large ε region in stably stratified ocean. This parameter is determined from,

$$\chi_T = 6k_T\overline{\left(\frac{\partial T'}{\partial z}\right)^2} \qquad (2)$$

where k_T is molecular conductivity of heat (k_T= 1.39×10^{-7} m^2 s^{-1}). The $\partial T'/\partial z$ is obtained from instantaneous temperature gradient. In our observation, the falling speed (∼0.65 m/s) of TurboMap was slightly faster than that suitable falling speed for measurement of FPO7

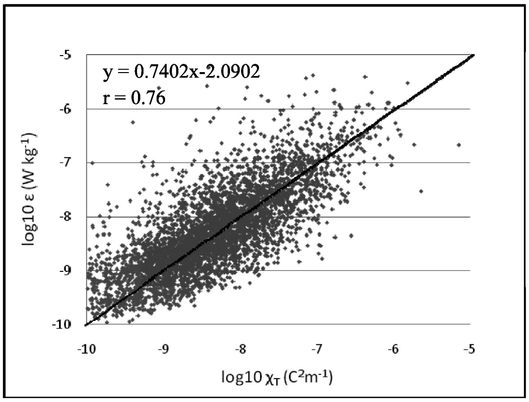


Fig. 4. Scatter plots of turbulence kinetic energy dissipation rate ε and rate of loss of temperature variance χ_T off Jogashima during summer of 2007 to autumn of 2010.

(GREGG,1999), so as the FPO7 data would cause underestimated χ_T value. Therefore, we did not describe the structure of χ_T in detail. The FPO7 data were only used to examine the contribution of double diffusion in Sagami Bay. As discussed by OAKEY, 1988 and INOUE et al. (2007), the contribution of double diffusion is expected to appear in the relation of χ_T and ε, and through the value of mixing efficiency, Γ_T. When we assume $K_\rho = K_T = K_S$ (where K_ρ, K_T and K_S are the diffusivity coefficient of density, temperature and salinity, respectively), the value of Γ_T can be estimated by

$$\Gamma_T = \frac{\chi_T N^2}{2\varepsilon\left(\dfrac{\partial\bar{\theta}}{\partial z}\right)^2} \qquad (3)$$

The value of mixing efficiency has been estimated to 0.25–0.33 in the stably stratified ocean (OAKEY, 1988; MOUM, 1996). On the contrary, the value has been known larger than unity in the case of active double diffusive convection, larger than 1 (OAKEY, 1988; INOUE et al., 2007).

Figure 4 shows the relation of ε and χ_T for all observed data. The relationship of ε and χ_T is almost linear, implying that the effect of double diffusive convection was not significant. Figure 5 shows the frequency distribution of Γ_T for all 5-m grid data by using equation (3). In temporal variation, the Γ_T values varied from 0.02 to 0.25, having relatively small values in summer and large values in winter. A few of

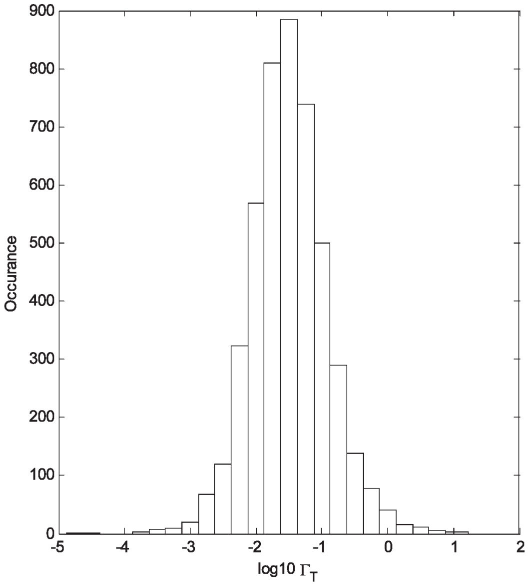


Fig. 5. Histogram of logarithm of mixing efficiency Γ_T of all observed data off Jogashima during summer of 2007 to Autumn of 2010.

large values of Γ_T appeared in weak stratification layer of wintertime. When averaging all observed values of Γ_T, we obtained 0.1. The average value of our observation was less than 0.2 as suggested by OSBORN (1980) literally. However, the reason for the smaller value of Γ_T may arise from our observation method as discussed in GREGG (1999). Namely, the falling speed was somewhat faster than that suitable falling speed, which might with the result in our underestimation of χ_T. Even if we assume that our value was the half of real value of Γ_T, there is a few occurrence frequencies with $\Gamma_T > 0.5$. Consequently, we may say that the effect of double diffusive convection was not significant in the Sagami Bay.

4.3. Distribution of eddy diffusivity of density

Other turbulence parameter, the diapycnal eddy diffusivity was estimated to quantify the strength of turbulent mixing. The diapycnal eddy diffusivity K_ρ is computed from ε, Γ_T and buoyancy frequency by

$$K_\rho = \Gamma_T \frac{\varepsilon}{N^2} \tag{4}$$

(OSBORN, 1980). In the present study, $\Gamma_T = 0.2$ was used because our FPO7 data might be underestimated, besides the $\Gamma_T = 0.2$ is traditionally used in many papers so that convenient in comparing them. Figure 6 shows the vertical section of K_ρ over the continental shelf and slope. Relatively large turbulent diffusivity, $K_\rho > 10^{-4}$ m^{2}s^{-1}, is found near the shelf region in summertime and September 2008. On the other hand, a relatively large turbulent diffusivity is found in the upper layer up to 100 m in winter January. The K_ρ on the shelf edge was in O (10^{-4}—10^{-3}) m^{2}s^{-1}, mostly one order higher than that on the continental slope O (10^{-5}—10^{-3}) m^{2}s^{-1}. The mid-slope mixing signal shows a high K_ρ of order (10^{-2}) m^{2}s^{-1} in July 2008. Even it was weaker in September 2008, K_ρ still in high values (O (10^{-4}—10^{-2}) m^{2}s^{-1}). No beam-like structure of K_ρ as seen on ε. The regions of large value of K_ρ are found near the bottom in many cases. It is interesting that K_ρ is large below 300 m depth and reaches 10^{-3} m^{2}s^{-1}.

4.4. Seasonal Variability of Turbulence

In the present study turbulence parameters were obtained in all season, while observations were not made in every month. In this subsection, we examined the seasonal variations of ε, χ_T and K_ρ (Fig. 7). Monthly averaged values are indicated in the figure. In order to get the common features of variability of turbulence properties, we averaged all depth, above permanent thermocline layer (10–300m), below permanent thermocline layer (more than 300m up to the deepest observation depth) and mid-slope mixing signal found at 255—440m depth of station T3 and T4. Both of ε and K_ρ are the largest in July and smallest in January as a whole. We can see that the ε in Sagami Bay has high level ($>10^{-8}$ Wkg^{-1}) throughout the year except in January. Seasonal variation of K_ρ is also not clear and monthly average values are greater than 10^{-4} m^{2}s^{-1}. The active layer in slope region has the highest averaged-ε and K_ρ compared with others and strong turbulence occurs throughout the year. Besides of the internal tides that significantly observed in summertime in Sagami Bay, mid-slope mixing may also contributes to the mixing process of the shelf edge region.

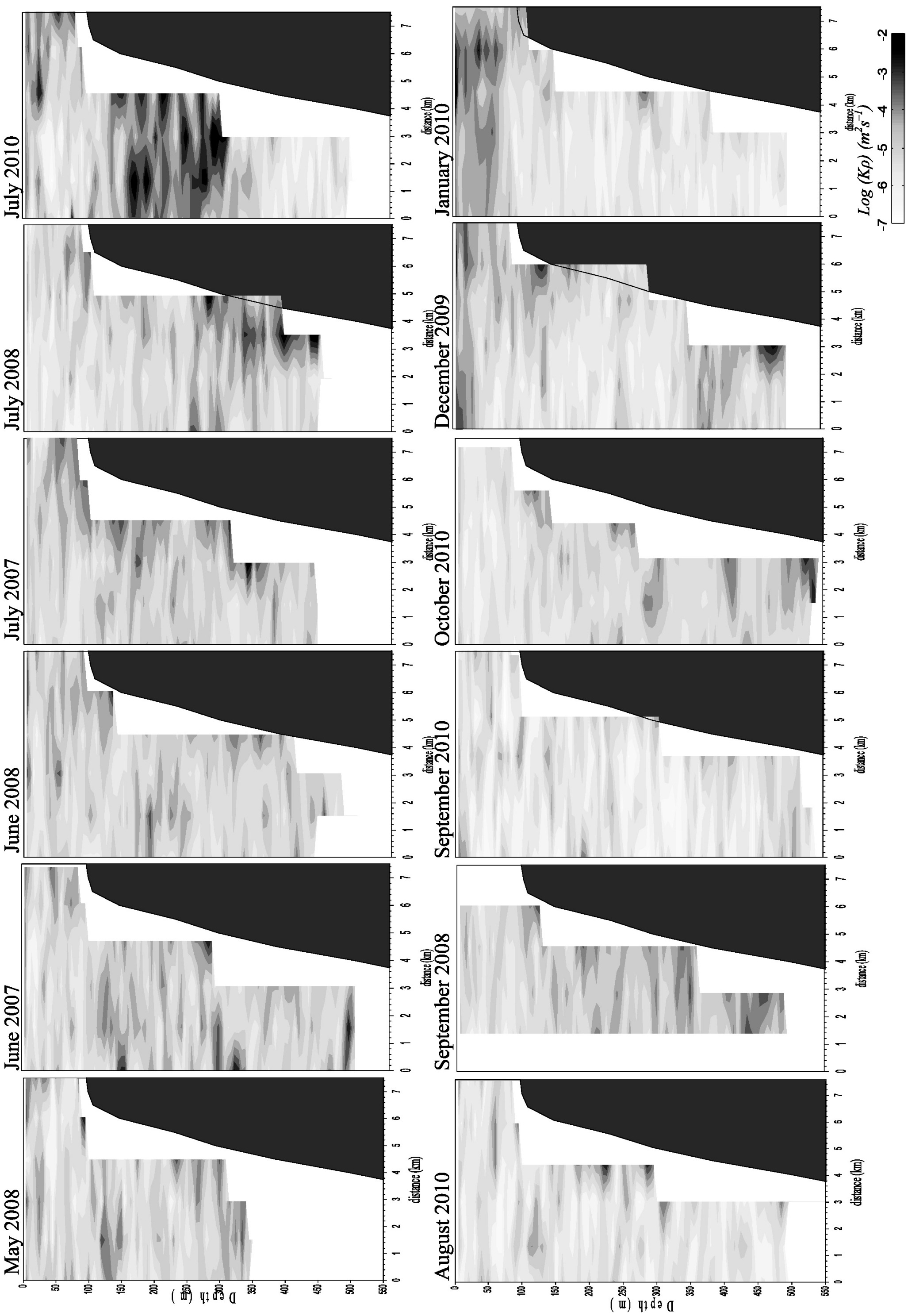
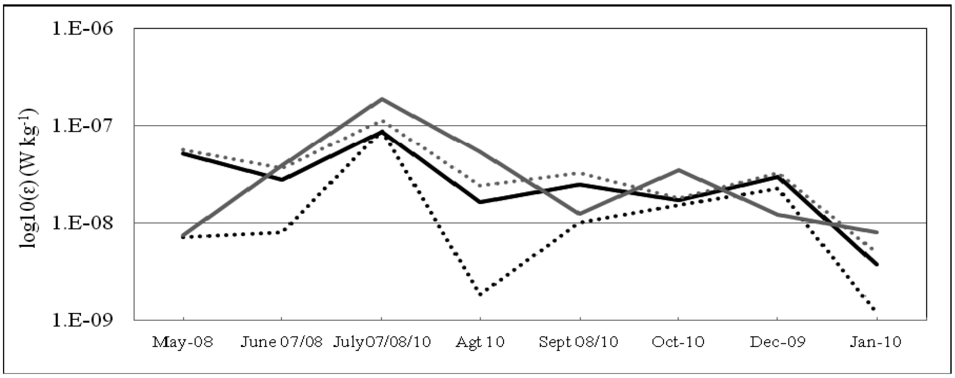
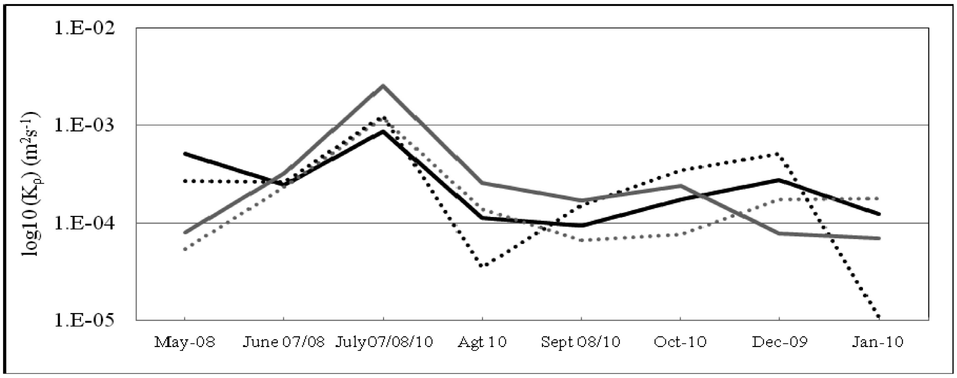


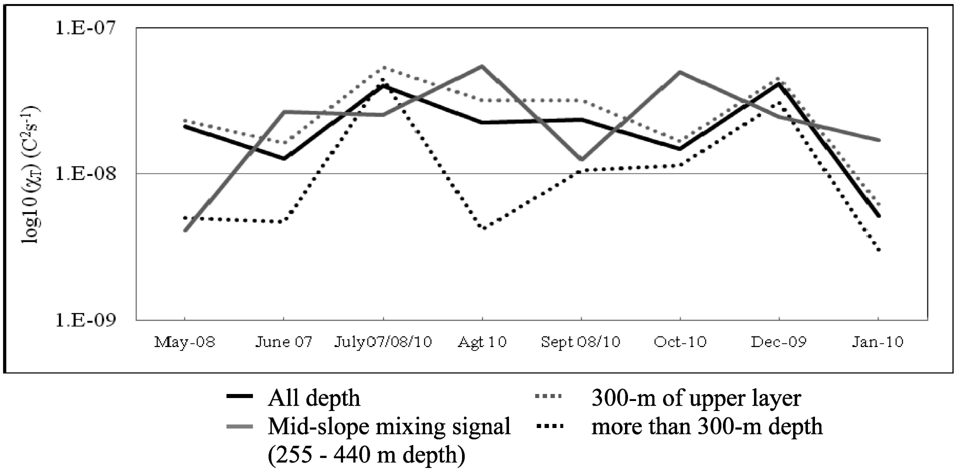
Fig. 6. The distribution of diapycnal eddy diffusivity K_ρ off Jogashima during summer of 2007 to autumn of 2010.



a. Averaged of turbulence kinetic energy dissipation rate ε



b. Averaged of diapycnal eddy diffusivity K_ρ



c. Averaged rate of loss of temperature variance χ_T

Fig. 7. Seasonal variation of averaged turbulence kinetic energy dissipation rate ε, diapycnal eddy diffusivity K_ρ and rate of loss of temperature variance χ_T off Jogashima during summer of 2007 to autumn of 2010.

Table 2. Tidal amplitude and buoyancy frequency during June of 2007 to October of 2010

Month	May	June		July			August	September		October	December	January
Year	2008	2007	2008	2007	2008	2010	2010	2008	2010	2010	2009	2010
Tidal amp. (m)	0.616	0.795	0.435	0.448	0.704	0.767	0.519	0.652	0.633	0.399	0.813	0.626
N^2 throughout water column (s^{-2})	6.82E-05	6.83E-05	6.11E-05	8.67E-05	8.12E-05	7.74E-05	8.70E-05	1.18E-04	7.95E-05	7.70E-05	5.81E-05	2.63E-05

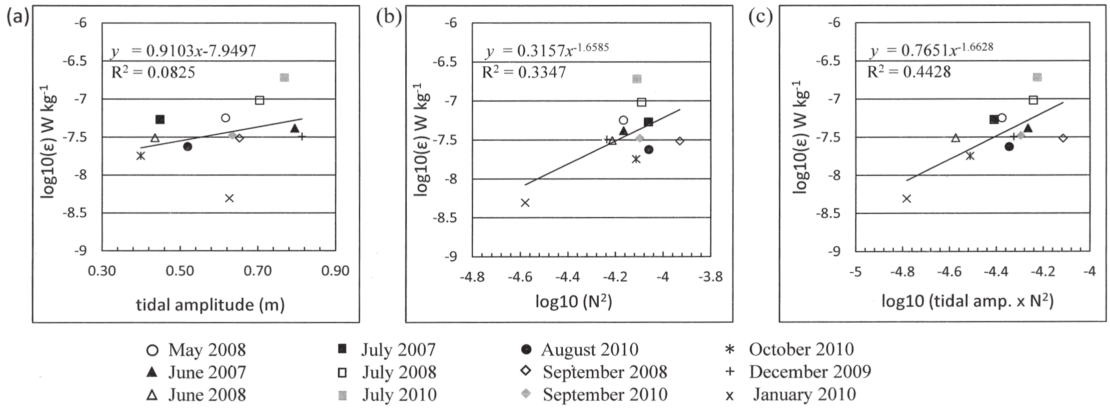


Fig. 8. Scatter plots of averaged turbulence kinetic energy dissipation rate ε against Tidal amplitude (a), N^2 (b) Tidal Amplitude x N^2 (c) in upper 300 m layer off Jogashima during summer of 2007 to autumn of 2010.

Consequently, we may say that the turbulence parameters in Sagami Bay depend on oceanographical condition of observational period rather than seasonal variation. To investigate the cause of variation of turbulence properties, we have examined the physical background which potentially contributes to observed variability in the following section.

5. Discussion

Semidiurnal internal tide in Sagami Bay is frequently observed in summer and its generation area has been considered at the northern part of Izu Ridge and the shallow region off southwest of Boso peninsula (KITADE and MATSUYAMA, 1997). The internal tides are expected to reflect and scatter at the continental shelf off Jogashima at the mouth of Sagami Bay. From the microstructure measurement along the small ridge off Jogashima in Sagami Bay, a beam-like structure of active turbulence patch was found to be following the ray path of M_2 internal tides which is originating from continental shelf. Thus, the beam-like structures of the active turbulence patch were considered to be regenerated by the scattering of internal tide at the shelf edge off Jogashima. These results imply that an internal tide is one of the major energy sources of turbulence in Sagami Bay. However, energy dissipation rate ε was not so large in August, while the seasonal thermocline was strengthened and the internal tidal energy was expected to be large in summer. The reason of the low ε observed in August may relate to tide age, that is, spring and neap tidal cycle. Therefore, in this sub section, relationship between ε and effects of internal tide were tried to be examined. Unfortunately, no current data are available during the microstructure survey, in which internal tide property can be obtained. Therefore, the sea level data and stratification condition were analyzed and compared with the strength of turbulence.

Table 2 presents tidal amplitude estimated from sea level difference in one day including the observation period. The tidal amplitude ranges was vary from 0.40 to 0.81 m while the observation has been conducting. Figure 8 (a) and (b) show relation between amplitude of sea surface displacement and ε, and buoyancy frequency and ε in the permanent thermocline layer (10 to 300m depth), respectively. However, the tidal amplitude might not enough to

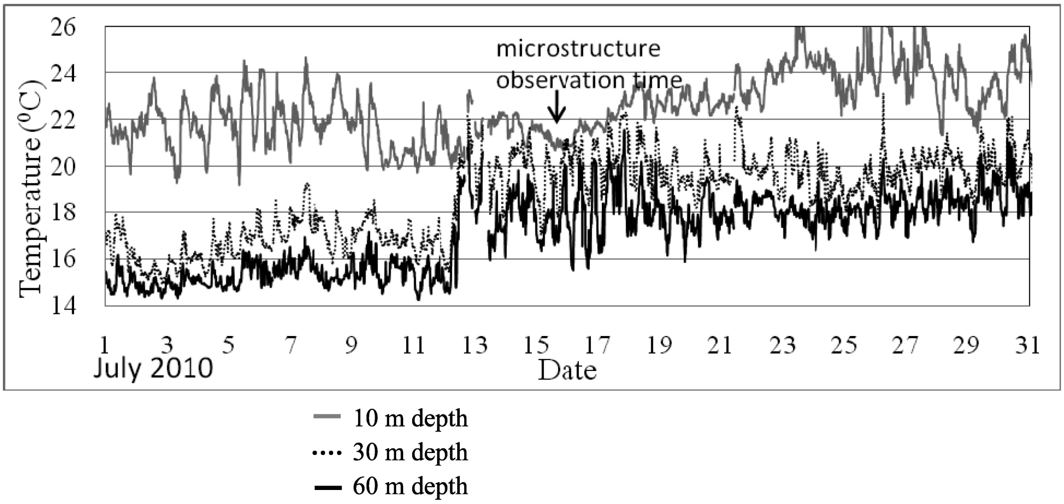


Fig. 9. Time variations of temperature obtained at monitoring station off Odawara in July 2010. Water depth of the monitoring station is 65m. The date started at 0:00.

explain the variation of turbulence. There is a linear relation between buoyancy frequency and ε, and correlation coefficient is about 0.58. Forcing from surface tide to internal tide is expressed by the forcing term F as follows (e.g. BAINES, 1982),

$$F = -\frac{QN^2}{\omega}\frac{zh'(x)}{h^2}\sin\omega t \qquad (5)$$

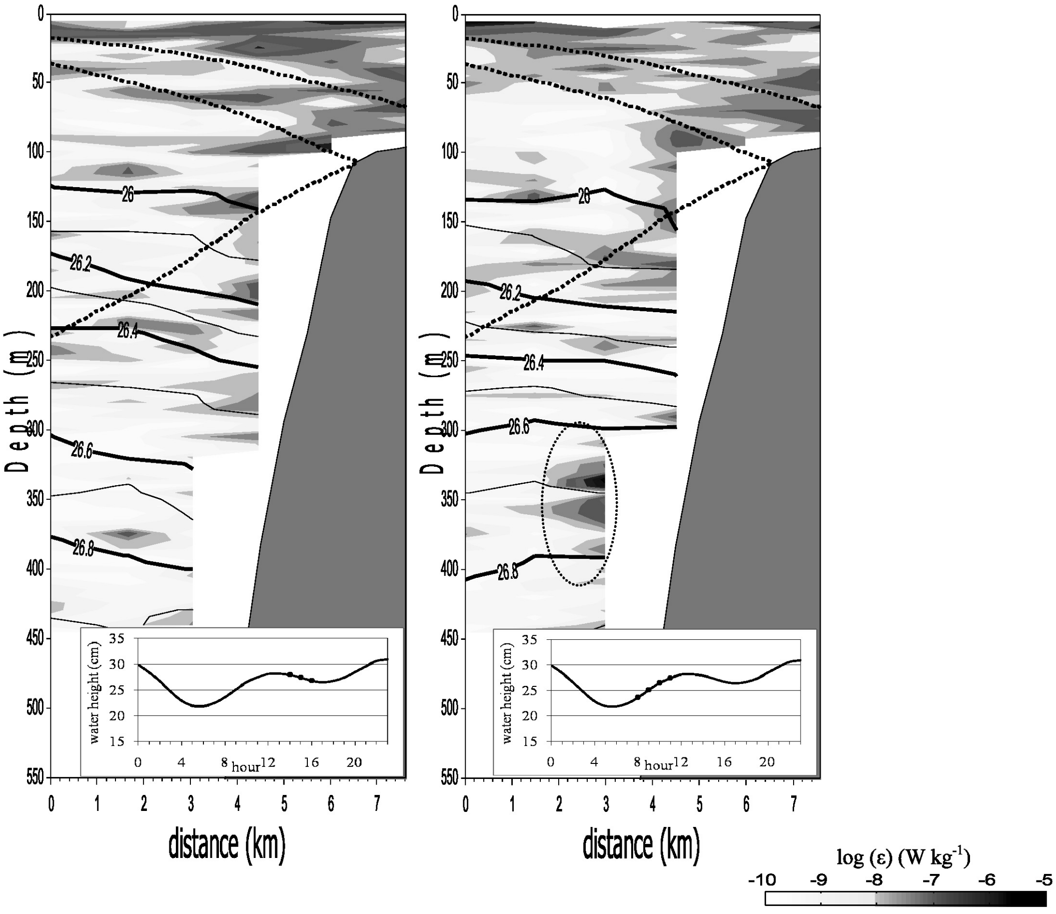
where ω is the frequency of forcing, h and h' are the water depth and its horizontal gradient, and Q is mass flux by surface tidal current and expressed by $Q = u_0 h$ (where u_0 is the amplitude of barotropic tidal current over the topography), respectively. Generation area of internal tides in Sagami Bay is the northern part of Izu Ridge and the shallow region off southwest of Boso peninsula. We cannot easily separate the contribution of each generation area. However we can expect that the forcing term (5) affects on generation of internal tides in the same way at each generation site every time. Furthermore, barotropic tidal current is considered to be proportional to sea surface elevation. Thus we can expect that the amplitudes of internal tides, A_{internal}, is proportional to the value of N^2 times amplitude of sea surface displacement, A_{surface}, as follows,

$$A_{\mathrm{internal}} \propto N^2 Q \propto N^2 A_{\mathrm{surface}} \qquad (6)$$

Hereinafter we call $N^2 A_{\mathrm{surface}}$ index of forcing.

We found an increasing of correlation coefficient of linear regression ε with the index of forcing (Fig. 8 (c)). Correlation coefficient of 0.67 is higher than the 5% significant level. These results indicate that internal tides are one of the major energy sources of turbulence in Sagami Bay.

However, ε obtained in July 2010 was one order in magnitude larger than that obtained in the other periods. The reason of such an extremely active turbulence is considered to be associated with strengthen of anti-clockwise circulation in Sagami Bay, because the density surface in main pycnocline tilted in the active turbulence layer. Variations of surface circulation in the bay have been studied by IWATA and MATSUYAMA (1988) who explained that it related to the variation of the Kuroshio. The intrusion of Kuroshio water into the Sagami bay in July 2010 can be seen through the temperature time series data obtained off Odawara (Fig.9). The warm water started came into the bay two days before the microstructure observation time (indicated by arrow in Fig.9), specifically in deeper depth (60 m depth). The warming took place in long term and fluctuated with large tidal amplitude. Thus, both effects of current shear associated with the warm water intrusion and amplified tidal fluctuation are expected to be important for the strong



(a) Ebb condition (b) Flood condition

Fig. 10. Distribution of kinetic energy dissipation ε in ebb tide (a) and flood tide (b) of July 2007. Lower panels : tidal condition at Aburatsubo during observation.

turbulence in July 2010. However, it is difficult to separate each effect and discuss each process in detail by the present our data set.

Finally, we should pay attention to the active turbulence layer which found at deep part near the slope region, that is, the intense turbulence layer ($\varepsilon > 10^{-6}$W kg^{-1}) occurred at the depth from 255 m to 440 m over the continental slope in June and July of 2007, July and September of 2008, and August of 2010. Since the barotropic tidal current in Sagami Bay is very weak, it is difficult to explain that the mid depth strong turbulence is directly caused by the barotropic tidal current. One possible mechanism is the internal hydraulic jump induced by internal tidal current. LIEN and GREGG (2001) showed the strong mid-depth mixing layer induced by internal hydraulics as a result of along shore currents flowing across the fan ridge. In internal hydraulic turbulence, the strong turbulence path shifted to both sides of obstacle during different surface tide. To confirm the structure of intense turbulence layer in detail, we present two sections of ε in July 2007 as shown in Fig. 10, which have been discussed before in the averaged fields in Fig. 3. In July 2007, we conducted 2.25 hours observation in rising tide and 2 hour later, continued to 2.25 hours observation in falling tide. We found the active layer occurred only when the surface tide was rising (Fig.10 (b)). From comparison of Fig.10 (a) and (b), we can see that the mid-slope mixing signal is accompanied by elevated isopycnal surface of σ_θ 26.6 –26.8. The variation of the isopycnal surface reaches 15 m in vertical within about four hours. These results led us to suggest the possibility of turbulence controlled by the internal hydraulic caused by internal tidal current at the small ridge off Jogashima in Sagami Bay. However, to clarify the mechanism of active turbulence layer which has been found in the mid depth, it is necessary to carry out detailed observation along the shelf including deployment of current meter mooring.

6. Summary

Direct measurements of turbulence using TurboMap were carried out along the ridge west off Jogashima in Sagami Bay twelve times from June 2007 to October 2010. Turbulence kinetic energy dissipation rate ε was large near the bottom of shelf edge. In some case, large value of ε was found along a characteristic curve for semidiurnal internal tide emanated from near-critical bottom slope off Jogashima. These results imply that the scattering of semidiurnal internal tide energy near the shelf and shelf break is one of the major processes on the generation of turbulence.

The effect of double diffusion was considered to be small on mixing process in the bay. It is inferred from linear relationship between the rate of loss of temperature variance χ_T with ε and almost all of mixing efficiency Γ_T was smaller than unity. The distribution of K_ρ is different from ε, where large values of K_ρ was found mostly near the bottom of continental slope and no large K_ρ along the characteristic curve for semidiurnal internal tide.

No clear seasonal variation in monthly average values of turbulent parameter ε and K_ρ, except high in summer and low in winter. The averaged values of ε show good linear relation with the surface tidal amplitude time square of buoyancy frequency. Therefore, we considered internal tides as one of the major energy source of turbulence in Sagami bay.

The effect of warm water intrusion on turbulence mixing is shown in July 2010, where the large value of ε was found in thermocline layer of all stations. From present observation, the possibility of internal hydraulic jump was appeared. We have found shifted strong turbulence signal in middepth associated with tidal fluctuation which accompanied by elevated isopycnal surface of σ_θ 26.6—26.8. However, it is difficult to describe the detail of mechanism because of the snap short observation. It is necessary to performs detailed observation along the shelf and deploys mooring observation. Therefore, together with other strong turbulence layer which is found in July 2010, will be our future study.

Acknowledgement

We wish to thank Drs. Yuji KAWAMURA, Masao NEMOTO and Daisuke HIRANO for their help in caring out the observation. We also wish to thank captains and crews of TR/V Seiyo-Maru of Tokyo University of Marine Science and Technology.

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Received: April 4, 2011
Accepted: July 1, 2011