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Warm water structure that approaches to Kii Peninsula, separated from the straight zonal Kuroshio Path

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Abstract : The warm Kuroshio water approach to Kii Peninsula which separates from coastal (northern) side of the straight zonal path and shifts along the eastern coast of the peninsula is frequently observed by the satellite thermal infrared imagery. Fortunately, we could observed the Kuroshio water approach to Kii Peninsula by Training Vessel "Seisui-maru" of Mie University in November 1997. The CTD and ADCP observations were carried out and the northward shift of the warm water along eastern coast of Kii Peninsula was observed. The main results of the observation is reported in this paper. It is detected that the warm water has a shallow thickness less than 50 m. The warm water shift to northeastward along the eastern coast of Kii peninsula with a velocity of 30 cm sec^{-1}, which agrees with those of Kimura and Sugimoto (1993, 2000) observed by direct current measurements. The observed northeastward velocity also agrees with that evaluated from satellite infrared imagery. It is suggested the velocity of 30 cm sec^{-1} along the eastern coast of the Kii Peninsula is mainly due to the westward velocity given in the separation process from the mean flow of the Kuroshio.

Key words : *Warm water separation, warm Kuroshio water tongue, Kii Peninsula*

1. Introduction

There have been various observations on the approach of the warm water separated from the Kuroshio to Kii Peninsula (TAKEUCHI, 1989; KIMURA and SUGIMOTO, 1987, 1990, 1993, 2000; SEKINE *et al.*, 1991; KASAI *et al.*, 1993). It is pointed out by SEKINE *et al.*, 1991 that the warm Kuroshio water approaches to the eastern coast of the Kii Peninsula are classified into four types; the shallow warm streamer around the large cold water mass of the Kuroshio, the water tongue and the large detached warm eddy, both of which comes from the main axis of the Kuroshio, and the main axis of the Kuroshio. They also show that the warm water approaching to the eastern coast of Kii Peninsula is furthermore classified into two types by its thickness. One type is thinner than 100 m, which corresponds to the warm streamers and the warm water tongues. Another type is thicker than 200 m, which corresponds to the main Kuroshio axis and the large warm eddies detached from the main axis of the Kuroshio.

It is also commonly shown by KIMURA and SUGIMOTO (1990) and SEKINE *et al.*, (1991) that the way of the approach of the warm water depends on the bimodal path of the Kuroshio. In periods of the large meander path, separated warm water is mainly formed in western side of the Izu Ridge south of Izu Peninsula and it shifts westward. In this case, the warm eddy approaches to Kii Peninsula from east and it shift southward along the coast of Kii Peninsula. Conversely, in periods of non-large meander path, as the main Kuroshio path runs zonally south of Kii Peninsula, the warm water comes from south and shifts northward.

Recently, KIMURA and SUGIMOTO (1993) showed that the spectrum of the current velocity by direct current measurements off Kii Peninsula has a dominant periods of 17–19 days with a wavelength of 400 km and a phase

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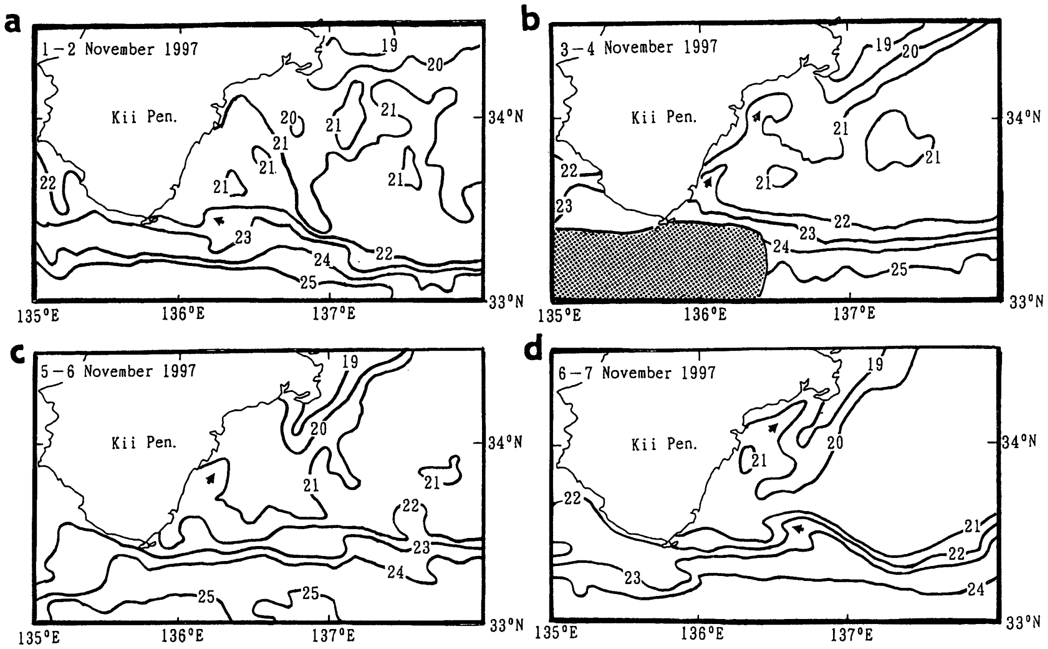

Fig. 1. SST (℃) shown by NOAA AVHRR composite on November (a) 1〜2, (b) 3〜4, (c) 5〜6 (6.13 AM) and (d) 6 (14.02 PM) 〜7, 1997. Small arrows indicate direction of the shift of the warm water, estimated by the comarison of the sequential imagery map of SST. Stipple area in (b) shows the cloud area.

velocity of 26 cm sec^{-1}. Furthermore, KIMURA and SUGIMOTO (2000) showed that there exists a phase velocity of 3 m sec^{-1}, which is estimated as a topographic Rossby wave. Since there exist many processes in the movement of the warm eddy detached from the Kuroshio, their classification and dynamics have not been well understood.

To know the dynamic process of the warm eddy detached from the main axis of the Kuroshio, detailed internal structure of the warm Kuroshio water should be observed more clearly. In this context, we can luckily observe a warm water approach to the Kii Peninsula by use of Training Vessel "Seisui-maru" of Mie University on 5–6 November, 1997. Composite of the satellite imageries of thermal infrared by NOAA 12–14 before and during the observation are shown in Fig. 1. Although repetition of the approach of the warm water is suggested on 1–4 November, a new warm water approach which is indicated by isotherm of 21℃ occurs on 5–6 November and it shifts northeastward along the eastern coast of the Kii Peninsula. We have observed this warm water off Kii Peninsula by use of CTD and ADCP and its oceanic structure has been clarified. Therefore, we presents the main results of the observation in this paper.

Details of the observation of the present study are described in the next section. The results of the observation are given in section 3, with a discussion in section 4.

2. Observation

CTD (Mark Ⅲ System of Niel Brown Instrument Systems, Inc.) observations along the observational lines shown in Fig. 2. were made by use of the Training Vessel "Seisui-maru" of Mie University during 5–6 November 1997. Three offshore observational lines are set off Kiinagashima, Owase Bay and Kata Bay, to observe the cross section of the warm water mass. The CTD observational points are placed every one nautical mile at the nearshore region and more two nautical miles at the offshore region. In order

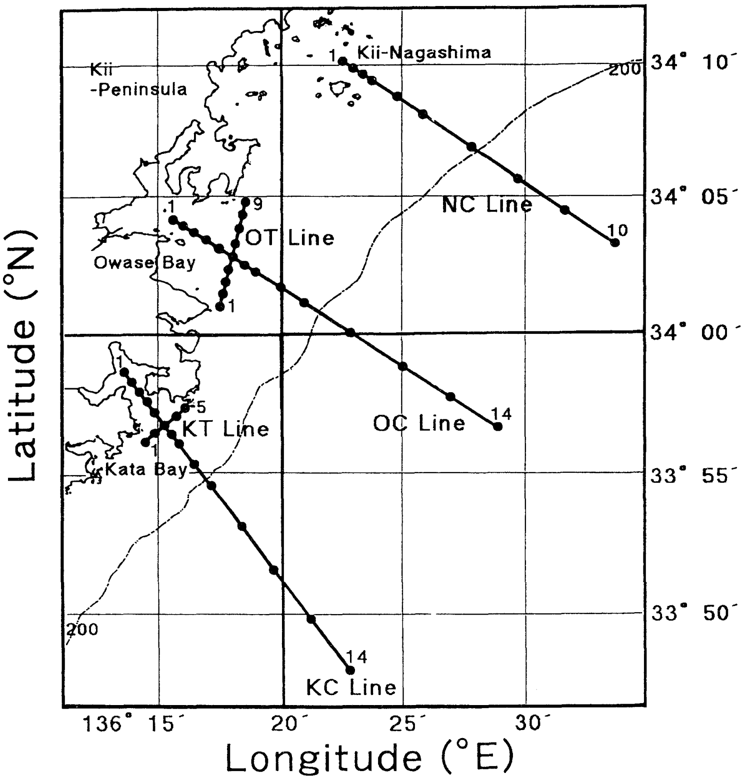

Fig. 2. Observational points and lines of CTD of the present study on November 5-6, 1997.

to see the influence on the oceanic condition of Owase Bay and Kata Bay, alongshore observational lines are set, which are referred to as OT line and KT line, respectively. ADCP observations at depths of 10m, 50m and 100m were also carried out along these observational lines.

CTD observation began at Station 1 of NC line (Fig. 2) at 5 PM on 5 November and that of the station 10 ended at three hours later. The observation of OC line began at 20.5 PM of the same day from the station 14 to the station 1, and ended at 12 PM. The observation of KC line began at 2 AM on 6 November from the station 14 to the station 1 and ended at 7.5 AM. In next, CTD observations along the observational lines off the Kata Bay (KT line) were carried out from 8 AM at Station 1 and it took 30 minutes. The observation of OT line began at 9 AM from the station 1 and ended at 10 AM at the station 9. Checks of the observed CTD data in comparison with standard salinity water were carried out at three observational points with about 10 layers and the worst-case accuracy of the observed CTD data was found to be 0.02 psu.

3. Results

Observed temperature, salinity and density (σt) fields along three offshore observational lines are shown in Fig. 3. As is indicated from Fig. 1, the warm Kuroshio water warmer than 21℃ is detected at the KC line (Fig. 3c). The warm water is also seen at OC line and NC line with a maximum temperature of 20.25℃. A saline water more than 34.45 psu is found at the KC line (Fig. 3c), however, such a saline water does not exist in other two lines of OC and NC (Fig. 3ab). Although the tongueshaped intrusion of the warm water is commonly suggested in three observational lines, the salinity is different between KC line and lines OC and NC. The CTD observations along NC line and OC line were carried out on 5 November, while the observation of KC line was made on 6 November (for details, see section, 2). It is suggested

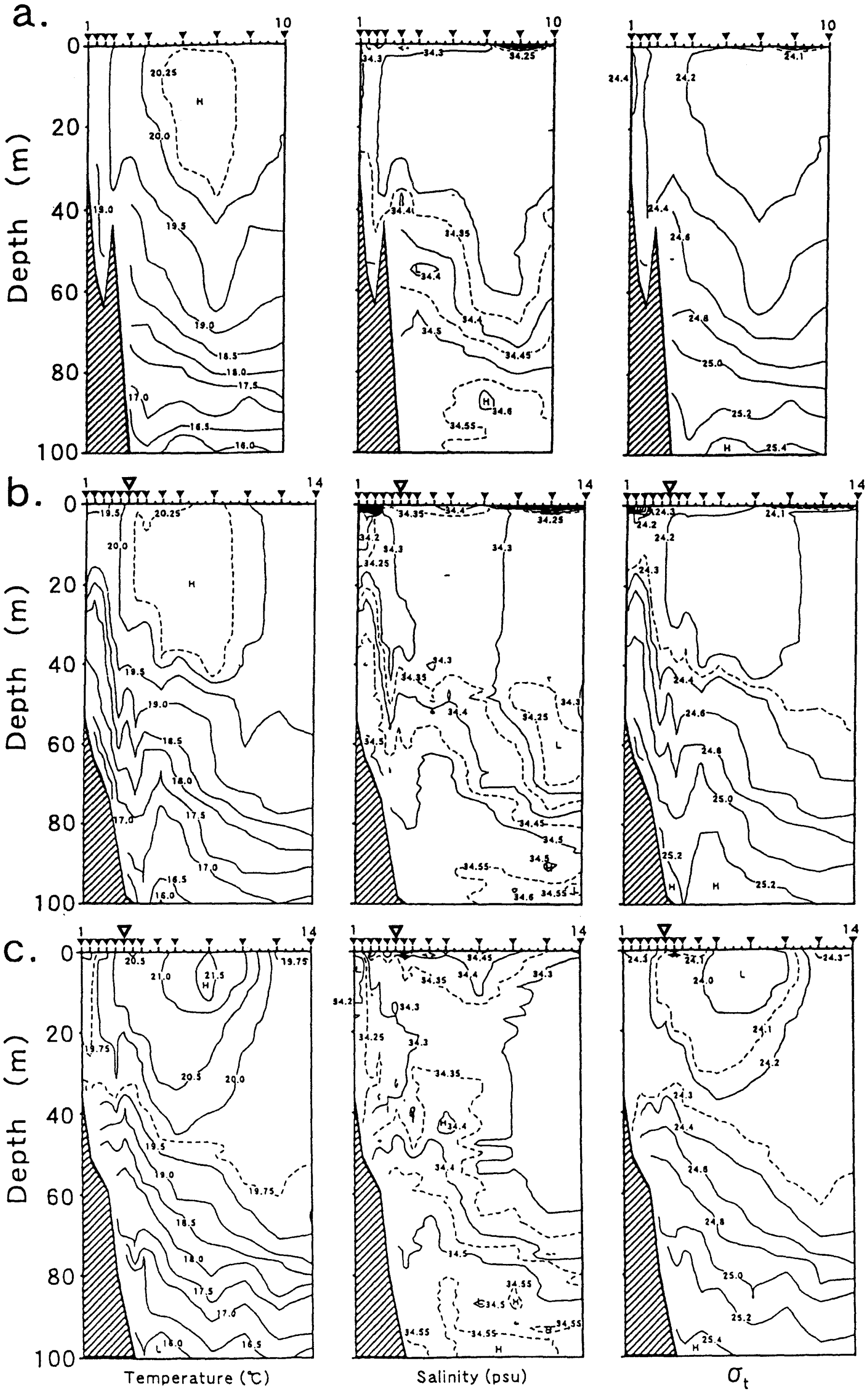

Fig. 3. Observed temperature (℃) (left), salinity (psu) (center) and density(σ t) (right) fields along NC line (a), OC line (b) and KC line (c). Large open triangles upper the small triangles showing each observational point correspond to the cross points with the observational line of OT line (b) and KT line (C).

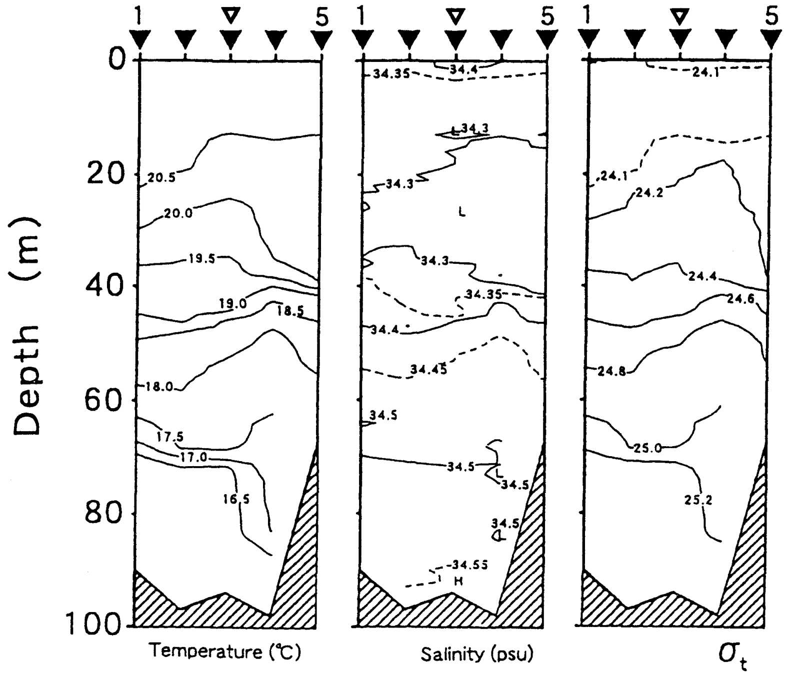

Fig. 4. Same as in Fig. 3 but for the KT line shown in Fig. 2. Cross point with the KC line is shown by open triangle.

that the observations along lines NC and OC were carried out after the approach of the warm water with the isotherm of 21℃ shown in Fig. 1b. However, the observation of line KC was made after new warm water approach shown in Fig. 1c, in which the front of the new warm water have not arrive at the observational lines OC and NC.

It should be noted that the warm water core has a thickness of 50 m (Fig. 3), which indicates that the warm water separated from the main Kuroshio path (Fig. 1) has a thickness smaller than that of the detached warm eddy with a thickness more than 200 m. It is also seen from the salinity fields of Fig. 3 that less saline water exists in a surface layer shallower than 2m along the observational lines OC and NC, while such a less saline water does not exist in line KC. On the basis of the T–S diagram of the Kuroshio region (e.g., ISHII *et al.*, 1983), there exists a less saline water in the surface layer due to the precipitation. The less saline water shown in Fig. 3ab may be caused by the precipitation, which suggests that the low salinity of the northeastward intrusion water at OC line and NC line in comparison with that of the KC line is also caused by the difference in vertical mixing with the less saline surface water.

Observed temperature, salinity and density fields along two alongshore observational lines KT and OT are shown in Figs. 4 and 5, respectively. As for KT line (Fig. 4), a warm water with the temperature of 20.5℃ and the salinity of 34.3 psu, which is detected along the KC line (Fig. 3c), exists horizontally along KT line and similar horizontal temperature and salinity distributions are perceived between KT line and KC line. Namely, lower layer water seen in Fig. 4 with a temperature of 16.5℃ and a salinity of 34.55 psu exists in the deepest layer of Fig. 3c. Although the observational line of OT line is longer than KT line, similar tendency is seen in Fig. 5, if we focus the common observational point; CTD observations at Station 5 of OT line and Station 6 of OC line are carried out independently, of which observational time difference is about 9 hours. It is suggested that a

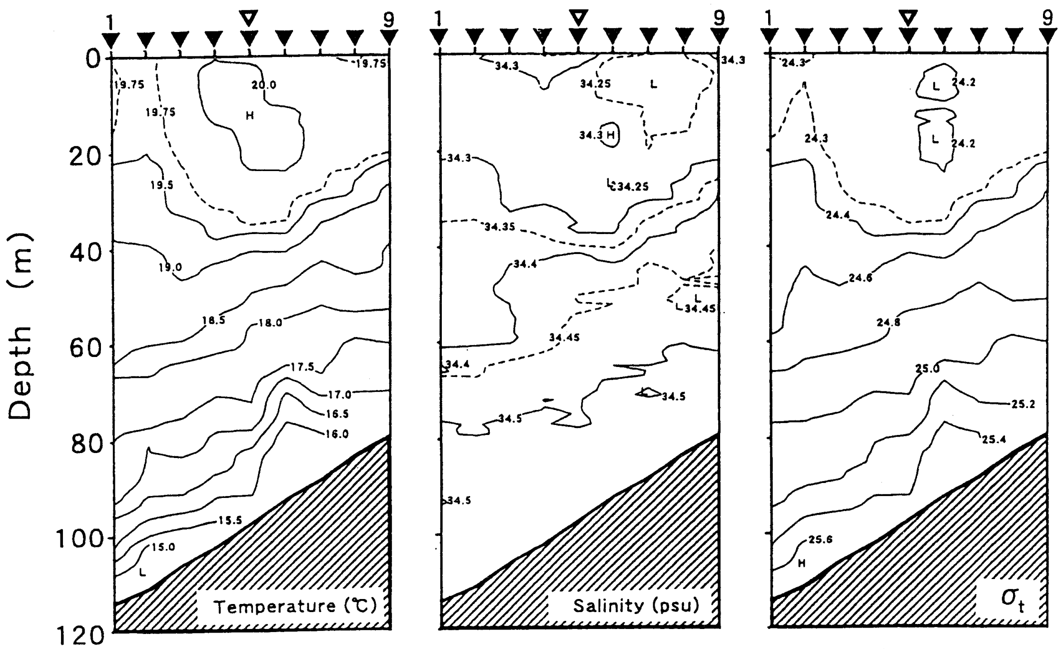

Fig. 5. Same as in Fig. 4 but for the OT line shown in Fig. 2

warm water structure is homogeneous along in the downward direction. Since the core water of the warm Kuroshio water does not reach to the bay mouth of Kata Bay (Fig. 4) and Owase Bay (Fig. 5), its influence on the oceanic condition of each bay is less in this case.

Observed velocity distribution by ADCP is shown in Fig. 6. Northeastward flow is dominated in a southern region at depths of 10m and 50m, while the northeastward flow is unclear in a northern region. This difference also implies that the new warm water shown in Fig. 3c approaches at the southern observational line KC, but it has not arrived at the two northern observational lines, OC and NC. It should be noticed that the northeastward flow in the southern region is clear at depths 10m and 50m, but it is unclear at a depth of 100m. This difference is explained by the fact that the thickness of the warm water tongue is about 50m (Fig. 3). The mean velocity of the northeastward flow along the eastern coast of the Kii Peninsula is 30 cm sec^{-1}, which agrees with the velocity of warm SST shift estimated from the SST imagery shown in Fig. 1.

4. Discussion

It is pointed out that the northeastward intrusion of the Kuroshio water has a velocity of 30cm sec^{-1}. This velocity agrees with that evaluated from satellite infrared imagery by use of the northeastward shift of the isotherms showing the warm water. This velocity also agrees with that shown by KIMURA and SUGIMOTO (1993, 2000) with a wavelength of 400 km and a period of 17–19 days. It is shown that the northeastward velocity shown by the present study is not due to the planetary or topographic Rossby wave, nor coastal Kelvin wave, because direction of the northeastward shift of the warm Kuroshio water shown by Figs. 1 and 6 is different from the directions of these waves.

The westward velocity of 30cm sec^{-1} after the separation from the eastward main Kuroshio path observed on 1－2 November shown in Fig. 1, which has the same velocity of the westward shift of the warm water newly separated on 6–7 shown in Fig. 1, is not considered as a external planetary Rossby wave; we assume that the wavelength of the planetary Rossby wave is 300km at most from Fig. 1, its phase velocity is about 8.1cm sec^{-1}. Here, the

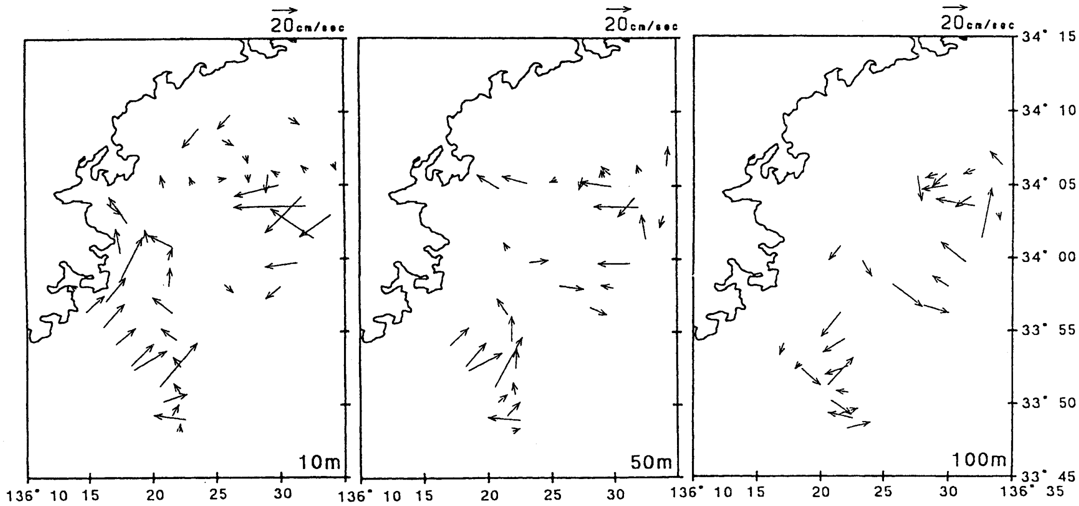

Fig. 6. Observed ADCP velocity at depths of 10 m (left), 50 m (center) and 100 m (right).

wavelength is estimated by assuming that the northward curve of isotherms of 21℃ and 22 ℃ in the zonal flow shown in Fig. 1d with a generation of new warm tongue east of Kii Peninsula is considered as a half wavelength of the planetary Rossby wave. As a phase velocity of the baroclinic planetary Rossby wave is much slower than the external wave, these two velocities are too small in comparison with the observed velocity of 30cm sec^{-1}. It is thus suggested that the northeastward velocity along the eastern coast of Kii Peninsula and westward velocity after the separation from the mean Kuroshio path of 30cm sec^{-1} are mainly associated with that given during the separation from the main Kuroshio path. However, more quantitative discussion is needed on this problem and it will be examined in the next stage of this study.

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