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Internal tidal waves and internal long period waves in the Sanriku coastal seas, eastern coast of northern Japan*

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Abstract: The study of internal tidal waves in a bay was carried out on the basis of observed records in Toni Bay (located in the northeastern area of Honshu) in autumn 1984.

a) It was found that the internal tidal waves were predominant and appeared intermittently with a duration of several days in the bay. On the basis of T-S diagram analyses, it was suggested that the intermittency of the internal tidal waves in the bay was closely related to the intermittent vertical displacement of the offshore thermocline.

b) The cause of the intermittent vertical displacement of the thermocline was investigated by analyzing subsurface water temperature at two bays and the variation of sea surface level anomaly (local difference of tidal deviations) among three bays adjacent to Toni Bay. From the analysis of the variation of the thermocline depth, some evidence was obtained for the existence of internal long period waves propagating southward along the coast. The intermittent appearance of the internal tidal wave in the bay occurred from the superposition of the internal tidal wave propagating onshore and the internal long period wave propagating alongshore. Moreover, it is suggested that the internal long period waves are related to the behaviour of an offshore density front at the sea surface in Sanriku coastal seas.

c) The internal tidal waves of semidiurnal period in the bay were likely related to the 2nd mode of the offshore internal tidal waves from comparison of the dispersion relations of the internal tidal waves in the bay with those out of the bay and from the simple model estimation of an energy efficiency of the offshore internal tidal waves propagating into the bay.

1. Introduction

In reports on observations of internal tidal waves, the intermittency of occurrence of internal tidal waves has been noted only recently. In the open ocean, the internal tidal waves are found as predominant semidiurnal fluctuations of the current velocity in several subsurface depths. For example, WUNSCH (1975) quoted from MAGAARD and MCKEE (1973) and indicated that the intermittency of about 10 days was remarkable in the variation of the amplitude of the internal tidal waves.

In coastal sea areas, there are reports on the propagations of semidiurnal internal waves and their breaking at the shelf break in the northwestern coastal sea area of Australia (HOLLOWAY, 1984, 1985). The intermittency of about 10 days was noticeable in his records of water temperature and velocity components, though he describes nothing about it. In Japan, the reports of the internal tidal waves have increased in recent years; there are only two reports indicating the intermittency of the internal tidal waves for the present. INABA (1981) reported that in the subsurface layer of Suruga Bay, a diurnal period was dominant in the tidal current in contrast to the predominance of a semidiurnal period in the sea surface tide and this was due to the existence of an internal wave in the subsurface layer. MATSUYAMA (1987) suggested the intermittency of 7-10 days in the records of the velocity components in INABA (1981). In Uchiura Bay located at the head of Suruga Bay, the record of sea water temperature in the subsurface layer showed a predominant semidiurnal fluctuation, and this was due to resonance of the semidiurnal tide with the internal seiche in Uchiura Bay (MATSUYAMA, 1985). In addition, he de-

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scribed that the semidiurnal fluctuations intermittently disappeared in 3-5 days due to the passing of a typhoon near Suruga Bay. In the coastal sea of Joban, southern neighbour of the Sanriku sea area, the internal tidal waves were dominant in semidiurnal period and propagated onshore, and the intermittent behavior of the semidiurnal internal tide was noticeable in his record of the subsurface water temperature (MATSUNO, 1989).

Sanriku coast is one of the suitable fields for studying the phenomena of the internal mode, since the Tsugaru Warm Water (TWW) is lighter than the Oyashio Cold Water (OCW) (in spite of higher salinity, smaller water density than that of OCW is attributed to higher temperature of TWW), the strong thermocline is usually kept offshore. The lighter and warmer water flowing through the Tsugaru Strait to the Pacific Ocean from the Japan Sea is the origin of TWW, which is generally flowing southwards along Sanriku coast in a surface layer with thickness of 150-200 m (HANAWA, 1984). In autumn, TWW spreads sometimes about 100km to the east of the Tsugaru Strait before flows southward along the Sanriku coast. A remarkable pycnocline front (or thermocline front) at the sea surface is observed at the eastern boundary of TWW, because the heavier OCW is found under and off TWW. The depth of the thermocline under TWW becomes deeper shoreward as an extension of the surface front in contrast with the Kuroshio front which is shallower shoreward in the south sea area of Honshu. Thus, the thermocline is also clear near the coast, and the internal wave is easy to generate in such a sea area.

A phenomenon of "Sakashio", named by Japanese fishermen, occurs sometimes in many bays of the Sanriku coast. "Sakashio" means the subsurface tidal flow opposite to the surface flow. When "Sakashio" occurs in a bay, it is difficult to wind up "the Set Net", which is a kind of fish net widely used in Sanriku coast. This phenomenon is closely related to the occurrence of the internal waves in the bay. Therefore the internal waves are one of the important oceanographic phenomena for coastal fishery, and they are also important for cultural fishery, since the internal tidal waves force the exchange of coastal sea waters in the bay for offshore sea waters.

In order to clarify the behavior of the internal tidal waves in Sanriku coastal seas, the observations were carried out in one of the bays in Sanriku coast (Toni Bay, located in Kamaishi) from October to December 1984.

In this paper, several properties of the internal tidal waves become clear, especially their intermittent appearance in the bay. In chapter 2, the outline of observations will be given. In chapter 3, some typical examples of records are shown, and the properties of the internal tidal waves observed in Toni Bay and the intermittency in the internal tidal waves with duration of several days are explained. In addition, the intermittent property is described with relation to the vertical displacement of the thermocline. In section 1 of chapter 4, some evidence for the existence of the internal long period wave will be shown. Discussion is extended to the role of such waves as a cause of the intermittent vertical displacement of the thermocline and the relation between such waves and the oceanic front. In section 2 of chapter 4, the properties for propagation of the internal tidal waves in the bay will be stated in relation to the properties of the offshore internal tidal waves, and the shoaling up of the internal tidal waves into the bay will be discussed concerning the nature of the exchange of sea water in the coastal seas.

2. Observations and data

The Sanriku coast is called a Rias type in geology, and has a complicated coast line. The configuration of sea bottom in this sea area is also complicated in areas shallower than 130 m depth, and the bottom contours run almost straight north to south in deeper seas. The sea floor increases gradually in depth toward the Japan Trench. The complicated coast line is conspicuous, especially southward of Miyako Bay in the Sanriku coast. Otsuchi Bay is 33km southward, Kamaishi Bay is 45km southward of Miyako

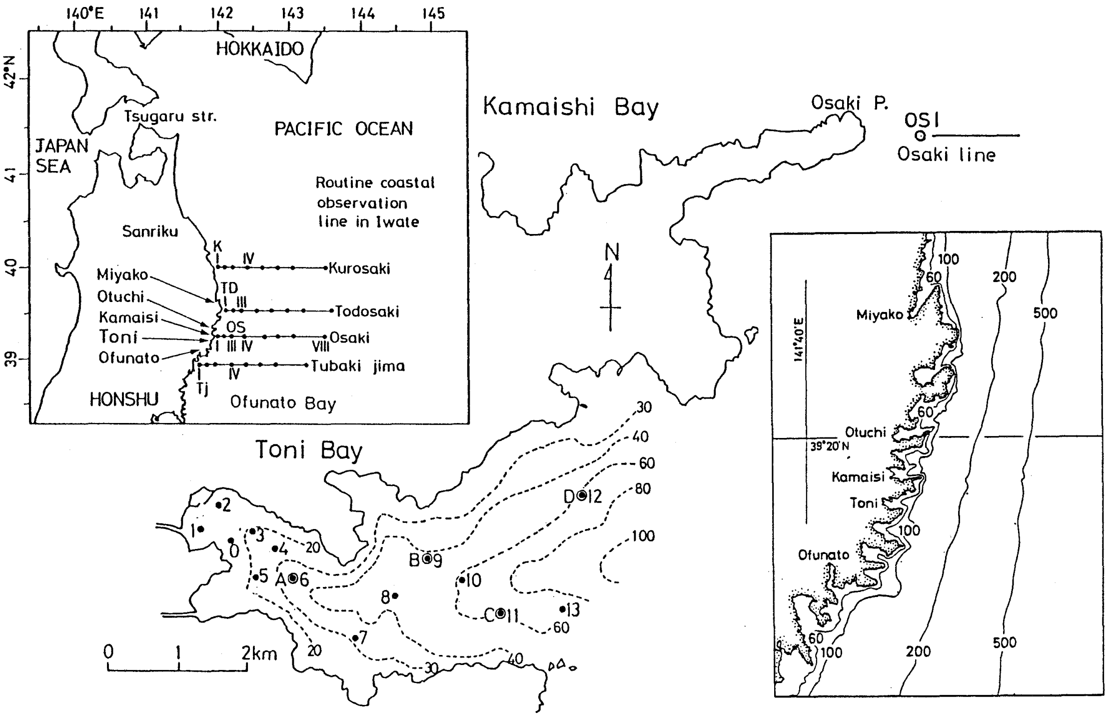

Fig. 1. Maps of Toni Bay and the adjacent sea area off Sanriku. A–D, mooring stations of Aanderaa current meters. 0–13, stations of STD-observation ; Stations A to D correspond to Stations 6, 9, 11 and 12, respectively.

Bay, and Ofunato Bay is 35km southward of Kamaishi Bay. Toni Bay is 8km southward of Kamaishi Bay (Fig. 1). Its bay mouth faces eastwards to the Pacific Ocean. The sea valley runs into the center of Toni Bay, and the breadth of the bay mouth is about 4km. The depth is about 90 m at the center of the bay mouth and about 40 m on the average; the length of the bay is 5–6 km.

Previous physical oceanographic research in Toni Bay showed that there was a counter-clockwise circulation in the bay and the flow in the bottom layer differed from that in the surface layer (TSUJITA, 1974).

Two observations were carried out in Toni Bay from 1 October to 15 December 1984. The first observation was made at 14 stations in Toni Bay (Sta.0 – Sta.13) every three days on a ship-contained STD (portable) which measured water temperature and salinity at 1 m intervals from the sea surface to the bottom (or maximum 80 m deep) (Fig. 1). The second observation was the continual observation by means of current meters which were fixed to the bottom by anchors and subsurface buoys of the mooring system. Sta. A (33 m depth) was settled near the head of the bay, Sta. D (65 m depth) was north of the center of the bay mouth, Sta. C (63 m depth) was south of the center of the bay mouth and Sta. B (44 m depth) was at the midpoint of the north side of the bay (Fig. 1). At all stations, Aanderaa current meters were set in the surface layer (10 m below sea surface) and in the bottom layer (5 m above bottom) to measure current speed, current direction, water temperature and salinity every 10 minutes. The record of a current meter was averaged over an hour before analysis. The continual record was divided into two parts, 1 October – 8 November and 9 November – 15 December. Unfortunately, the record of the current meter in the bottom layer at Sta. D was not obtained because of

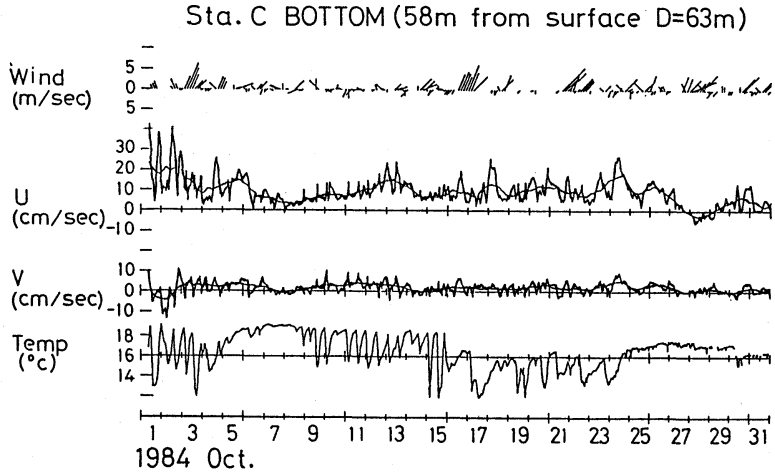

Fig. 2. An example of the time series of Aanderaa current meter record in the bottom layer at Sta. C (Oct. 1-31, 1984). Wind, vector expression of wind every 3 hours. U, eastward component of velocity (thick line) and its 25 hour running mean (thin line). V, northward component of velocity (thick line) and its 25 hour running mean (thin line). Temp., sea water temperature.

mechanical trouble.

In addition to those records, the following data of the routine observations by governmental offices were available to the present paper:

1) The monthly data of routine coastal observations in 4 lines off the Sanriku coast by Iwate Prefecture Fishery Experimental Station (Fig. 1).

2) The hourly data of tidal observations in Miyako Bay, Kamaishi Bay and Ofunato Bay (the forecasted data and the observed data) by Branches of Meteorological Agency and others.

3) The meteorological data every three hours at Miyako, Kamaishi and Ofunato (air pressure, wind speed and wind direction).

4) Simultaneous data of temporal deep sea observations far off Sanriku, by Meteorological Agency.

The Iwate Prefecture Fishery Experimental Station has carried on the monthly observation of water temperature and salinity in several depths shallower than 300 m at each station in 4 observation lines off the Sanriku coast. In each observation line, 8 stations are set, for example, Sta. 1 is 0.7 km and Sta. 8 is about 130 km from the coast in the Osaki line. Details of 4 coastal routine observation lines are:

Kurosaki Line (K I - KVIII) (40°00'N, 141°52'−143°30'E);

Todosaki Line (TD I - TD VIII) (39°32'N, 142°06'−143°35'E);

Osaki Line (OS I - OSVIII) (39°15'N, 142°04'−143°30'E);

Tsubakijima Line (TJ I - TJVIII) (38°56'N, 141°44'−143°14'E).

Those routine data were very useful to the present work as indicators of information in the offshore sea area, especially the Osaki line located about 3 km from Toni Bay (Fig. 1).

3. Analysis and results

1) An example of records

a) Time series of current meter records

Time series of several components of the current meter record in the bottom layer at Sta. C are shown in Fig. 2. The variation of water temperature is apparently different from that in the surface layer (refer to Fig. 6). Water temperature fluctuated periodically and its range was 6℃ in maximum value. Before 15 October, the period of the fluctuations was semidiurnal, but it was near-

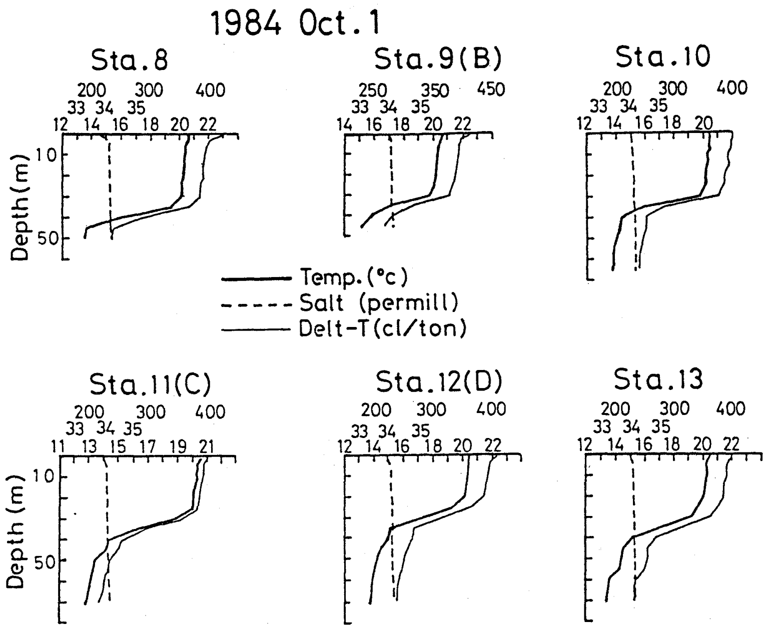

Fig. 3. Vertical distribution of temperature (℃), salinity (permill) and specific volum anomaly (cl/ton) of sea water in the mouth of Toni Bay (14:43 - 15:46, Oct. 1, 1984).

ly diurnal in 16-24 October, though its fluctuation was considerably disturbed. It is of interest that the days of steady and high temperature were 5-8 and 25-29 October. After 29 October, the record is obscure because of some loss of record from troubles with the water temperature sensor. On the other hand, in the surface layer, water temperature tends to decrease gradually, and sometimes drops 1-2℃ per day (Fig. 6). This change corresponded to the duration of fluctuation of water temperature in the bottom layer, which suggested that the dominant fluctuation of bottom water temperature was relivant to the lowering of surface water temperature.

The eastward component of velocity (U) in the bottom layer mostly fluctuated in the positive area, which meant that the flow was generally eastward (Fig. 2). The basic flow in the bottom layer at Sta.C was eastward and it seemed to be related to counterclockwise circulation in Toni Bay (TSUJITA, 1974). The magnitude of fluctuation of the U or V component in the surface layer was equal to that in the bottom layer (figure of the record in the surface layer at Sta.C is not shown). U and V fluctuated periodically, but they were rather disturbed by noise compared with the fluctuation of water temperature. The fluctuation of semidiurnal period prevailed in the beginning of October and the fluctuation of diurnal period was found with that of semidiurnal period in the second half of October. When the tidal fluctuation of bottom water temperature was large, fluctuation of U reached to 40 cm/sec in range of U (in the term of about 6 hours).

The vector expression of wind was composed of records of wind speed and direction every 3 hours at Kamaishi. During the observations, the wind blew weaker than the usual condition in late autumn. For example, the wind speed was usually 3-4 m/sec and sometimes 7-8 m/sec.

b) Data of STD measurement

Fig. 3 is an example of the vertical distribution of water temperature, salinity and specific volume anomaly at six stations near the bay mouth from STD measurements during the afternoon on 1 October. A very clear thermocline was found at a depth of 30-40 m

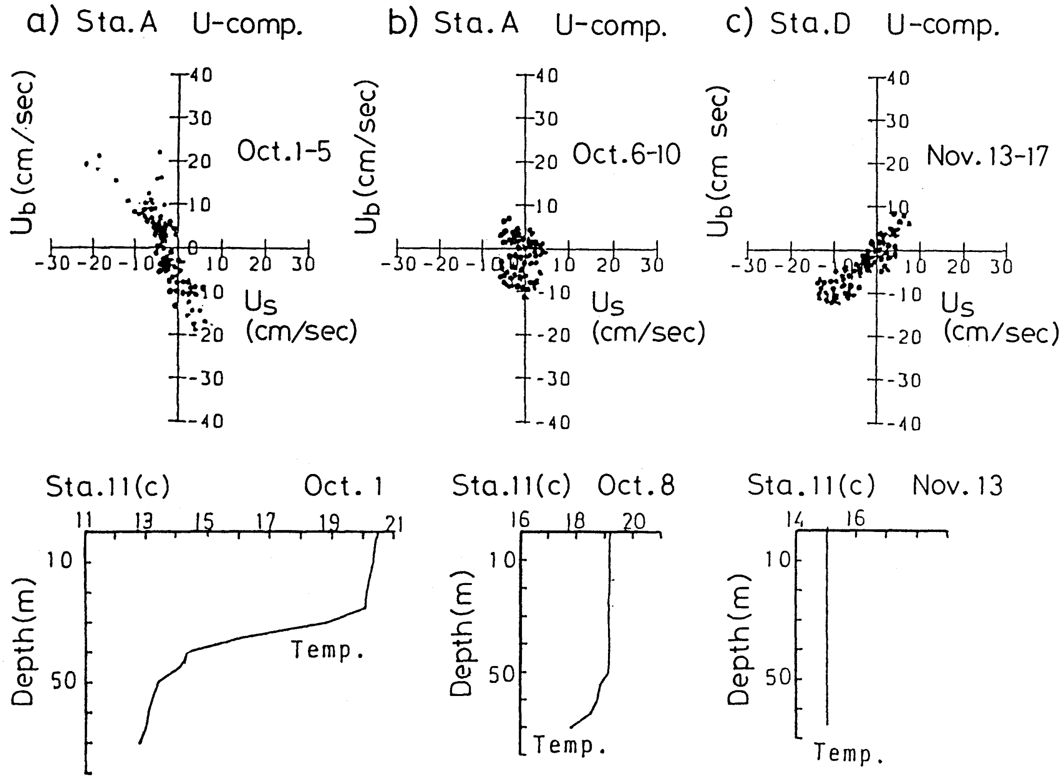

Fig. 4. Correlations between velocity components in the surface and in the bottom layers, and vertical distributions of sea water temperature. X-axis, Us (velocity component in the surface layer); Y-axis, Ub (velocity component in the bottom layer). a) strong density stratification (Oct. 1-5, 1984); b) transient density stratification (Oct. 6-10, 1984); c) vertically homogeneous density (Nov. 13-17, 1984).

in Toni Bay. The thickness of the thermocline was about 10 m and the temperature difference between upper and lower layers was 6℃ (20-14℃) in maximum value. On the other hand, salinity was almost homogeneous (Sal. > 34.0 permill) at all depths in Toni Bay, hence, colder sea water in the bottom layer of Toni Bay was not the Oyashio Water (Sal. < 33.8 permill) but the cooled Tsugaru Warm Water.

The strong density stratification in Toni Bay depended on the vertical distribution of water temperature.

2) Properties of the internal tidal waves

Vertical distribution of specific volume anomaly of sea water and currents in stratified sea

The thermocline of about 10 m thickness between the upper warmer sea waters about 20℃ and the lower colder sea waters less than 14℃ has a very large vertical gradient of water temperature (0.6℃/m, Fig. 3). When stratification occurs in Toni Bay, an inverse correlation between the velocity components in the surface and the bottom layers is shown at top of Fig. 4a. This correlation of currents between both layers indicates a dominant internal mode.

On the other hand, the density distribution in the bay was homogeneous on 13 November at the bottom of Fig. 4c. The vertical distribution of currents was also homogeneous in 13-17 November (top of Fig. 4c).

The density stratification was weak on 8 October, and the correlation between the velocity components in the surface and the bottom layers seemed to be zero (Fig. 4b). This shows that the vertical distribution of currents in the bay was in a transient state between the strong density stratification state (Fig. 4a) and the homogeneous distribution state (Fig. 4c).

Spectral property of fluctuations

As the fluctuation of bottom temperature was different between the terms of 1-4 and 16-24 October (Fig. 2), power spectra of water temperature in the bottom layer at Sta.C were calculated for each of the terms (Fig. 5a). Power spectra of water temperature for the former had predominant period of 13 hours, which nearly equaled the semidiurnal period (left of Fig. 5a). Power spectra in the bottom layer at Sta.A and Sta.B had a prevailing semidiurnal period in this term.

On the other hand, for 16-24 October, the

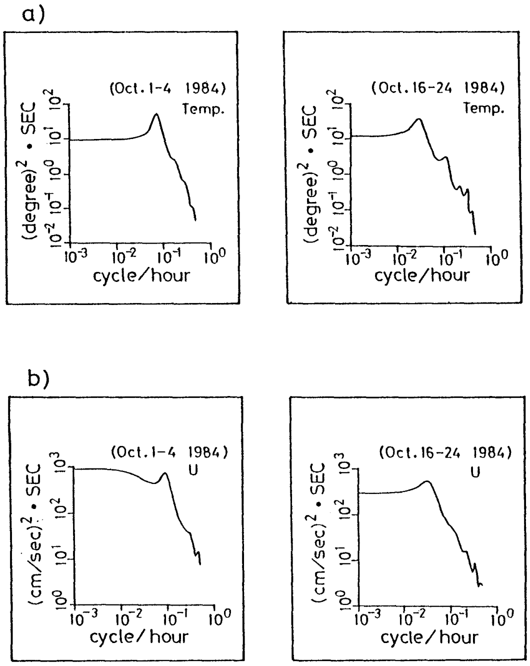

Fig. 5. Power spectra for variations of sea water temperature and for the eastward component of velocity at Sta. C bottom. a) Temperature; dominant periods are 13 hours (Oct. 1-4, 1984) and 35 hours (Oct. 16-24, 1984). b) Velocity; dominant periods are 11 hours (Oct. 1-4, 1984) and 31 hours (Oct. 16-24, 1984).

predominant period was about 35 hours in the bottom layer at Sta.B and Sta.C (right of Fig. 5a), and there was no dominant period in density distribution of power spectra at Sta. A in the bay head (refer to Fig. 6).

Comparing eastward components of velocity (U) for 1-4 October with those for 16-24 October at Sta.C (Fig. 2), the amplitude of fluctuation in the former was larger than that in the latter, and those seemed to have a similar period. The power spectral density of U for 1-4 October had a dominant period at about 11 hours near the semidiurnal period (left of Fig. 5b). The density of low frequency was large; this was shown in a gradient of the smoothed curve (running mean velocity) in the fluctuation of U in Fig. 2. In the bottom and surface at Sta.A and Sta.B, and in the surface at Sta.D, the predominant period of the semidiurnal was obtained, but it was about 14 hours in the surface at Sta.C.

For 16-24 October, the power spectra of U had a dominant period of about 31 hours, similar to the case of water temperature (right of Fig. 5b), and in the bottom at Sta.A and Sta.B the dominant periods were about 22 and 19 hours, respectively.

As mentioned above, there was apparently a difference of period between the two terms in both water temperature and velocity component (U).

The characteristics in fluctuation of water temperature in Toni Bay

In Fig. 6, water temperature in the surface layer varies similar to an envelope of water temperature in the bottom layer at each station. The patterns of bottom water temperature at the three stations are similar to each other, and their fluctuations seem to decrease gradually from Sta.C at the bay mouth to Sta.A at the bay head. The other noticeable feature of the fluctuation of water temperature in the bottom layer is that there are several calm days or the days of no periodicity. The internal tidal waves seem to be strongly intermittent (Fig. 6). It should be noted that for 8-15 October, the maximum of water temperature at the bottom layer at Sta.C was nearly equal to that at the surface throughout the term. This suggests that the

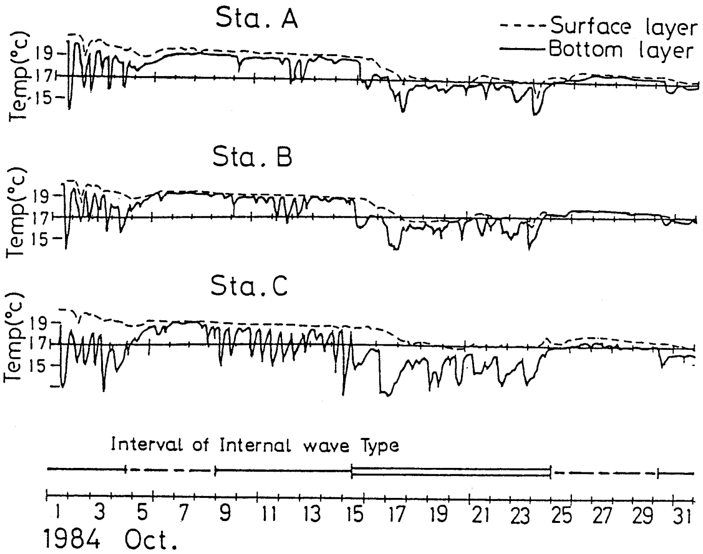

Fig. 6. Comparison of sea water temperature variations in the surface with those in the bottom layer at Stations A, B and C. At the bottom of the figure, the term of the internal wave type is shown: single line, the term of the semidiurnal fluctuation of sea water temperature at Sta. C in Fig. 2; double line, the term of diurnal fluctation; chain line, the term of stable and high temperature (no fluctuation).

thermocline disappeared in the bay; the thermocline sank deeper than the depth at the bay mouth and the warm surface water filled the whole depth in the bay. The colder sea water at the bay bottom repeated to flow in and to flow out every tidal period for 8-15 October. This is an interesting mechanism for the exchange of sea water in a shallow bay.

3) Intermittency of the internal tidal waves and vertical displacement of pycnocline

a) Intermittency of the internal tidal waves

The pattern of fluctuations of water temperature in Fig. 2 suggests the intermittency of the internal tidal waves. In the record of water temperature, semidiurnal internal tidal waves were predominant for 1-4 and 9-15 October, near diurnal were dominant for 16-24 October, and the terms of the stable and higher water temperature were for 5-8 and 25-29 October. In fluctuations of velocity component (U), amplitudes of U seemed to be diminished in the terms of stable and higher water temperature and this was due to the intermittency of the internal tidal waves in the bay.

To confirm the intermittency, "the figures of the day by day variations of density of power spectra" from records in the bottom layer at Sta.C are shown in Fig. 7. The figure has frequency of fluctuations on the X-axis and the elapsed days of 3-21 October are marked on the Y-axis. Isosteric lines of the power spectra of fluctuation are shown in the figure. Power spectra of fluctuations were calculated at terms of every 5 days from 1 to 23 October. For example, the power spectra of 3 October at bottom in the figure were calculated on data in 1-5 October, next power spectra of 4 October were calculated from data in 2-6 October. Those calculations were carried out to 21 for data in 19-23 October day by day. The dominant periods for fluctuations of water temperature are at 11 hours near the semidiurnal period and at long period component (above 50 hours) on 4 October (the representative day of 2-6 October, Fig. 7a). The density of power spectra decreases to lower levels at all frequency fields in 5-8 October. The semidiurnal period component increases in 10-14 October. After 15 October, the components of frequency shorter than 25 hours disappear and those of frequency longer than 25 hours

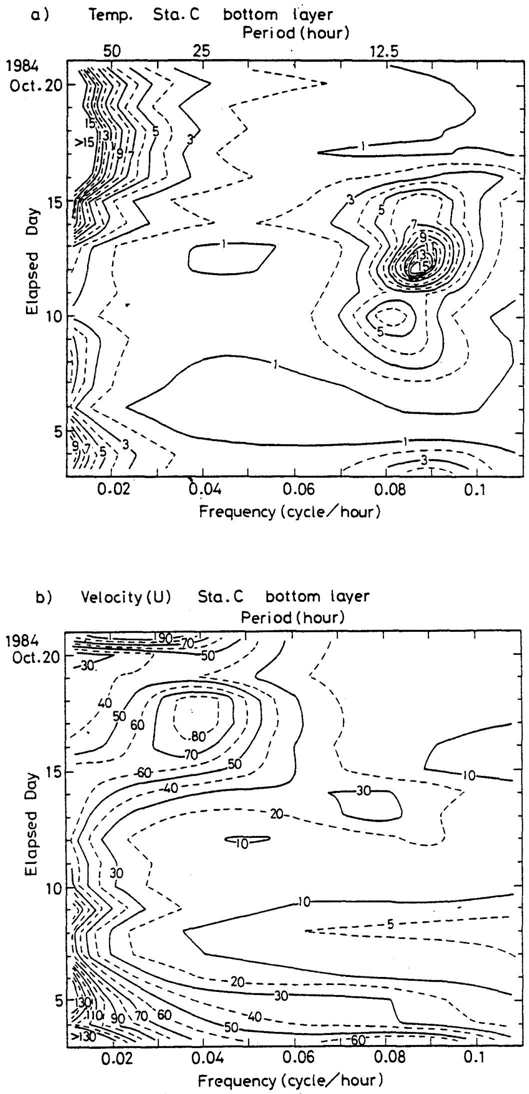

Fig. 7. Day by day variations of power spectra at Sta. C bottom layer. Power spectra were calculated every 5 days sliding a day (Oct. 1-23, 1984). a) Sea water temperature (Temp.). b) Eastward component of velocity (U).

become more dominant.

Another figure of day by day variation in density of power spectra is shown in the eastward component of velocity (U, Fig. 7b) in a similar manner to water temperature. Distributions of isosteric lines differ from those of water temperature, and the peaks at each frequency in each elapsed day are more obscure than those of water temperature. The components of near semidiurnal period and long period (above 50 hours) are dominant for the first 5 days, and the components at all frequencies are at lower levels for 7-13 October. The predominant component is a semidiurnal period for 13-14 October and a diurnal period is prevailing for 16-18 October.

To conclude, the figures were very suggestive of the intermittency of the internal tidal waves in the bay.

b) Vertical displacement of pycnocline (thermocline)

The inflowing of colder sea water to the bottom of Toni Bay from offshore was confirmed from the result that the lowering of water temperature generally took place earlier at Sta. C than at Sta. A (for example, Fig. 17).

Next problems were where the origin of colder waters offshore was and how deep the layer of colder waters was. In order to solve those problems, T-S diagram analyses of sea waters for the term of density stratification were made (Fig. 8). The waters in the hatched area (13-15℃, about 34.2 permill) in Fig. 8a were the bottom water in the bay, the waters in area enclosed with broken lines (19-21℃, 33.9-34.2 permill) were the surface water. The waters of similar property to the bottom waters in the bay were found in 70-100 m layer at nearshore stations in three lines north of the Osaki line (Fig. 8b, c, d). An offshore thermocline of 13-17℃ (near Sta. OSV) was found at 40 m depth, increased in depth towards the coast, and was found at 75-100 m depth at Sta. OS II (8 km off coast, Fig. 14c). This deepening of the thermocline near the coast is usual in the vertical distribution of water temperature in this season. The bottom sea water in the bay was different from the offshore sea water at the correspondent depth; therefore, it might be the offshore sea water rising up from a slightly deeper thermocline by an unknown external force. When the thermocline nearshore rose intermittently the density stratification appeared in Toni Bay and the internal tidal waves propagated into the bay.

The sea waters similar in T-S property to

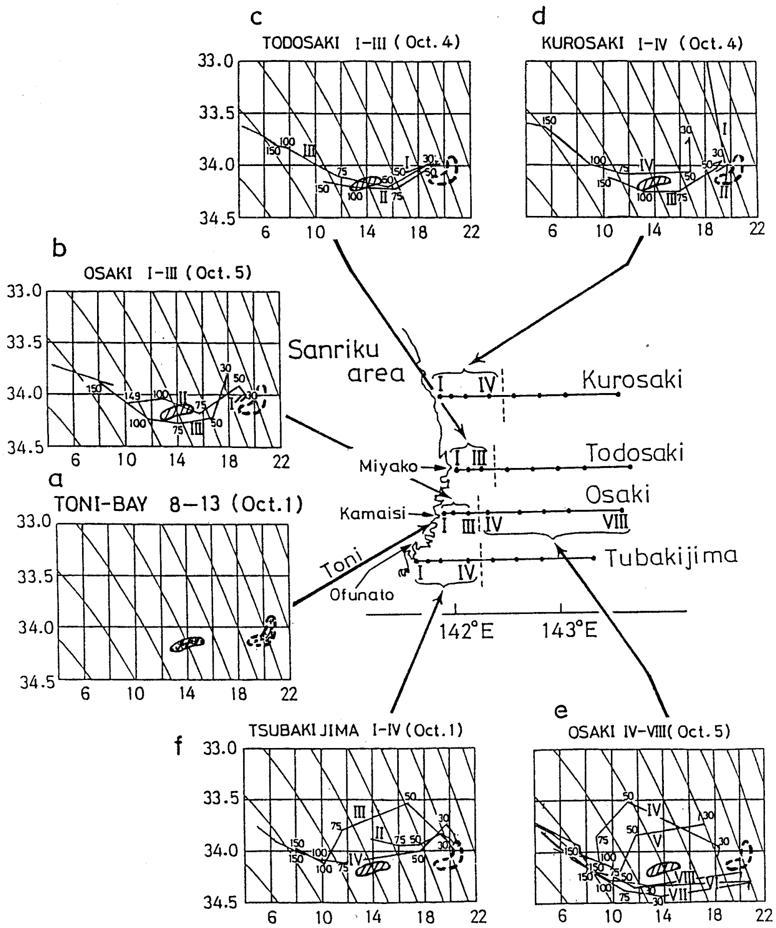

Fig. 8. Comparisons of the sea water property in T-S diagram in Toni Bay with that in the offshore sea area. Hatched area in T-S diagram: T-S property of the colder sea water at the bottom in Toni Bay. Area bounded by broken line in T-S diagram: T-S property of the warmer sea water at the surface in Toni Bay. I, II, III·····: number of the offshore station. 10, 50, 75···: observed depth (m). a) T-S diagram of Stations 8-13 in Toni Bay. b) T-S diagram of Stations I-III in Osaki line. c) T-S diagram of Stations I-III in Todosaki line. d) T-S diagram of Stations I-IV in Kurosaki line. e) T-S diagram of Stations IV-VIII in Osaki line. f) T-S diagram of Stations I-IV in Tsubakijima line.

the bottom sea water in the bay were not found at stations offshore from Sta. OSV and at all southern stations in the Tsubakijima line (Fig. 8e, f). Therefore, the intermittent vertical displacement of the thermocline occurred only in the northern sea area of Toni Bay.

It is confirmed from observations that the intermittency of the internal tidal waves in Toni Bay was due to the vertical displacement of the thermocline on a time scale of several days. Remarkable meteorological disturbances were not found in the term under investigation since wind was usually weaker than 5 m/sec in October 1984 (Fig. 2). Therefore, the long period waves were of interest for the cause of vertical displacement of the thermocline on a time scale of several days, if those waves existed in the Sanriku coastal seas.

4. Discussions and conclusions

1) Some evidence on the internal long period waves

In chapter 3, it was pointed out that the internal tidal waves appeared intermittently in the time scale of several days, and the T-S property of colder sea waters in Toni Bay coincided with colder sea waters under the thermocline in a slightly deeper layer outside of Toni Bay.

It is only recently that the intermittency in the internal tidal waves attracted scientist's attention (e.g. WUNSCH, 1975). However, there are very few reports on this problem. In Japan, a few researchers have noticed such an intermittency in the continual records of sea water temperature and current velocity in the subsurface layer. They concluded that this resulted from the disappearance of stratification of the ocean caused by a change in the wind system, e.g. access of a typhoon (INABA, 1981; MATSUYAMA, 1985). The intermittent variations were clearly found in the record of bottom water temperature in the Joban coastal sea area, southern neighbour of the Sanriku sea area, though he described nothing about it (MATSUNO, 1989). Similar intermittent variation was found in the record of bottom water temperature and current velocity components in subsurface layers in the northwestern coastal sea of Australia (HOLLOWAY, 1985). Thus the intermittency in the internal mode occurred generally in every sea area in the world, though its origin and structure were different in each sea area.

In the Sanriku coastal seas, it was possible that the space scale of the intermittency of the internal tidal waves had a larger horizontal scale than that of Toni Bay (Fig. 8). Similar variations of temperature were expected in the bay adjacent to Toni Bay. It was very convenient that a continuous measurement of sea water temperature had been carried out in several subsurface layers above 15 m deep at Otsuchi Bay to the north of Toni Bay (Fig. 1, SHIKAMA *et al.*, 1985). A variation of sea water temperature (1 hour running mean values of every 10 minutes records) at 10 m depth in Otsuchi Bay (observing station was located at about 6 km inward from the bay mouth) was very similar to that in the surface layer at Sta.D in Toni Bay (Sta.D was located at about 1 km inward from the bay mouth). The records in Fig. 9 are the subsurface water temperature deviations of 25 hours running mean values from mean value of full data in Toni Bay and Otsuchi Bay. A temporal decrease of water temperature appeared in Otsuchi Bay on 3 and 17 October, and a similar temporal decrease appeared in Toni Bay a day later. Those variations of water temperature in the two bays were in high correlation with each other and the cross correlation coefficient (α) was 0.89. The propagating speed of this decrease was estimated from the difference of the propagating distances for the two stations in the bays and the lag (22 hours) of the time when α was maximum in the cross correlation. Therefore, it corresponded to the length of 15 km ($=20-6+1$), and the propagation speed of a long period wave was estimated about 19 cm/sec and from north to south in direction.

This propagating speed was compared with the phase speed of the coastal trapped wave (internal Kelvin type wave) calculated from observed data. The dispersion relation of the coastal trapped wave was calculated by means of a reduced gravity model taking into account the details of bottom configuration. The estimated phase speed of the coastal trapped wave was more than 30 cm/sec; this was considerably larger than the propagating speed of the above long period wave (19 cm/

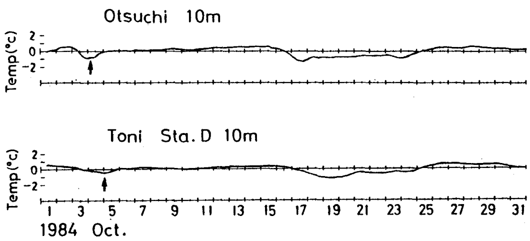

Fig. 9. Comparison of sea water temperature variation in Toni Bay with that in Otsuchi Bay (Oct. 1-31, 1984). Deviations of 25 hour running mean value from the mean value of full data. Arrows: the moment of temporal decrease of sea water temperature.

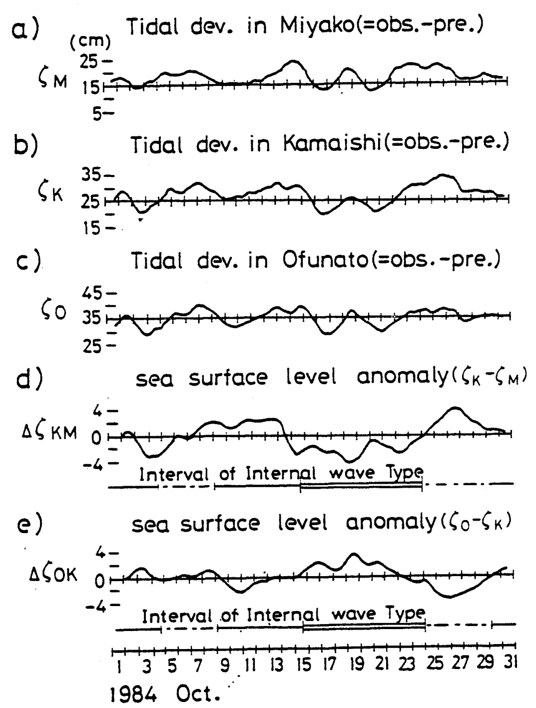

Fig. 10. Comparison of sea surface levels in three bays (cm). Terms of internal wave type in d) and e) are the same as those in Fig. 6. a) ζ_M is value of 25 hour running mean of the tidal deviation in Miyako Bay. b) The same as in a) except for in Kamaishi Bay. c) The same as in a) except for in Ofunato Bay. d) $\Delta\zeta_{KM}$ is the sea surface level anomaly (local difference of tidal deviations) between Kamaishi Bay and Miyako Bay ($\Delta\zeta_{KM} = \zeta_K - \zeta_M$). e) The same as in d) except for between Ofunato and Kamaishi Bays ($\Delta\zeta_{OK} = \zeta_O - \zeta_K$).

sec). The small magnitude of the phase speed suggested that the long period wave was a kind of internal wave; the internal long period wave treated here was different from the coastal trapped wave.

In the coastal seas of Japan, some results on the long waves were reported. In the Joban coastal sea area (southward of the Sanriku coast), the periodical current fluctuation (about 100 hours) was dominant and it propagated southward with speed of 3-5 km/hour (83-139 cm/sec), and this corresponded to the second mode and the third mode of the shelf waves (KUBOTA *et al.*, 1981; KUBOTA, 1982, 1985). These reports were related to the external long wave, and the propagation speed was larger than that of the internal long period wave in the present study.

On the other hand, there are few reports in Japan on observations of the internal long period wave as yet. When the internal long period waves propagate from north to south along the coast, it is expected that the sea surface level changes out of phase to the depth of the thermocline, even if it is very small. The deviations of the observed tide (after correction by atmospheric pressure) from the predicted tide were obtained in each of Miyako Bay, Kamaishi Bay and Ofunato Bay (Fig. 10a, b, c). These sea surface level anomalies are shown in Fig. 10d, e. Although $\Delta\zeta_{KM}$ contains some noise, $\Delta\zeta_{KM}$ is evidently negative with its magnitude of 3-4 cm for 1-5 October and 14-24 October when the internal tidal waves were dominant in Toni Bay (except 9-13 October). The negative $\Delta\zeta_{KM}$ means that sea surface level at Kamaishi Bay was lower than that at Miyako Bay. Because the sea surface level variation caused by the internal wave changes out of phase with that of the thermocline as mentioned above, the negative sea surface level anomaly ($-\Delta\zeta_{KM}$) in Fig. 10d probably indicates upward displacement of the thermocline at Kamaishi, and the dominant fluctuation of the thermocline may appear in the shallow bay in those terms (Fig. 10d and Fig. 6). The time variation of $\Delta\zeta_{OK}$ (Fig. 10e) is out of phase with that of $\Delta\zeta_{KM}$ and the amplitude of $\Delta\zeta_{OK}$ seems to be a little smaller than that of $\Delta\zeta_{KM}$. $\Delta\zeta_{KM}$ is inversely proportional to $\Delta\zeta_{OK}$ (Fig. 11), and the variation of sea surface level near Miyako Bay was in phase with that near Ofunato Bay. Therefore, the tendencies of $\Delta\zeta_{KM}$ and $\Delta\zeta_{OK}$ indicated the existence of the internal long period wave along the Sanriku coast.

Those results suggested the existence of internal long period waves propagating alongshore with an appropriate space scale (about 100 km) that was nearly twice the distance between Miyako Bay and Kamaishi Bay

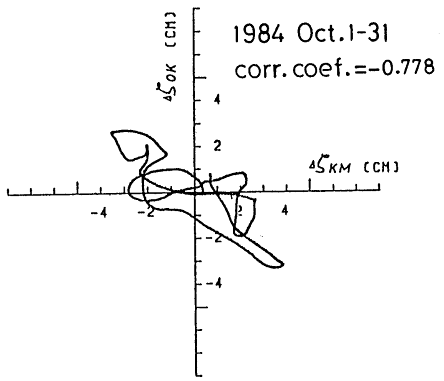

Fig. 11. Correlation between the sea surface level anomalies, $\Delta\zeta_{KM}$ and $\Delta\zeta_{OK}$ (cm) (Oct. 1-31, 1984).

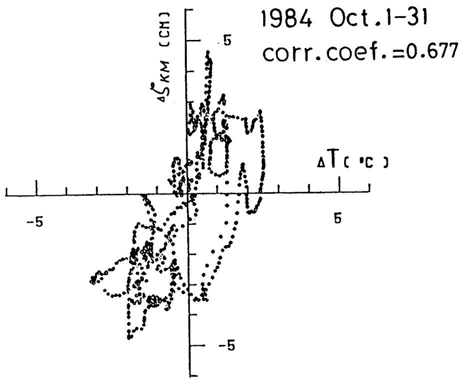

Fig. 12. Correlation between the deviation of sea water temperature (ΔT, ℃) at Sta. C bottom and the sea surface level anomaly ($\Delta\zeta_{KM}$, cm) (Oct. 1-31, 1984).

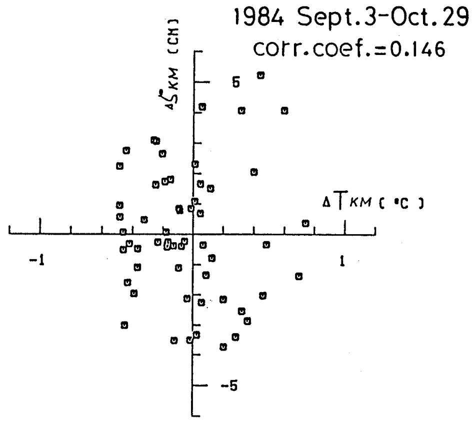

Fig. 13. Correlation between the sea surface level anomaly ($\Delta\zeta_{KM}$) and the local difference of sea surface water temperature (ΔT_{KM}, Kamaishi and Miyako, data is one a day) (Sept. 3-Oct. 29, 1984).

(about 45 km). The tendency that the amplitude of $\Delta\zeta_{OK}$ was a little smaller than that of $\Delta\zeta_{KM}$ was speculated to occur because the distance between Ofunato Bay and Kamaishi Bay was about 35km which was fairly shorter than a half of the space scale of the internal long period waves. Also, the amplitude of $\Delta\zeta_{KM}$ (3-4 cm) in Fig. 10d was a reasonable order in relation to the magnitude in the density difference of sea water ($\Delta\rho=0.0011$-0.0017) in the surface and bottom layers, compared with the vertical displacement of the thermocline (H_L: about 20m, estimated later) caused by propagation of the internal long period waves ($\Delta\zeta_{KM}/H_L=\Delta\rho/\rho$, $\Delta\zeta_{KM}=0.0017\times 20m=3.4cm$).

Next, the relation of the time changes in $\Delta\zeta_{KM}$ (or $\Delta\zeta_{OK}$) and in the vertical displacement of the thermocline will be examined. Unfortunately, there was no continual record of the vertical displacement of the thermocline during this observation. Hence, the record of sea water temperature (after 25 hours running mean) in the bottom layer at Sta.C in Toni Bay was treated instead of the vertical displacement of the thermocline. When the thermocline becomes shallower (deeper), the deviation of sea water temperature in the bottom (ΔT, ℃) will decrease (increase). The correlation between $\Delta\zeta_{KM}$ and ΔT was positive and the correlation coefficient (α) was 0.68 (Fig. 12). This meant that negative $\Delta\zeta_{KM}$ corresponded to the lower sea surface level near Kamaishi than that near Miyako, and the lower sea surface level corresponded to a shallower thermocline near Kamaishi in the internal mode. Consequently, a shallower thermocline corresponded to the lower water temperature in the bottom layer of Toni Bay near Kamaishi. The positive correlation between $\Delta\zeta_{KM}$ and ΔT in Fig. 12 was very reasonable. These results suggested propagation of a wave from Miyako Bay to Ofunato Bay, and supported statistically the existence of the internal long period waves.

However, there was another possibility of high correlation between $\Delta\zeta_{KM}$ and the deviation of sea water temperature; the time change of $\Delta\zeta_{KM}$ was possible to depend on the variation of the local difference of sea surface water temperature between Kamaishi Bay and Miyako Bay (ΔT_{KM}, ℃). NISHI and KUNISHI (1985) investigated the influence of the local difference of sea water temperature in the surface layer upon the difference of sea levels in two distant stations off Shikoku Island. In the present study, there was no relationship between $\Delta\zeta_{KM}$ and ΔT_{KM} (the latter was only one observation each day, Fig. 13). Therefore, the variation of $\Delta\zeta_{KM}$ and $\Delta\zeta_{OK}$ was possibly due to the internal long period waves, and the existence of the internal long period waves was highly possible.

The space scale (about 100 km) was a match for the time scale (several days) of the internal long period waves. Thus, the space scale through the local difference of sea surface levels in the two bays also verified the propagation of the internal long period waves along the Sanriku coast.

As mentioned above, the intermittency of the internal tidal waves in Toni Bay was attributed to the propagation of the internal long period waves accompanied by the vertical displacement of the thermocline. The internal long period waves were independent of the internal tidal waves in their mechanism of generation and propagation. The superposition of these two kinds of waves created a

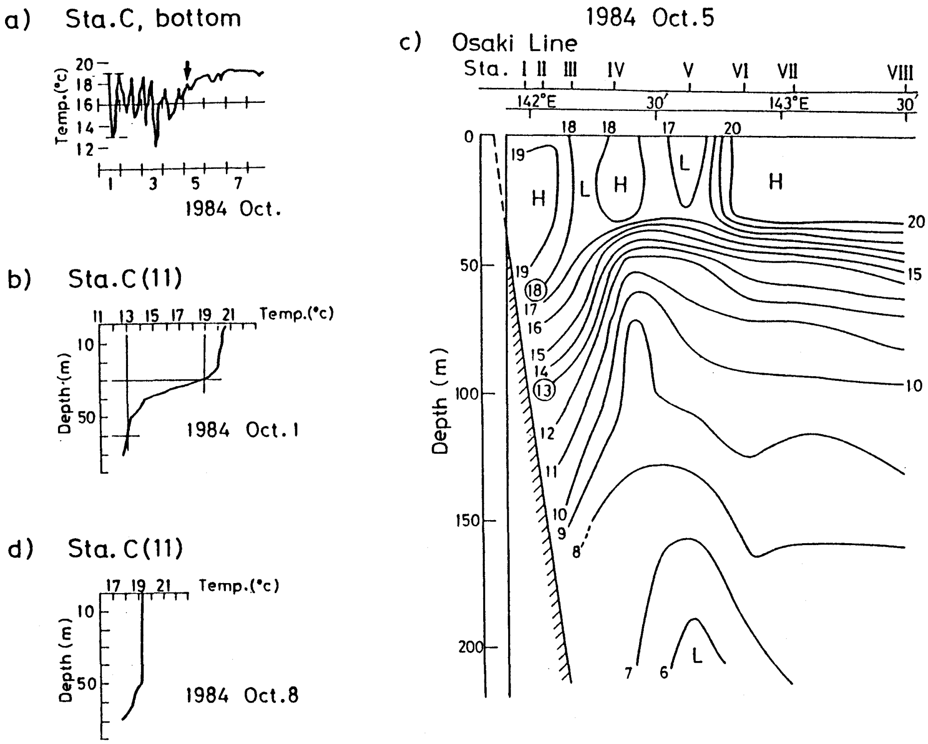

Fig. 14. Time series record and vertical distributions of sea water temperature. a) Time series record of the sea water temperature at Sta. C bottom (Oct. 1–7, 1984). Arrow corresponds to the observation time of vertical distribution of sea water in c). b) Vertical distribution of the sea water temperature at Sta. C (Oct. 1, 1984). c) Vertical distribution of the sea water temperature in Osaki line (Oct. 5, 1984). d) Vertical distribution of the sea water temperature at Sta. C (Oct. 8, 1984).

new phenomenon (the intermittency of the internal tidal waves) in the bay.

The wave heights of the internal tidal waves and the internal long period waves

From two kinds of records of water temperature in Fig. 14, wave heights of the internal tidal waves (H_T) and the internal long period waves (H_L) were estimated. From the continual record of the sea water temperature (Fig. 14a) in the bottom layer (58 m deep) at Sta.C, the sea water temperature fluctuated semidiurnally between 19 and 13℃ on 1 October. As the magnitude of the semidiurnal fluctuation is related to the height of the internal tidal wave (H_T), H_T can be estimated when the vertical distribution of the sea water temperature is simultaneously obtained. Fig. 14b is the vertical distribution of the sea water temperature at Sta.C in the afternoon on 1 October and shows a very conspicuous thermocline in the bay. The isotherm of 19℃ was 30 m deep and that of 13℃ was 60 m deep, and the difference of these depths was about 30 m. From (a) and (b) of Fig. 14, the wave height of the internal tidal wave (H_T) was estimated to be about 30 m (on 1 October).

On the other hand, the continual record of sea water temperature in Fig. 14a shows a fluctuationless period of water temperature higher than 18℃ at the bottom in several days after 5 October. This shows that the warmer sea water in surface layer extended all layers and the thermal stratification of sea water was weak in the bay (Fig. 14d). The thermocline existed in the bay on 1-4 October and then it sank deeper and disappeared in the bay on 5-8 October (Fig. 14a, d). The vertical distribution of offshore water temperature (in the Osaki line) was obtained in the morning of 5 October and the sea water of 18℃ was distributed from the sea surface to about 60 m deep (Fig. 14c), and the corresponding sea water temperature at 58 m deep (the bottom layer) in the bay was about 18℃ (indicated by the arrow in Fig. 14a). The sea water of 13℃ found at about 60 m deep in the bay on 1 October (Fig. 14a, b) descended about 40 m from 60 m deep to 100 m deep on 5 October (Fig. 14c). This vertical movement of the isotherm probably corresponded to the vertical displacement of the thermocline by the superposition of the internal tidal wave (H_T) and the internal long period wave (H_L). Therefore, the wave height of the internal long period wave (H_L) of about 10 m was obtained as the difference of 40 m ($H_T + H_L$) and 30m (H_T). In addition, the sea water temperature of 18℃ in the morning of 5 October was not the maximum temperature of the sea water yet, but the maximum temperature (about 19℃) was found on 7-8 October (Fig. 14a). This meant that, for example, the maximum depth of the isotherms on 7 October in phase with the deepest thermocline might be found about 10 m deeper than that on 5 October (Fig. 14a, c). Accordingly, the vertical displacement of waves ($H_L + H_T$) of about 50 m corresponded to the height of the internal long period wave (H_L) of about 20 m. Ultimately, the height of the internal long period wave in the beginning of October 1984 was estimated about 20 m in the Sanriku coastal seas.

The internal long period waves and the behavior of offshore front at sea surface

Considering the characteristic ocean structures off Sanriku containing the Tsugaru Warm Current (coastal boundary current), the internal long period waves are very possibly the internal coastal boundary wave.

In some satellite images, there is often a solitary wavelike behavior of a clear front at the sea surface between the Tsugaru Warm Water (TWW) and the Oyashio Cold Water (OCW) off the Sanriku coast. In autumn 1984, TWW spread over the eastern sea area of the Tsugaru Strait. For example, it was found in satellite picture images that the offshore convex-shaped front moved southward with a phase speed of about 16 cm/sec (Fig. 15, YASUDA *et al.*, 1987). This propagation speed of the offshore convex-shaped front was quite similar to the propagation speed (19 cm/sec) of the internal long period waves described above and this suggested some relationships between them. The offshore front between TWW and OCW extended the thermocline in the coastal sea area, and the thermocline became deeper approaching the coast (Fig. 14c). From this relation between them, the vertical displacement of the thermocline nearshore was possibly related to the offshore convex-shaped front.

There are many examples of the coastal boundary currents with the sea surface front and those flow generally along the coast on the right-hand side (in the northern hemisphere) in the world ocean. The wavelike behavior of those oceanic fronts is clearly seen in recent picture images of satellites.

Theoretical research on the wavelike behavior of oceanic fronts has been activated in the 1980's.

The semigeostrophic coastal current has two waves in a reduced gravity model in which a little lighter sea water (of uniform potential vorticity) in the upper layer flows along the coast as quasi-geostrophic current over a heavier sea water (of no flow) in the lower layer which has a thickness much larger than that of the upper layer (KUBOKAWA and HANAWA, 1984; KUBOKAWA, 1986). The first wave is a Semigeostrophic Coastal Wave (SCW, Kelvin wave type) and is characterized by the variation in the depth of the upper layer near the coast without change in the breadth of the current. The second wave is a Semigeostrophic Frontal Wave (SFW) characterized by the variation in the breadth of the current and propagates upstream. This was a very simple model neglecting the flow in the lower layer and the sea bottom configuration.

Following these papers, KUBOKAWA (1987, 1988a, b) studied a two layer model with a finite depth of the lower layer, taking into account the effects of shallow depth nearshore and the flow in the lower layer. When there is a flow in the upper layer and the mean flow is zero in the lower layer, a pycnocline between the two layers inclines and a vorticity gradient arises in the lower layer, and the wave of vorticity mode appears in the lower layer. When the wave of vorticity mode in the lower layer couples with SFW in the upper layer, the baroclinic instability is generated and the disturbance of the density front propagates at the speed of the wave of vorticity mode in the lower layer. This disturbance of the front from the baroclinic instability exists when the basic current in the upper layer is weak near the coast or the breadth of the current is large. These conditions were satisfied in the Sanriku sea area in autumn 1984. Furthermore, KUBOKAWA showed that it was possible to grow for small amplitudes of the initial disturbance of the front by coupling the waves of two types in the upper and lower layers as mentioned above, if its initial amplitude was larger than the critical amplitude, even though the basic flow was linearly stable in the upper layer or the basic flow was not small near the coast.

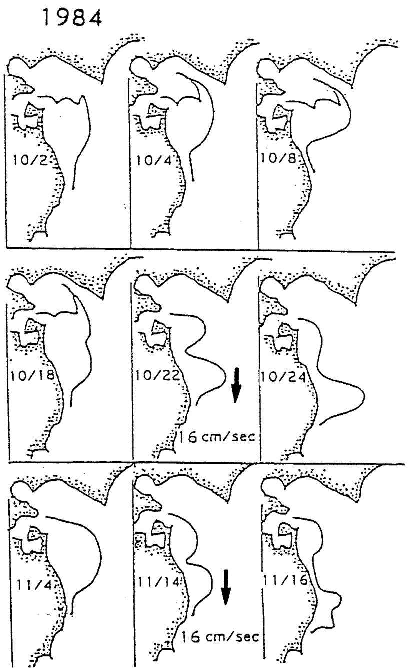

Fig. 15. Wavelike behavior of the sea surface front between the Tsugaru Warm Water and the Oyashio Cold Water from satellite images (by YASUDA *et al*., 1987). Arrow: the propagation of wavelike front.

This process suggests some possibility that the frontal disturbance propagates southward along the Sanriku coast with a phase speed of shelf waves, after warmer sea water spread in the eastern sea area of the Tsugaru Strait. The frontal disturbance traveling southward

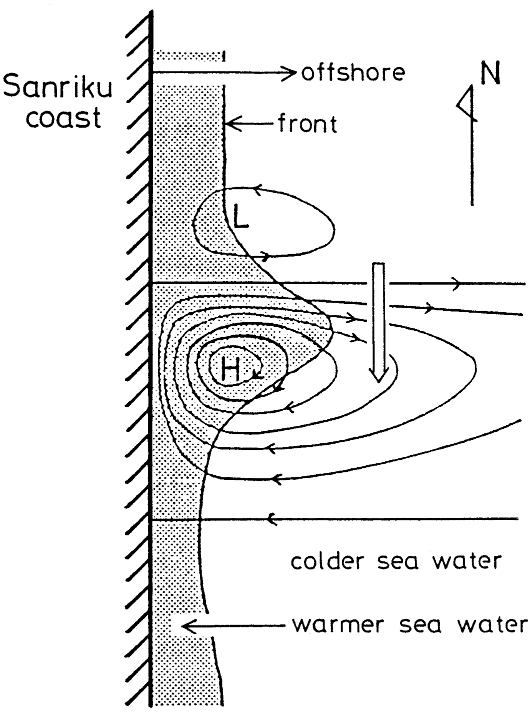

Fig. 16. Schematic diagram of circulation of cold sea water in the lower layer and growing solitary disturbance (wavelike front). The shadow indicates the warm water, and the solid lines represent the stream lines in the lower layer. This indicates that the cold sea water in the lower layer flows ashore at downstream side (southward) of wavelike front and the pycnocline becomes shallower (by KUBOKAWA, 1988b).

is accompanied by clockwise circulation in the lower layer at the downstream side (southward) of the peak of the frontal disturbance (the convex-shaped front) and counterclockwise circulation in the lower layer at the upstream side (northward) of the peak (Fig. 16). For this reason, the sea water in the lower layer tends to flow ashore and then the pycnocline becomes shallower in the southern coastal sea area of the peak of the frontal disturbance. Therefore, when the frontal disturbance approaches the northeastern sea area of Toni Bay, the pycnocline (thermocline) becomes shallower in the coastal sea area near Toni Bay (KUBOKAWA, 1987,

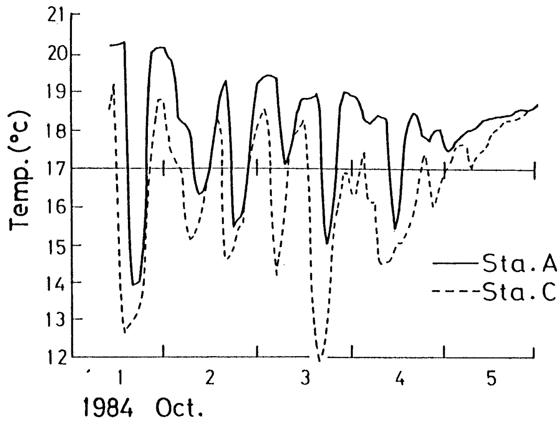

Fig. 17. Comparison of sea water temperature fluctuations at the bottom of Sta. A with those at the bottom of Sta. C (Oct. 1-5, 1984). —, Sta. A (at the bay head). -----, Sta. C (at the bay mouth).

1988a, b).

It was speculated that the internal long period waves were related to the behavior of the frontal disturbance offshore of Sanriku. It is important that some evidence for the existence and the propagation of the internal long period waves was obtained from the observation record in the coastal seas and was supported by a theoretical model study.

2) Propagation of the internal tidal waves into shallow bay

a) Phase speed and direction in propagation of the internal tidal waves

The propagation speed of the internal tidal waves was in the range of 35-50 cm/sec from the phase lag in sea water temperature records at the bottom between Sta.C and Sta.A and the distance between them (Fig. 17). If the median value, 42 cm/sec, was a typical propagation speed, the wave length of the semidiurnal internal tidal wave (L) was estimated about 20km (16-23 km, L = phase velocity × period (12.5 hours)). Those waves traveled from the northeast as estimated by the cross correlations of velocity components (U) at Stations B, C, D in Toni Bay (Fig. 1). MATSUNO (1989) reported that the propagating direction of the internal tidal wave in his observation was from the east in the Joban coastal seas. This difference in the direction

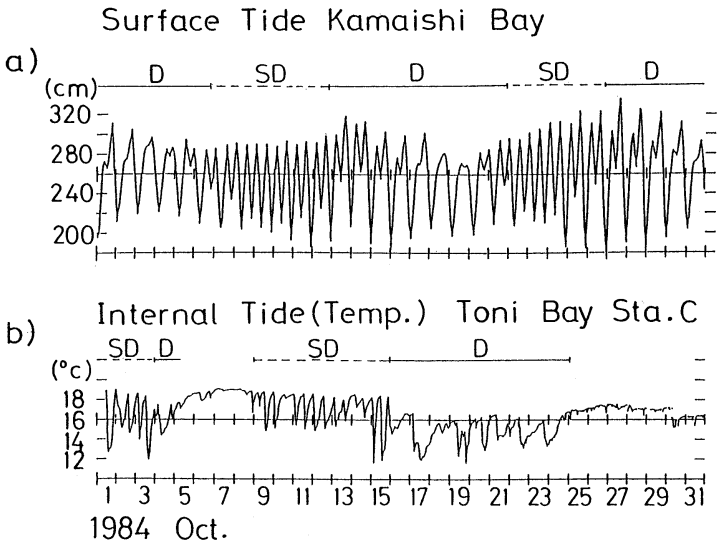

Fig. 18. Records of sea surface tide and the internal tide (sea water temperature) (Oct. 1-31, 1984). D, term of diurnal period fluctuation. SD, term of semidiurnal period fluctuation. a) Sea surface tide at Kamaishi Bay. b) Sea water temperature at Sta. C bottom in Toni Bay.

of propagation might be due to the offshore bottom configuration as a source area of the internal tidal wave.

The relation of the surface tide and the internal tidal wave

The period type is shown as D or SD in Fig. 18; "the day of diurnal period type (D)" was defined as the day when one in two peaks of fluctuation in a day was less than half of the other, and "the day of semidiurnal period type (SD)" was defined as two peaks of fluctuation in a day were comparable in amplitude. The surface tide was compared with the internal tide (subsurface water temperature); the internal tide had a semidiurnal period but the surface tide had a diurnal period for 1-3 October. Both had a semidiurnal period for 9-12 October, and the surface tide had a diurnal period but the internal one had a semidiurnal period for 13-15 October. For 16-21 October, both of them had a diurnal period. The surface tide was different in the period type from the internal tide for 22-24 October. INABA (1981) reported that in Suruga Bay the internal tide (tidal current) was predominant in the diurnal fluctuation from the observations of currents in the subsurface layer but the surface tide was prevailing in the semidiurnal fluctuation. The relation between them in Toni Bay was more complicated than that in Suruga Bay.

The surface tide already had a diurnal period on 1 October and the beginning day of a diurnal period was unknown, but the internal tide changed to the diurnal period on 4 October. The surface tide changed to the diurnal period on 13 October, and the internal one changed on 16 October. The beginning day of the diurnal period in the internal tide seemed to be 3-4 days behind that in the surface tide. If the internal tidal waves were generated far offshore by obtaining energy from the surface tide, the internal tidal waves with lower propagation speed than that of the surface tide must arrive at the coast behind the surface tide and both of the period types did not coincide at the coast. If the delay time of the internal tidal wave was 3-4 days and its propagation speed was 42 cm/sec, the generation area of the internal tidal wave was estimated at about 110-150 km offshore. The northeast sea area at 110-150 km from Toni Bay was the edge zone where the sea bottom configuration changed from the conti-

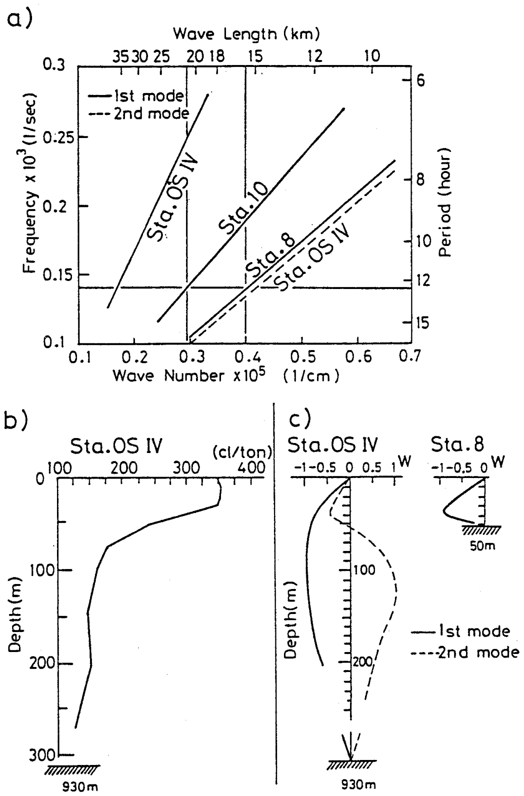

Fig. 19. Comparison of the dispersion relations of the internal tidal waves in Toni Bay with those offshore. a) Comparison of the dispersion relations: thick line, 1st mode; broken line, 2nd mode; thin line, wave length range at semidiurnal period. b) Vertical distribution of specific volume anomaly (cl/ton) of sea water at Sta. OSIV offshore. c) Comparison of vertical distributions of the vertical velocity at Sta. 8 with those at Sta. OSIV. Abscissa, ratio to maximum velocity.

nental slope to the slope of the Japan Trench.

b) Relationships between offshore internal tidal waves and those in Toni Bay

Comparison of the dispersion relations of the internal wave in a bay with that offshore

The internal tidal waves are able to propagate into a shallow bay only in the case of a thermocline formed initially in a bay. Fig. 19a shows the dispersion relations of the internal waves calculated from the vertical distribution of sea water density observed at stations inside and outside of Toni Bay. The dispersion relations of the internal wave at Sta.8 and Sta.10 were calculated as the representative data in the bay, and Sta.OSIV (930 m depth, 36 km offshore) was a representative offshore station and the vertical distribution of the specific volume anomaly of sea water at Sta.OSIV was shown in Fig. 19b. If the period was semidiurnal, the wave length of the 1st mode at Sta.OSIV was 35–40 km, and this was inconsistent with the estimated wave length (about 20 km) from observations in Toni Bay (Fig. 19a). The dispersion relation of the 2nd mode at offshore Sta.OSIV was very similar to that of the 1st mode at Sta.8 and Sta.10 in the bay. In this semidiurnal internal wave, the wave length was 16–23km from the estimated speed of 35–50 cm/sec from observations in the bay (thin lines in Fig. 19a show this range). This wave length (16–23km) was easy to resonate with the length of Toni Bay (about 5 km; length of area deeper than 20 m depth). The properties of the 1st mode of the internal tidal waves in the bay were nearly equal to those of the 2nd mode of the internal tidal waves outside of the bay, and the vertical distribution of vertical velocity (W, cm/sec) was also similar in the internal waves inside and outside of the bay (Fig. 19c).

In conclusion, these results showed that the 2nd mode of the internal tidal wave offshore was well related to the 1st mode of that in Toni Bay.

Comparison of propagation ratio of the energy of the internal wave into shallow bay

The probability that the 1st or the 2nd mode of the internal waves offshore propagates into a bay was studied by analytical calculation in a simple model in which the depth in the bay was 50 % of the depth outside of the bay and the basic condition of the vertical distribution of sea water density (ρ) outside of the bay was a constant Brunt-Väisälä Frequency, $N^2 = -(g/\rho) \times (\partial\rho/\partial z)$ (CRAIG, 1987). The left in Fig. 20a is the case of initially given the 1st mode of the internal wave outside of the bay, and the density of stream lines indicates the energy

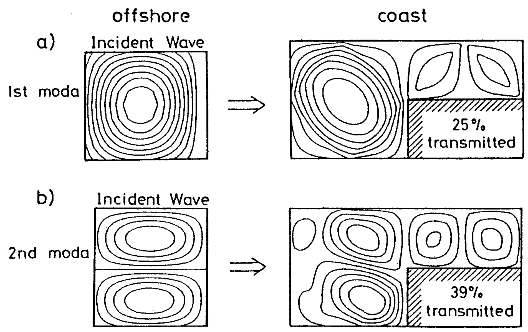

Fig. 20. Transport efficiency of the internal wave energy propagating into the shallow bay from the offshore sea. Solid lines represent stream lines. a) The case that the incident wave is the 1st mode of the internal wave. b) The case that the incident wave is the 2nd mode of the internal wave.

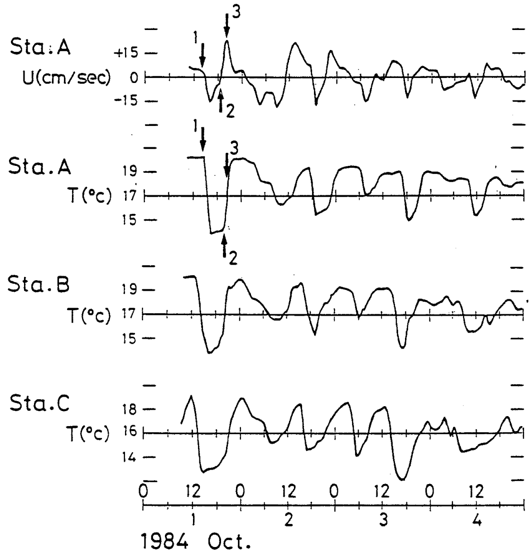

Fig. 21. Fluctuation patterns of sea water temperature and velocity component at bottom in Toni Bay (Oct. 1-4, 1984).

level. The right in Fig. 20a is the distribution of stream lines after the internal wave propagated into a shallow bay, and it shows that the wave energy transported into the bay is 25 % of the offshore incident wave energy. The case of initially given the 2nd mode of the internal wave outside of the bay is shown at left in Fig. 20b. In this case, it is indicated that 39% of the wave energy of the 2nd mode of the offshore incident wave propagate into the bay. It is sure that more energy of the 2nd mode of the offshore internal wave propagates into the bay than the energy of the 1st mode of that wave.

Shoaling up of the internal tidal waves into the bay

As mentioned in chapter 3, the record of the internal tidal waves as fluctuations of the sea water temperature in the bottom layer suggested that there were two cases for the propagation of the internal tidal waves into a bay. The first was the general case of the internal wave, and the internal tidal waves propagated through the thermocline which was already formed in the bay. The second was the case of no thermocline initially in the bay and the thermocline was formed after colder sea water flowed into the bottom layer of the bay. In the second case, therefore, the thermocline in the bay disappeared in every cycle of the tidal period.

Semidiurnal periods for 1-3 and 9-15 October corresponded to the second case, because the sea water temperature in the bottom layer rose to near the sea surface water temperature in every tidal cycle (Fig. 6). After the colder sea water in the bottom flowed out of the bay, the thermocline disappeared in the bay. If the thermocline remained always in the bay and the internal tidal wave was dominant, a thermometer (contained in the current meter) in the bottom layer stayed always in the colder sea water under the thermocline (the general case), and the sea water temperature in the bottom layer should remain at 15-16℃ (Fig. 6). However, the sea water temperature in the bottom layer was found at 19℃, near that in the surface layer (about 20℃) in the record. In particular, for 9-15 October, the maximum sea water temperature in the bottom layer agreed almost with that in the surface layer. This suggested that "a colder sea water front" shoaled up on the bottom of the bay every semidiurnal tidal cycle.

The raw records of velocity (eastward component (U), in the bottom layer at Sta.

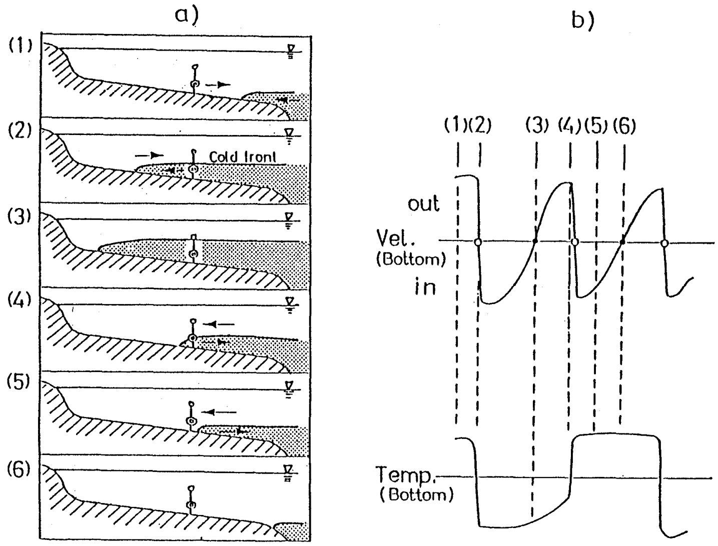

Fig. 22. Schematic pictures of shoaling up of the colder sea water front, and the corresponding figure of variations of velocity and sea water temperature at the bottom in the bay. a) Schematic pictures of the moving cold front : (1) cold front starts to flow into bay, (2) cold front passes the station into bay, (3) cold front stops at head of bay, (4) cold front flows out of bay, (5) cold front passes the station out of bay, (6) cold front stops out of bay. b) Schematic figure of variations of the velocity component and sea water temperature at the bottom in the bay. (1)-(6) correspond to (1)-(6) in figure (a).

A) and the sea water temperature (in bottom layer at Stations A, B, C) for 1-4 October are shown in Fig. 21. Fluctuation curves of the sea water temperature are not a sinusoidal pattern but have a peculiar pattern. On 1 October, the sea water temperature fell and rose suddenly at all stations and they were different from a sinusoidal wave. If it was the general case (the first case), the changes of the sea water temperature and that of direction of velocity (U) must occur simultaneously in the time when the thermocline passed the station of the thermometer (as shown by arrows 1 in Fig. 21). But, Fig. 21 showed that the sea water temperature changed at a different time from the change in the direction of velocity (as shown by arrows 2 in Fig. 21). At Sta.A, at 14:00 on 1 October when the flow changed suddenly from outward ($U>0$) to inward ($U<0$), the sea water temperature changed simultaneously to colder suddenly (arrows 1), but at 19:00 when the flow changed to outward, the sea water temperature was steady (arrows 2), and when the speed of the flow reached positive maximum, the sea water temperature began to be warmer (arrows 3).

The time interval of the minimum temperature on 1 October in the bay mouth (Sta.C) was longer than that in the bay head (Sta.A). This suggested that the flow in the bottom of the bay was not the internal wave case with steady thermocline in the bay, but was the shoaling up and down of the colder sea water front on the bottom of the bay.

The process of the shoaling up and down of the colder sea water front in the bay will be inferred in the schematic picture (Fig. 22).

At the beginning, the colder sea water front starts shoaling up from the bay mouth into the bay which is filled with warmer sea water only, and the flow at a station of the thermometer is outward ($U>0$), (1) in Fig. 22. When the colder front passes the station toward the bay head, the direction of velocity changes to flow inward ($U<0$) and the sea water temperature falls abruptly to the minimum, (2). The colder sea water front keeps on flowing inward and then stops at the bay head, (3). When the internal tide starts to ebb, the colder front at the bay head starts to shoal down and the direction of the flow at the station changes to outward of the bay ($U>0$), but the sea water temperature remains at almost the minimum, (4). When the colder front passes the station toward the bay mouth, the direction of velocity changes inward ($U<0$) and the sea water temperature rises suddenly up to the maximum, (5). Afterward, the colder front continues to flow outward and stops outside of the bay, (6). At this time, there is only the warmer water in the bay. Those variation patterns were similar to the variation patterns of the observed record of 1-2 October (Fig. 21).

In the case of the semidiurnal fluctuations in the beginning of October, it was concluded that the occurrence of the stratified structure in Toni Bay was temporal and cyclic, and the propagation of the semidiurnal internal tidal wave into the bay must be the shoaling up of the cold sea water front.

CAIRNS (1967) reported on the internal tidal bore in the shallow sea off south California, from the variation pattern of the water temperature observed by thermister arrays. His variation pattern was similar to the shoaling up in Toni Bay, and the shoaling phenomenon seemed to be considerably important in the exchang of the sea water in a shallow bay.

5. Summary

A study of the internal tidal waves in a small bay was carried out on the basis of the observed records in Toni Bay, autumn 1984.

1. The internal tidal waves in the bay were predominant and had the characteristics of intermittent occurrence in several days. From T-S diagram analyses of the sea water property at stations inside and outside of the bay, the property of the sea water in the bottom layer was closely related to that of offshore sea water in the layer (70-100 m deep, this was the depth under a thermocline) a little deeper than the bottom layer in the bay. It was found that the intermittency of the internal tidal waves was related to the vertical displacement of the thermocline outside of the bay, namely the internal tidal waves appeared in the bay predominantly when the thermocline became shallower.

2. The cause of the intermittent vertical displacement of the thermocline was investigated through the analyses of (a) variations in subsurface water temperature and (b) variations of the local difference of tidal deviations (sea surface level anomaly) at three stations along the Sanriku coast.

a) The cross correlation of variations of the sea water temperature in the surface layer between in Toni Bay and in Otsuchi Bay was very high with a correlation coefficient (α) of 0.89, and the phase of the variation in Otsuchi Bay was in advance of that in Toni Bay. It was found that the variation of the sea water temperature (variation of the thermocline depth) propagated southward at a speed of about 19 cm/sec. This was considerably lower than the wave speed of a coastal trapped wave (internal Kelvin wave, more than 30 cm/sec). The variation of the thermocline depth seemed to be due to a kind of the internal long period wave propagating southward alongshore.

This propagation speed was similar to the southward propagation speed (16 cm/sec) of the pycnocline front with a convex shape at the offshore edge of the Tsugaru Warm Waters from satellite images. It was suggested that the internal long period waves were related to the behavior of the pycnocline front. Recent theoretical research showed that the frontal disturbance propagated as a coupled wave of Semigeostrophic Frontal Wave in the upper layer (KUBOKAWA and HANAWA, 1984) with the wave to be restored by potential vorticity in the lower layer. This frontal disturbance travels southward accompanied by clockwise circulation in the lower layer at the downstream side of the peak of the front (KUBOKAWA, 1987, 1988a, b), where the sea water in the lower layer tends to flow onshore and the thermocline becomes shallower. These features and the lower propagation speed of the frontal distribution were in good agreement qualitatively with those of the internal long period waves.

b) When the internal long waves propagate along the coast, it is expected that the sea surface level changes out of phase to the depth of the thermocline, even if it is very small. When the sea level at Kamaishi minus that at Miyako ($\Delta\zeta_{KM}$) was negative, the thermocline off Toni Bay (near Kamaishi Bay) must become shallower. Accordingly, the cold sea water offshore was able to intrude into the bottom of the bay, and the duration of negative $\Delta\zeta_{KM}$ corresponded to that of the predominant internal tide in the bay near Kamaishi. $\Delta\zeta_{KM}$ was highly correlated with the variation of the sea water temperature in the bottom layer of Toni Bay; the correlation coefficient (α) was 0.68. Another local difference ($\Delta\zeta_{OK}$) between Ofunato and Kamaishi was out of phase with $\Delta\zeta_{KM}$, which supported also the alongshore propagation of the internal long period waves. The results indicated the existence of the internal long period waves propagating alongshore with a suitable space scale to their time scale, because the distance between Miyako and Kamaishi (45 km) was nearly a half wave length of the wave with time scale of several days and wave speed of 19 cm/sec.

The internal long period waves were independent of the internal tidal waves in their generation and propagation. The internal tidal waves appearing intermittently in the bay occurred from the superposition of the internal tidal waves propagating onshore and the internal long period waves propagating alongshore.

3. The propagation speed of the internal tidal waves was estimated about 42 cm/sec (35-50 cm/sec) from the observations. The source area of the internal tidal waves was roughly estimated at 110-150 km northeast from Toni Bay. The dispersion relation of the 1st mode of the internal waves in the bay was similar to that of the 2nd mode offshore. Moreover, the vertical distribution of the vertical veloctity of the lst mode of the internal waves in the bay was quite similar to that of the 2nd mode offshore. From the dispersion relations, the phase speed of the semidiurnal internal tidal waves was calculated aboout 40 cm/sec which was consistent with the phase speed estimated from the time lag of observed records mentioned above.

The energy flux transported into the bay due to the 2nd mode of the offshore internal wave was 1.6 times greater than that due to the 1st mode of the wave in an analytical calculation in a simple model. The semidiurnal internal waves in Toni Bay were closely related to the 2nd mode of the internal waves offshore.

In addition, it was suggested that the semidiurnal internal tidal waves shoaled up with the intrusion of a cold sea water front from offshore into the bottom layer of the bay.

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三陸沿岸における内部潮汐波と内部長周期波

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要旨: 内湾における内部潮汐波の特性について，1984年秋季，三陸沿岸の唐丹湾において行われた観測を基に，解析を行い次の事がわかった。
i）湾内の顕著な内部潮汐波は長期間連続的に現れるのではなく，数日程度の間欠性がみられた。湾内外の海水のT-S図解析の結果，この間欠性が水温躍層の深さの変動に関係していることが判明した。その間欠的上昇に応じて湾内底層に冷海水が流入して成層構造が形成され，内部潮汐波が間欠的に湾内に出現するものと考えられた。
ii）このような間欠的な水温躍層の深さの変動の原因を究めるため，唐丹湾近傍の2つの湾の水温変動の相関を調べ，また3つの湾の海面水位の変動と水温躍層の鉛直変動との関連を調べた。その結果，水温躍層は海岸に沿って北から南へ伝わる内部長周期波によって上昇することが示唆された。この内部長周期波は約19cm/secで南進し，約100km程度の空間規模を持っていることが示された。これは北東から岸向きに伝播する内部潮汐波とは独立な波であり，これら2つの波が重畳したときに，湾内の内部潮汐波に間欠性が現れる。この他，この内部長周期波は津軽暖水域東端の密度フロントの南への波動的伝播に関連のあることが示唆された。
iii）湾内外の観測データから求めた内部潮汐波の分散関係や波速等の比較，及び簡単なモデルによる沖合の内部波エネルギーの湾内への伝播効率の比較等の結果，湾内の卓越した半日周期の内部潮汐波は沖合のそれの第2モードに関連の深いことが示唆された。