PROCESS OF WATER EXCHANGE THROUGH THE MOUTH OF KAGOSHIMA BAY

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Abstract

This report presents an analysis of past observation of the current through the mouth of Kagoshima bay.

The result show: ① The flow pattern in February 1980 and 1981 accounts for 57% of the inflow in the upper layer and the outflow in the lower layer. ② The flow pattern in June 1980 and 1981 accounts for 55% of the outflow in the upper layer and the inflow in the lower layer. Next, we computed inflow and outflow volumes. The result show: ① The peak of the inflow corresponded to that of the outflow. ② A strong inflow current velocity became apparent in the east side upper layer when the inflow peaked.

During the observation periods extremely high inflow "events" occurred on five occasions and together accounted for a total inflow of $455 \times 10^8 m^3$. Total inflow apart from that at the time of these events was $260 \times 10^8 m^3$. Daily inflow during an event was $16.2 \times 10^8 m^3$. Daily inflow outside an event period was $7.7 \times 10^8 m^3$. From these figures it is clear that high inflow events have a great influence on the seawater exchange in the bay.

1. Introduction

It is the purpose of this paper to point out what phenomena plays an important role in exchange of sea water between Kagoshima bay and the open sea by means of direct measurement of current at some stations on the mouth of the bay and by utilizing temperature and salinity data. The exchange of sea water between a bay and an open sea occurs over wide range of time and in response to a variety of tidal current, meteorological forces, and density current. In the case of a bay opening upon Pacific Ocean, in addition to these forcing mechanisms, a direction of ocean current adjacent to a mouth of the bay and its changes play an important role in the exchange. For example, the circulation in Sagami bay is generally driven by Kuroshio and sometimes suddenly changes resulting from shift of its axis (S. Iwata, 1983). We call a sudden increase of inflow into the bay "Kyucho". The Kyucho occurs not only in such a bay which has a wide mouth opening upon open ocean but also in a bay which has a narrow mouth (M. Sakurai, Y. Nagata, K. Seki and D. Date 1970). The relative importance in the exchange depends on a configuration of the bay and on scales of time and space of the forcing mechanisms.

Kagoshima bay is some 60 km long and 21 km wide (Fig. 1). The bay is composed of northern and southern basins, which are connected by a narrow and shallow channel between Mt. Sakurajima and Kagoshima city, and of a sill between the southern basin and the open sea. The northern basin has the maximum depth of 200 m, the area of 243 km^2 and the volume 27 km^3. The southern basin has the maximum depth of 236 m, the area of 576 km^2 and the volume of 66 km^3. However, the sill has the depth of only 70 m

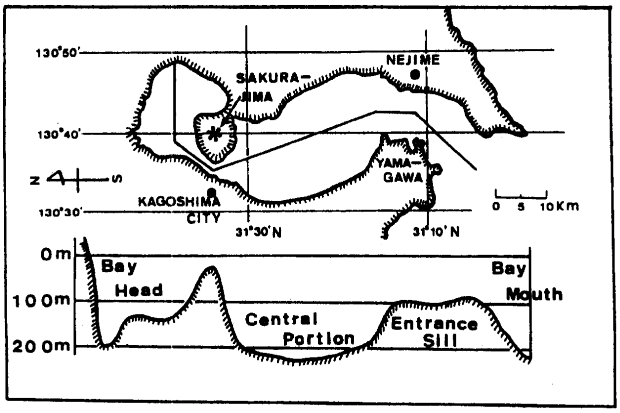

Fig. 1. Bottom topography in Kagoshima Bay.

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the cross section of only 0.7 km^2. The exchange of sea water between Kagoshima bay and the open sea occurs through such a small cross sectional area.

An investigation of the exchanges in Kagoshima bay should ideally extend over a time interval sufficiently long to include many times of the shift of current adjacent to the mouth, meteorological events lasting many days and monthly tidal periodicity's associated with the principal tidal constituents cycling. But unfortunately, a continuation of current measurement during such a long interval of time is usually impossible in Kagoshima bay, because fishing activities. We have only two chances to continue the current measurement during one mouth in February to March and in June a year.

Counterpart of Kuroshio on the south side of the mouth of the bay flows eastward to Oosumi peninsula (Fig. 2). The current shifts up north and strengthens on near the mouth two or three times a mouth (Y. Nagata and K. Takeshita, 1980). Meteorological factors in near Kagoshima bay usually vary with a period of three or four days. Accordingly, we can discuss the roles of the tidal current, the current near the mouth and its shift, and the meteorological forcing factors of the short time scale in the exchange of sea water by means of the direct current measurement during a mouth.

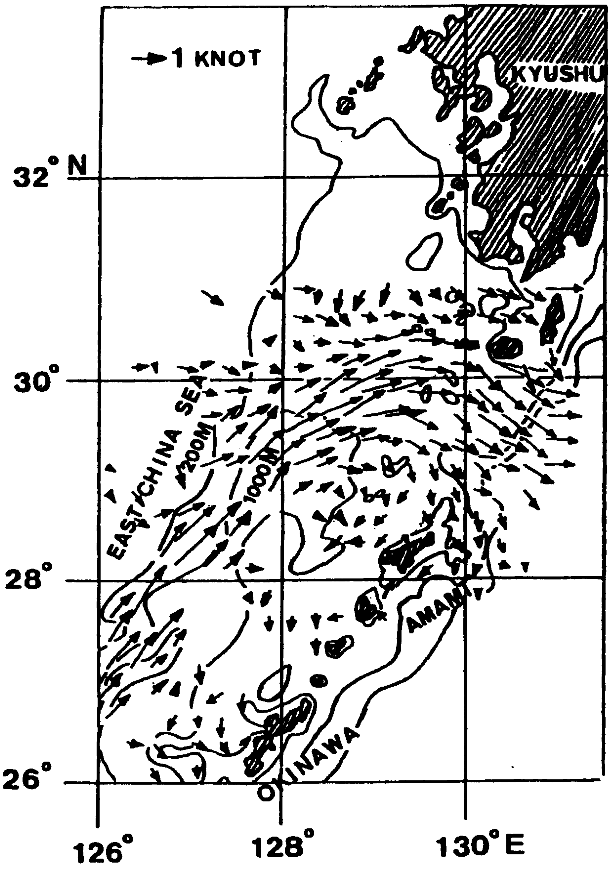

Fig. 2. Distribution of 25 years averaged surface flow direction south of Kyushu by GEK observations.

T. Takahashi (1974) estimated a flushing time at 110 days which is a time necessary for an outflow volume transport is calculated from velocities measured at several points on the cross section of the mouth. However, the accuracy of the volume transport is not satisfactory, because the measurement were made at different time among the points and during only one day.

He (1977) also estimated circulation's in summer and winter in a vertical section approximately along the axis of Kagoshima bay from temperature and salinity distributions in the section. However, the configuration of the bay and the current direction near the mouth suggests that the circulation on the horizontal plain is important in the exchange of sea water than that on the vertical section. We will estimate the horizontal circulation from an analysis of distributions of temperature and salinity observed on board of Nansei-maru (Department of Fisheries, Kagoshima University) and of Tansei-maru (Ocean Research institute, University of Tokyo).

2. Observations of temperature and salinity

Training ship "Nansei Maru" (Faculty of Fisheries, Kagoshima University) carried out serial observation every month about 5 years in the bay. Seasonal distribution of temperature, salinity and density determined on January for Winter, May for Spring, July for Summer and November for Autumn.

2-1. Horizontal circulation's

Seasonal distribution of salinity was determined on a isopycnal surface at $\sigma t = 25.1$ for Winter, $\sigma t = 24.6$ for Spring, $\sigma t = 23.0$ for Summer, $\sigma t = 23.6$ for Autumn. These layers corresponded to the depth at 20 m - 30 m. (See Fig. 3)

Horizontal circulation's in four seasons were examined from these distribution.

The horizontal distributions of salinity in May and July are similar, that is, higher salinity intruded

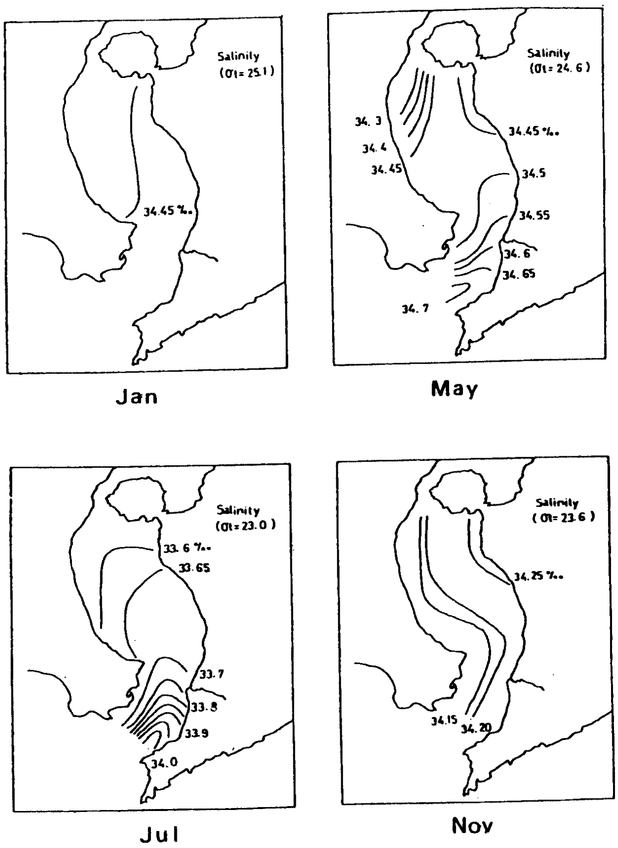

Fig. 3. Horizontal distribution of averaged seasonal variation of salinity on a isopycnal surface.

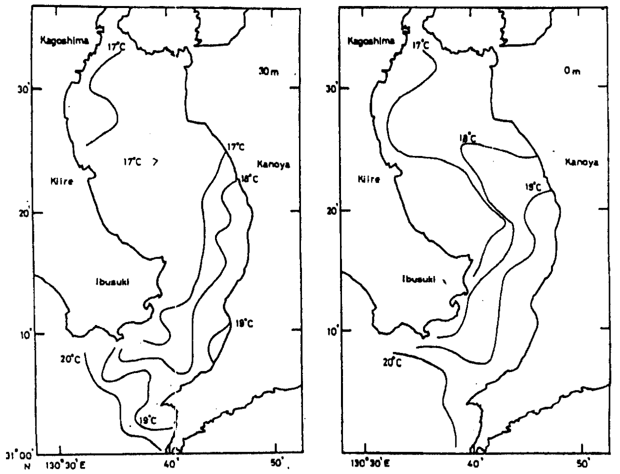

Fig. 4. Horizontal distribution of water temperature at 10 m (right) and 30 m (left) depths from January 31 to February 1, 1979.

along the eastern part of the bay and the contour line shaped the tongue like. Such tongue like intrusion does not exist in January and November, and the contour line runs from north to south. but it is also exist the high salinity in the eastern part of the bay.

Water temperature observation were carried out the cruises of R.V. "Tansei Maru" (KT-79-2) which belong to the Ocean Research Institute of the University of Tokyo, from January 31 to February 1 in 1979, 64 points in the bay. Horizontal distributions of water temperature 0 m and 30 m depth were obtained from DBT (Digital Bathythermograph) observation (Fig. 4).

Water temperature at 0 m depth is about 19 ℃ in the eastern part and is about 17 ℃ in the western part. Water temperature at 30 m depth has a maximum value 19 ℃ in the western part and has a little lower value of 17 ℃ in the western part. water temperature at two layers value are higher in the eastern part then in the western part of the bay. and the tongue like intrude from the eastern part. but water temperature at 50 m depth was nearly same in the whole of the bay and its value was 16 ℃ (not shown).

We see from both results of the isosteric analysis and water temperature distribution that the high salinity and temperature exist in the eastern part and the low that value exist in the western part in the bay. This may suggest that the warm water mass intrude through the eastern part in the bay. Horikoshi (1980) showed that he is caught the benthoses which live in the warm water more than subtropical water in the eastern part, but it is not caught in the western part in Kagoshima bay.

2-2. Vertical structure

A routine observations such as water temperature and salinity have been carried out around the Kagoshima from 1968 by the Kagoshima Prefecture Fisheries Experiment Station, and one of the observation line runs from north to south of central axis of the bay. Averaged values over the whole period from 1968 to 1983 in January and June are calculated and these results are shown in Fig. 5.

In the central portion, the density is nearly homogeneous of 25.0 to 25.1 from sea surface to about at 80 m depth (nearly equal to the entrance sill level) in January, and that water density is higher than outside of the bay. It may be formed that the high density of the central portion is due to cooling effect of the cold

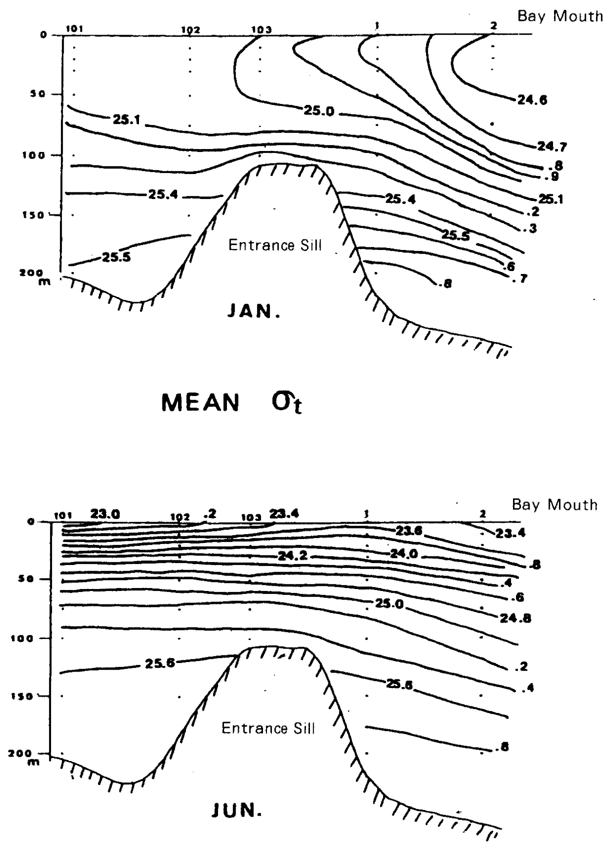

Fig. 5. Averaged vertical distribution of density along the bay axis line

atmosphere. It is suggest that the flow intrude into the bay from the surface to the entrance sill height level.

The other hand, the vertical structure of density is complete stratification in June. The central portion of the density near the surface layer is lower than outside of the bay. This decrease due to the drop of central portion salinity by precipitation. This is indicate that the low density in upper layer go out from the central portion to outside of the bay. In these results coincide with that of estimation by Takahashi (1977), but in the lower layer does not deference between inside and outside of the bay.

3. Observations and data analysis

3-1. Observations

Current meters were moored in the cross section about 10 km wide of Kagoshima Bay between Yamagawa and Nejime (See Figure 6). Eight current meters were used at four stations as show in Figures 6a and 6b. The measurements in February - March 1980, June - July 1980, February 1981 were made at the stations as shown in Figure 6a. The measurements in June 1981 were made at the stations as shown in Figure 6b. Date of the moorings are shown in Table 1. In an current meter a unit consisting of a Savonius rotor, magnetic compass and a temperature sensor.

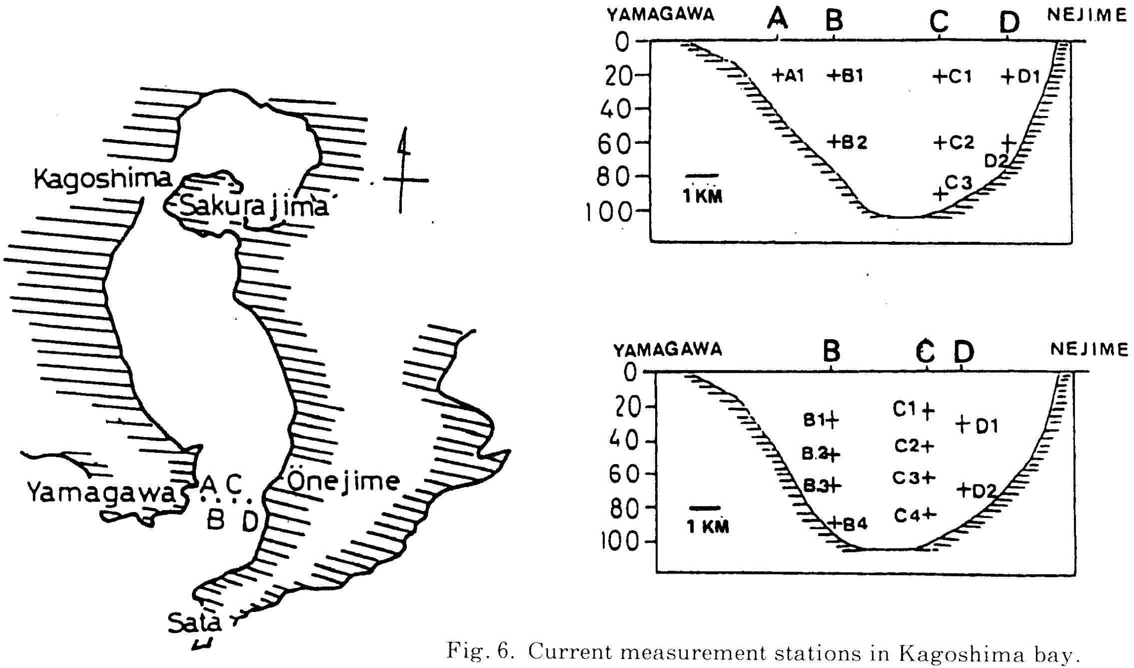

Fig. 6. Current measurement stations in Kagoshima bay. Mooring Station (left) and vertical section (right).

Table. 1 Periods of Observations

1.	13 Feb. ---16 Mar.	1980
2.	12 Jun. --- 1 Jul.	1980
3.	6 Feb. --- 24 Feb.	1981
4.	9 Jun. --- 24 Jun.	1981

The current speed and direction, temperature are recorded within the instrument on magnetic tape. There measured accuracy of respectively, ±0.012 m/s, ±1.4° and ±0.1℃.

3-2. Method of mooring

A mooring line adopted in this study is shown in Figure 7. Super tankers to the facility for crude oil reservation sail frequently through the bay north. A large number of fishing boats are operated everywhere in the bay. Trawl fishing is frequently operated. A maker buoy is necessary for warning to the trawling fish boats in order to protect the mooring line of current meters. The maker buoy on the sea-surface is apt to be lost by the ship traffic. Therefore, we used two marker buoys as shown in Figure 7. We have not been suffered from the loss of mooring line.

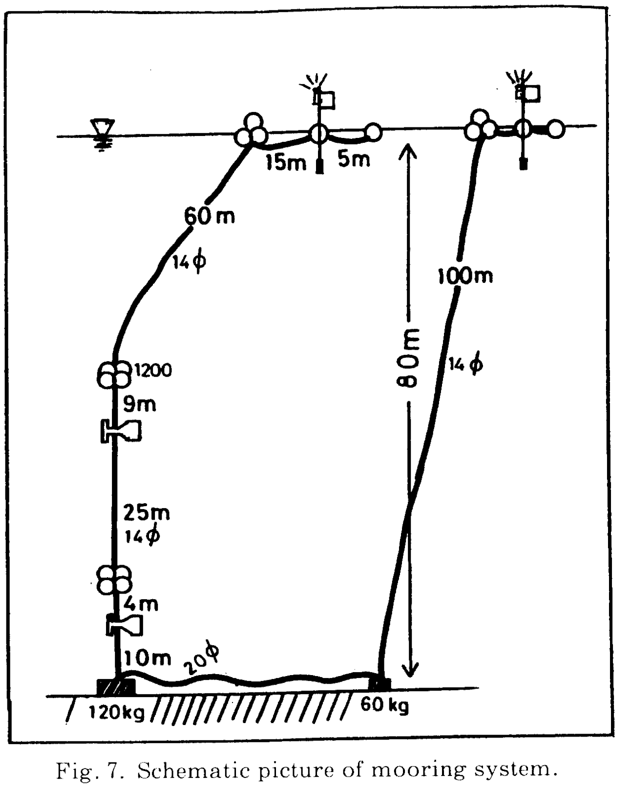

Fig. 7. Schematic picture of mooring system.

3-3. Analysis of the current record

Sampling interval of the current meter (TS-5A, Tsurumi Seiki) was selected to be five minutes. Natural frequency of bay oscillation is approximately 1/45 cycle per minute. The contamination due to the oscillation was expected to be reduced by the short sampling interval. The east and north components of velocity were computed from the record of the current meters. Northward velocity shows the flow into the bay, and southward velocity shows the flow out of the bay. Tidal currents were considered to be going and returning through the bay mouth. The velocity components were averaged by 25 hour running mean, in order to remove the tidal currents. The daily mean velocities at seven stations were plotted in a cross section of the bay. Contour lines showing a velocity profile were drawn from the daily velocities interpolating by the eye. Daily volume transports of the inflow and the outflow through the bay mouth were estimated from the current velocity profiles.

4. Results

Observed data of eastward velocity, northward velocity and water temperature are shown in Figure 8(a) - 8(d). The heavy solid line show the 25 hour running mean. The tidal current has dominant component of semi-diurnal. It is the average progressive wave of an amplitude of 20 cm s^{-1} ~ 30 cm s^{-1}. The maximum tidal current is 40 cm s^{-1}. The horizontal displacement during one half tide period when the tidal current is 30 cm s^{-1}, it is about 7 km.

The other hand, from the current data of the 25 hour average current speed (hereafter denoted by daily mean velocity in this paper), the maximum speed inflow is 28 cm s^{-1} on 27 February 1980 in winter and 31 cm s^{-1} on 17 June 1981 in summer, and the outflow is 17 cm s^{-1} on 16 February 1981 in winter and 25 cm s^{-1} on 17 June 1981 in summer.

We see that the duration of the inflow or the outflow continues 5 days to 15 days. If the constant flow speed is 30 cm s^{-1}, this displacement is about 10 km day^{-1} to the constant direction, therefore, we see that the effect of for the daily mean velocity of water renewal in the bay is lager than that tidal current.

In February that in the large fluctuation of northward current speed in the upper layer centered around in the section is accompanied by water temperature fluctuation. Water temperature began to goes up a half or one day after the north-ward strong current began (see Fig. 8(a), 8(b)).

In June that the flow direction between in the upper and in the lower layers are out of phase (see Fig. 8(d)).

The flow direction and its speed differ from station to station. An instance, that in February 1980, in the constant flow direction in the upper layer at Sta. C 1 change between the inflow and the outflow at intervals of several days. On the other hand, the same time flow direction at Sta.B2 are only outflow. This things give suggestion that the inflow and the outflow aria are time variations.

Accordingly, we will examine day to day variations which the daily mean velocities are plotted in a cross section.

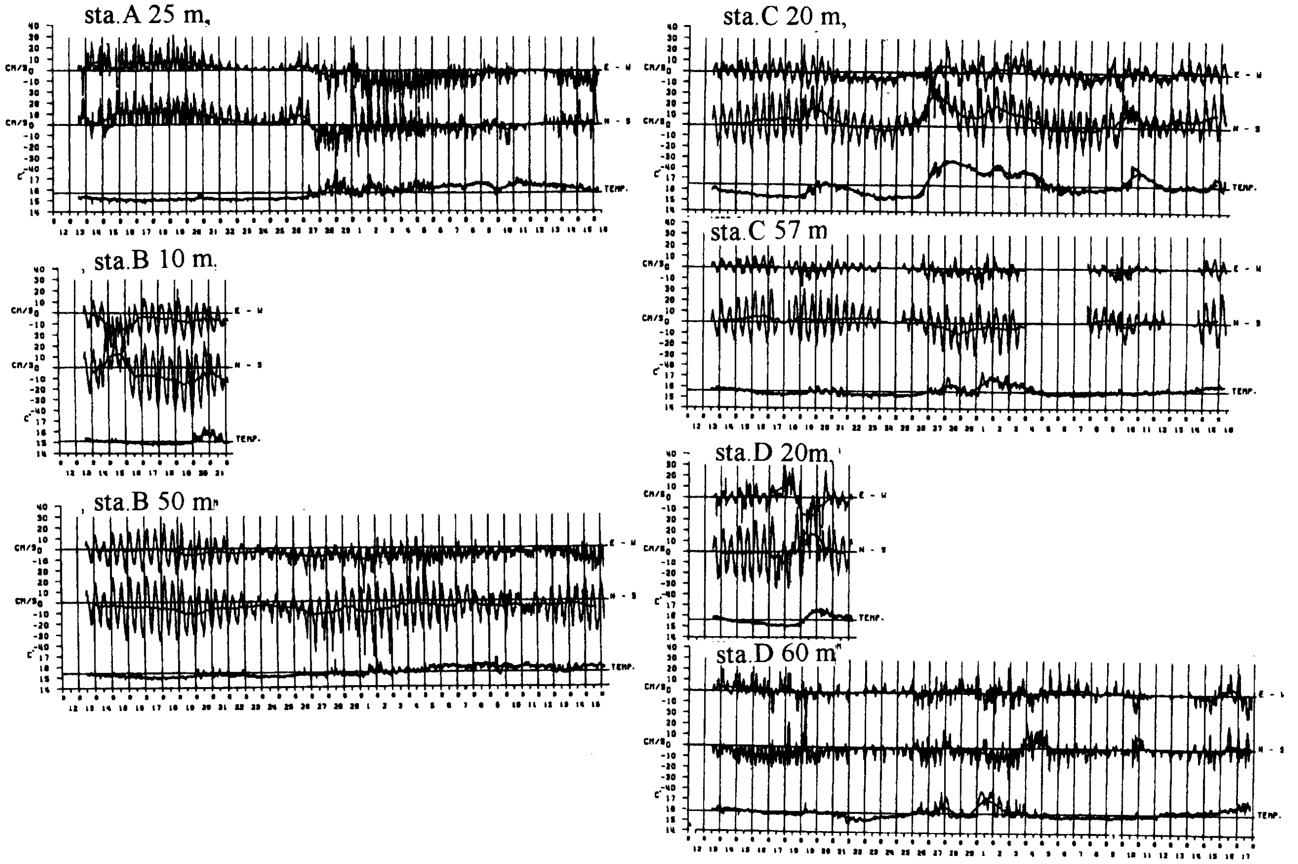

Fig. 8(a). Eastward velocity, northward velocity and mater temperature fluctuations.
Heavy solid line show the 25 hour running mean.
13 February – 16 March, 1980

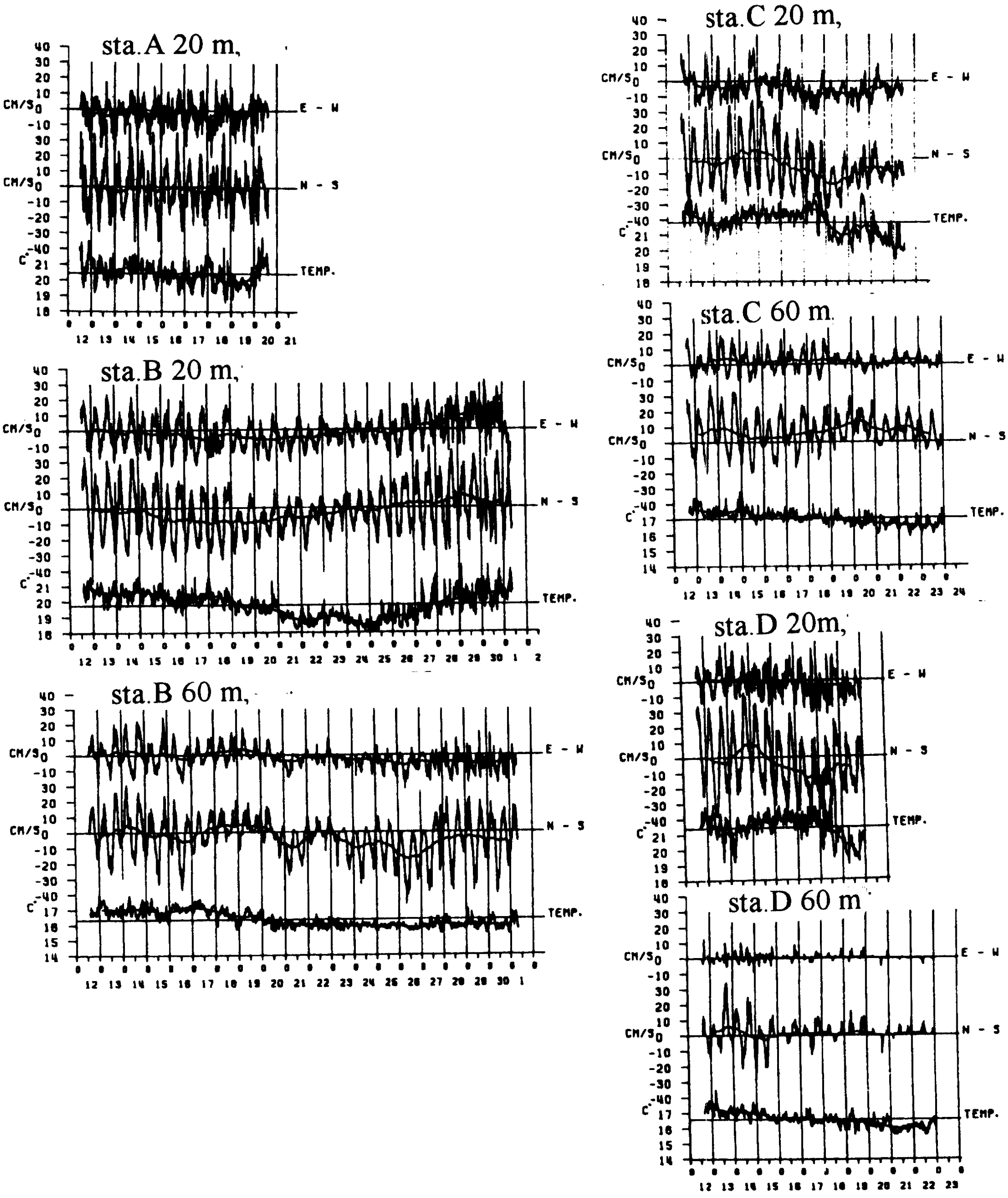

Fig. 8(b). Eastward velocity, northward velocity and mater temperature fluctuations.
Heavy solid line show the 25 hour running mean.
12 – 30 June, 1980

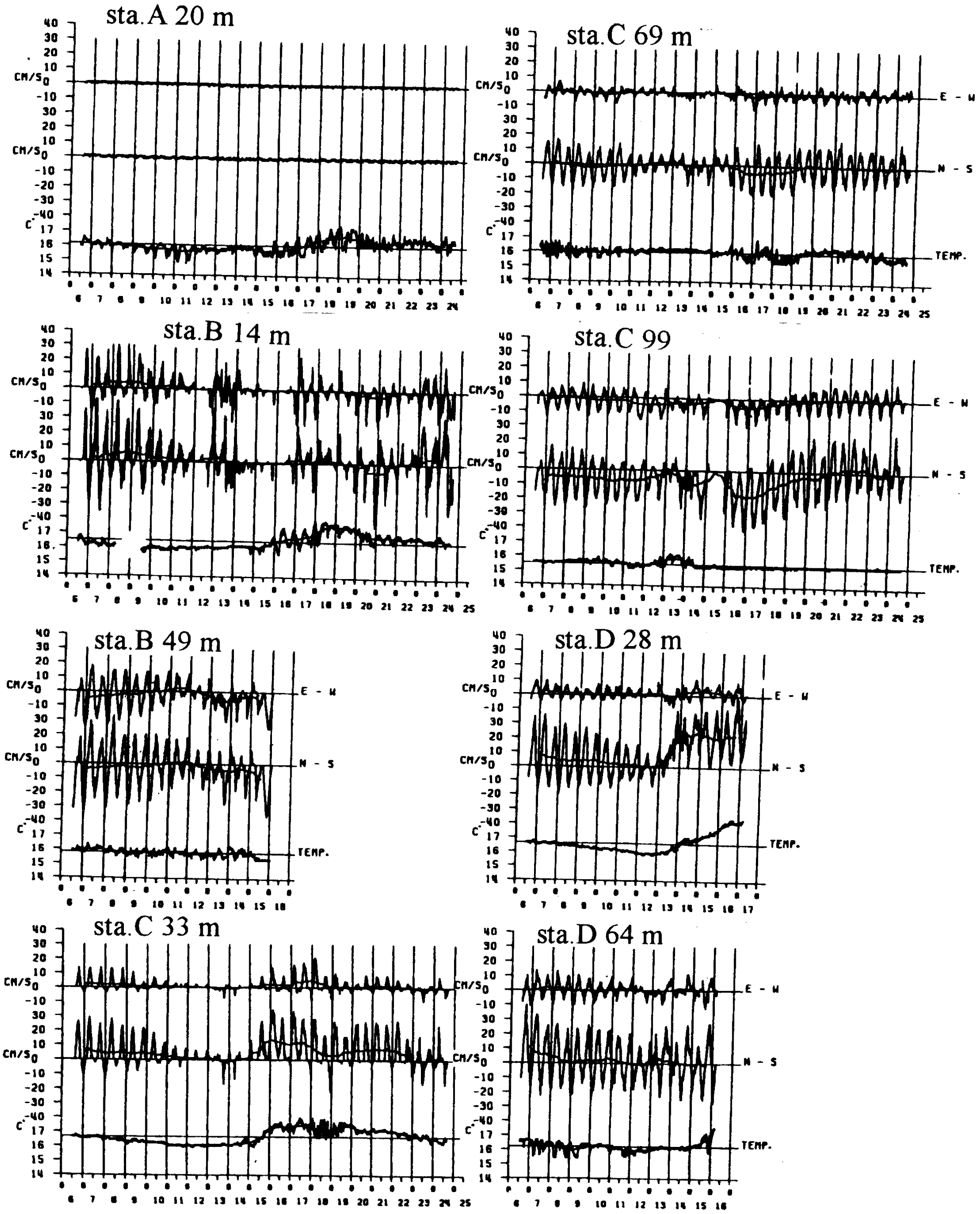

Fig. 8(c).　Eastward velocity, northward velocity and mater temperature fluctuations.
6 − 24 Feb, 1981

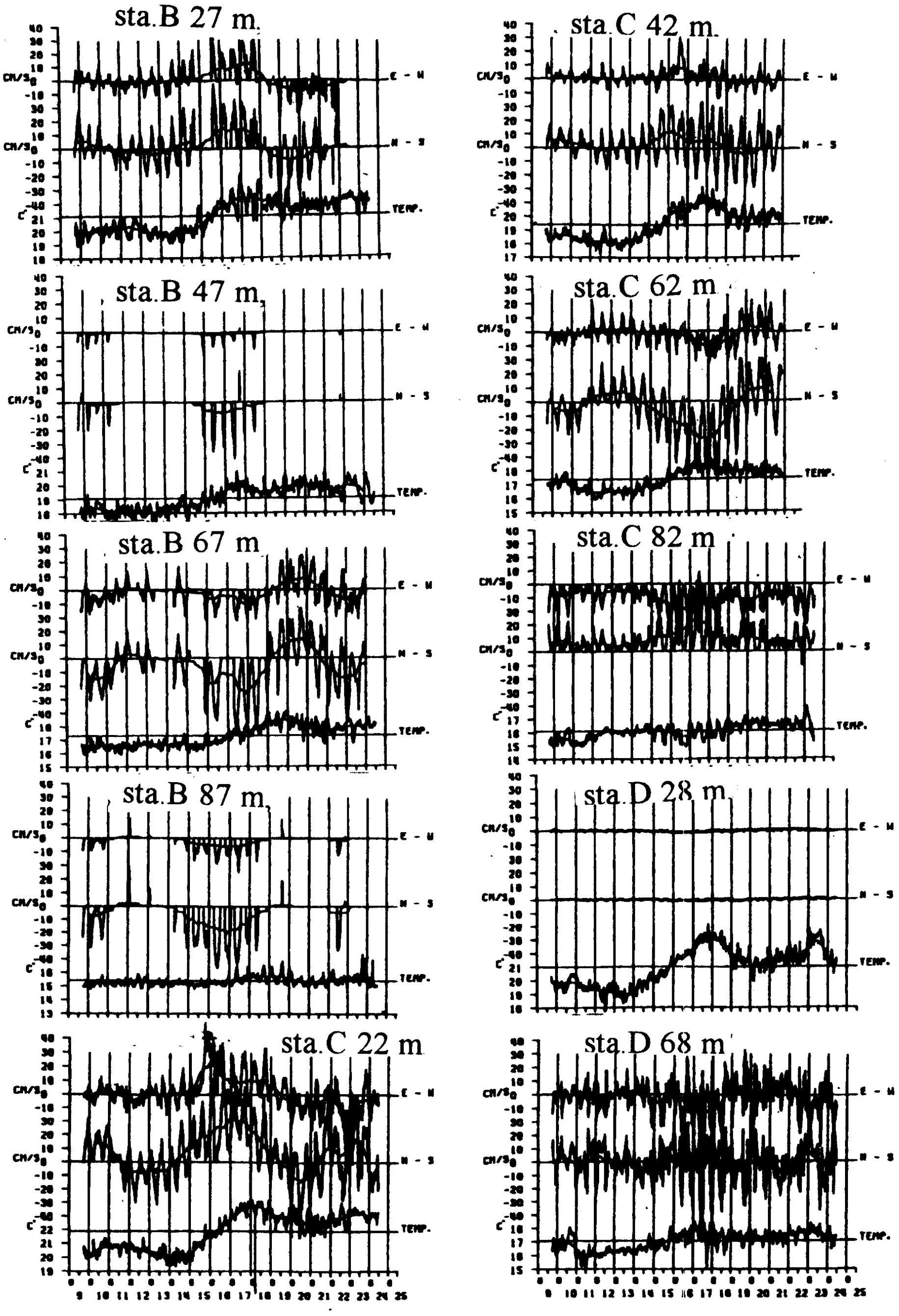

Fig. 8(d). Eastward velocity, northward velocity and mater temperature fluctuations.
June 9 to 24, 1981

4-1. Day to day variations of the flow and water temperature sections.

4-1-1. In winter

A. In February 1980

Fig. 9 (a) display the result of the cross section current profiling transacts in the bay. There is the inflow at the Sta.C and the outflow at the Sta. B from 16 February to 21 February 1980, it can be seen from this figure that the boundary of the inflow and the outflow is center of the section. Secondly, the characteristic state of the current flow pattern on 27 February to 4 March and 10 to 14 March. There is an inflowing in the upper layer and an outflowing in the lower layer of the section. Fig. 9 (a) shows that in

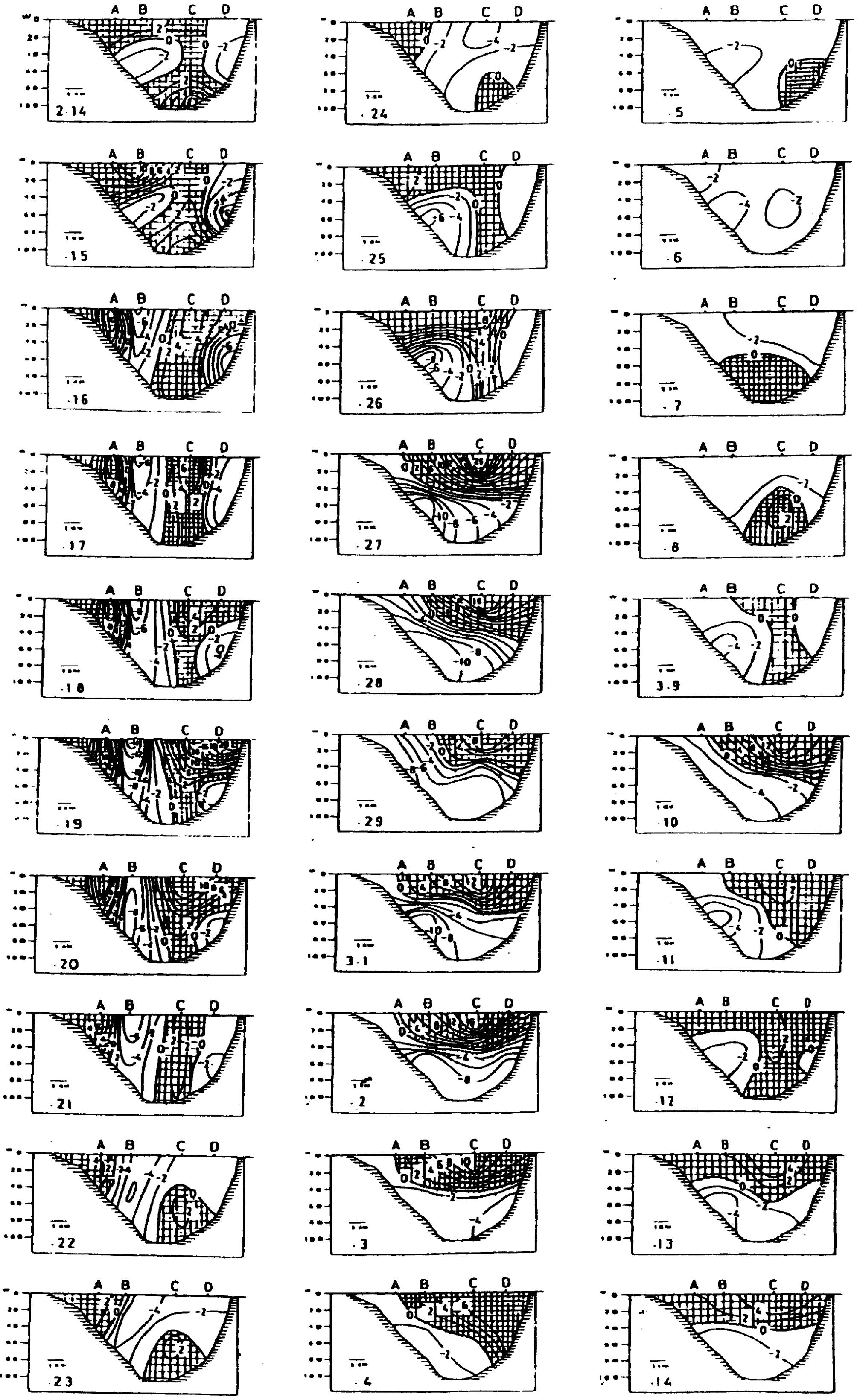

Fig. 9(a). Daily mean velocity profiling on the transverse section across the entrance sill (between Yamagawa and Nejime) of the Kagoshima bay from February 14 to March 14, 1980.
(+) inflow　　(−) outflow

both of the inflow and the outflow speed are weak in the section on 22 - 24 February and 5 - 9 March. Provided that the current is, for the most part, the inflow in the upper layer and the outflow in the lower layer although this flow is weak.

The strong inflow appears 5 days in this section, that is, on 19 February, 27 - 28 February, 2 March and 10 March. There are all 5 days strong inflow in the eastern upper layer. The strong outflow appears almost same days with the strong inflow that is, on 19 February, 27 - 28 February and 1 - 2 March. There is the strong outflow in the western upper layer on 19 February. The other 4 days are the strong outflow in the lower layer of the section.

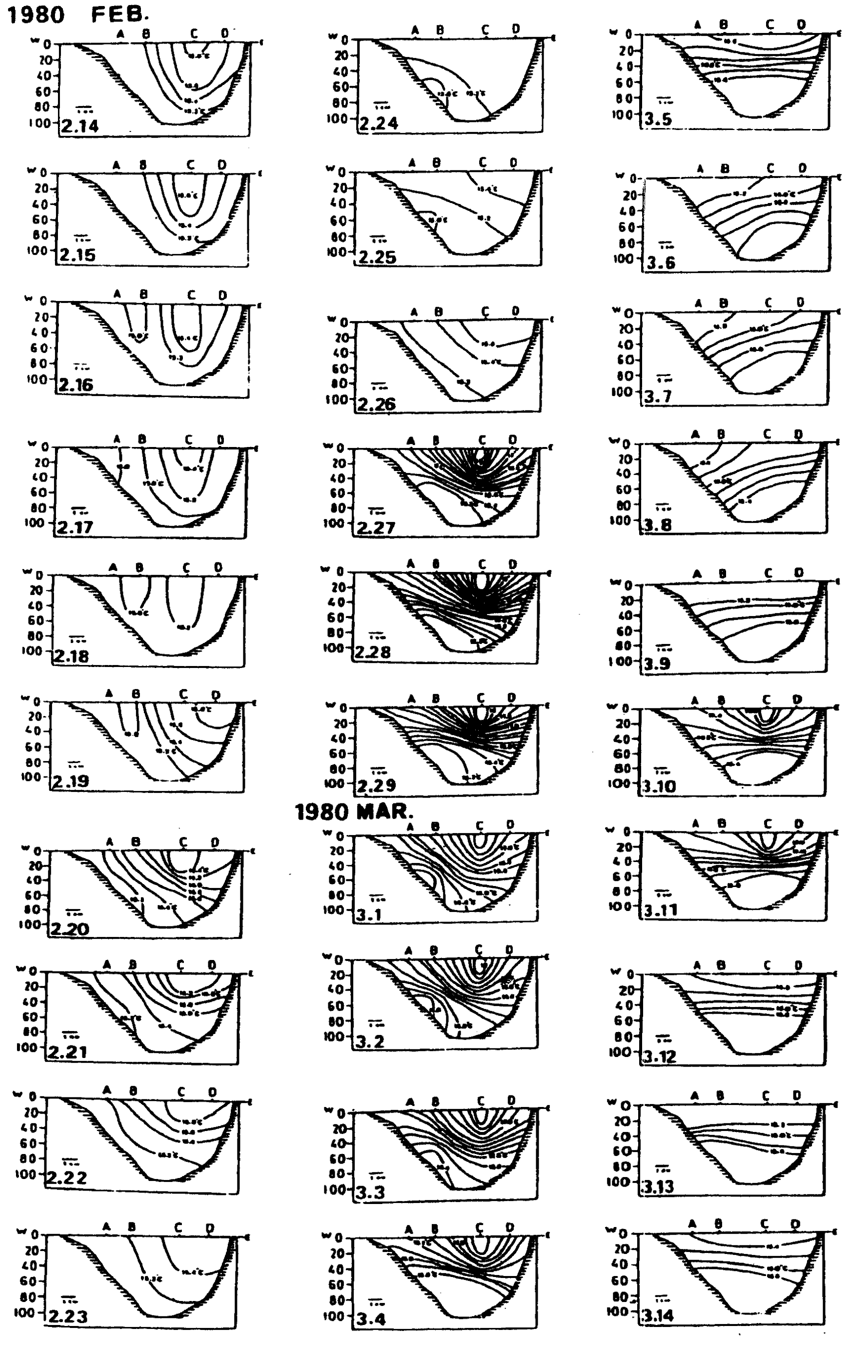

Fig. 9(b). Daily mean velocity profiling on the transverse section across the entrance sill (between Yamagawa and Nejime) of the Kagoshima bay from February 14 to March 14, 1980.

Temperature section, as shown in Fig. 9 (b) that the fluctuating pattern show a similar tendency with the flow. Especially, on the day of the strong inflow consist with the same day sudden go up temperature in the eastern upper layer of the section.

B. In February 1981

The time series of the 25 running mean northward component of the section from 7 to 18 February 1981 are shown in Fig. 10 (a). The inflow in the upper layer and the outflow in the lower layer began to flow on 7 February 1981 and that this condition lasted until 18 February 1981.

The strong inflow occurred three days and that on 14 - 16 February 1981 appeared in the eastern upper layer. The strong outflow occurred the same days as well the inflow but the strong outflow area is in the lower layer.

Fig. 10 (b) shows that temperature section, the fluctuating pattern show almost similar tendency with flow fluctuations. The strong inflow occurred the same days when water temperature goes up.

The flow pattern in February 1980 and 1981 accounts for 57% of the inflow in the upper layer and the outflow in the lower layer.

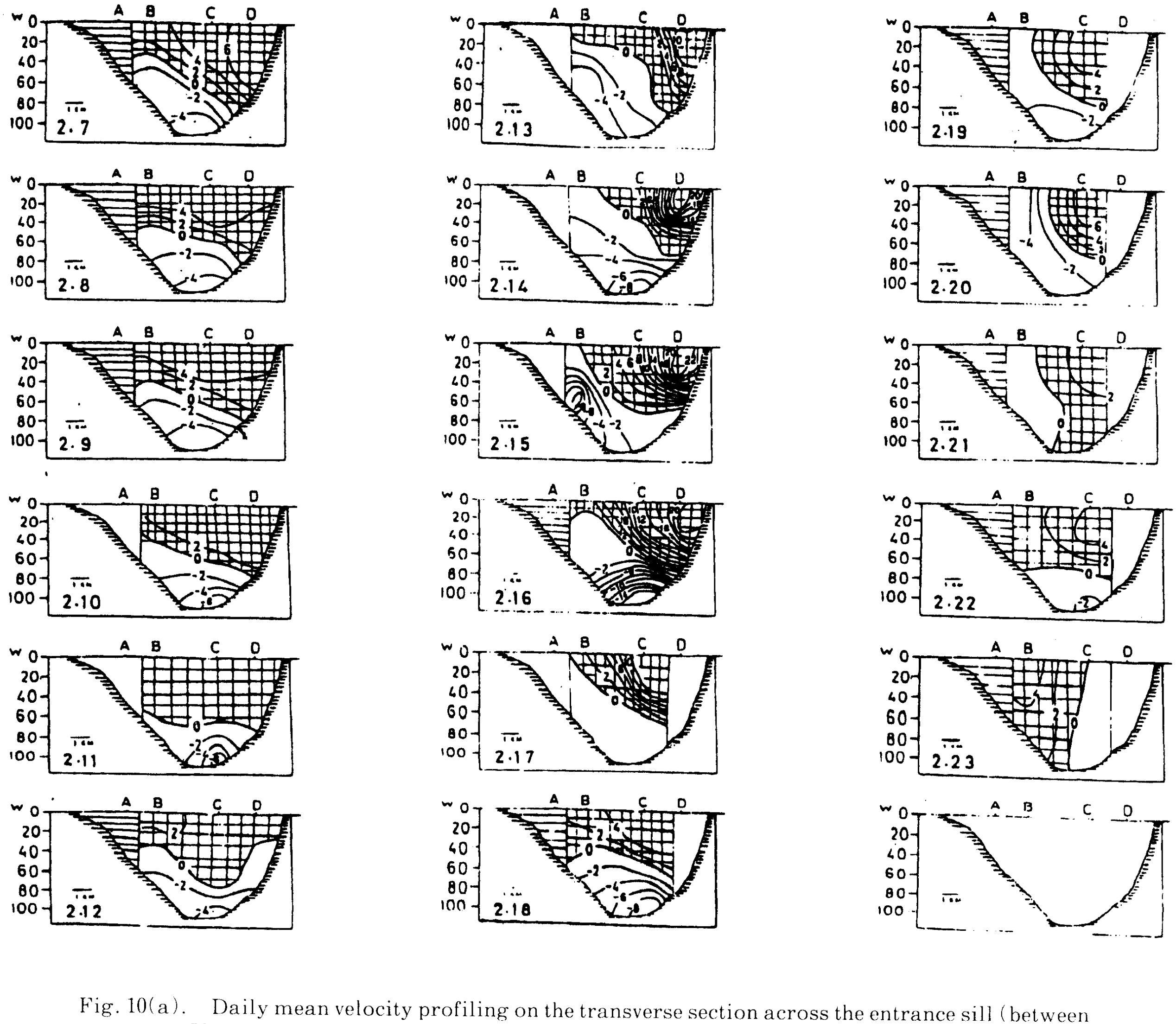

Fig. 10(a). Daily mean velocity profiling on the transverse section across the entrance sill (between Yamagawa and Nejime) of the Kagoshima bay from February 7 to 23, 1981.
(+) inflow (−) outflow

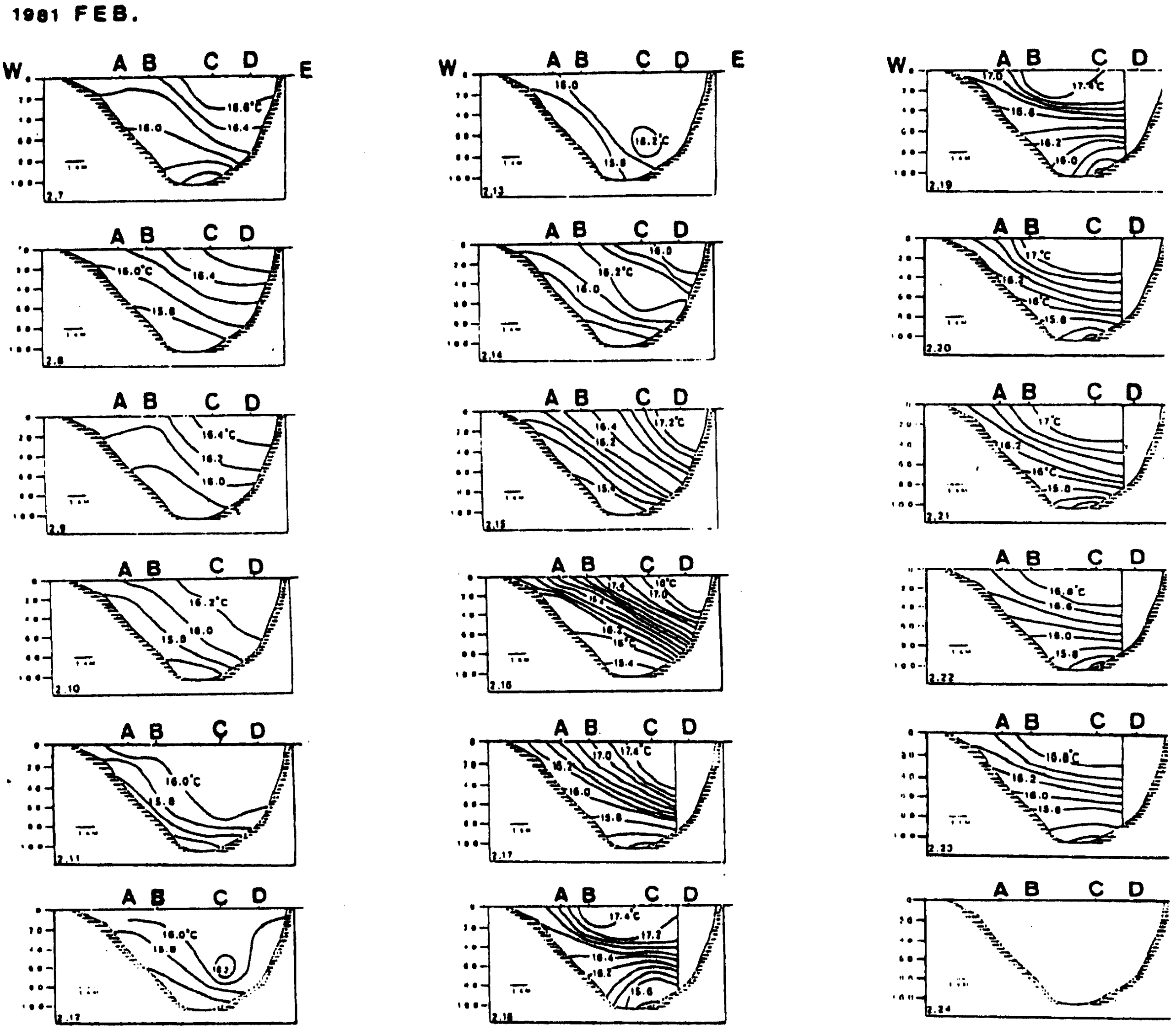

Fig. 10(b). Daily mean velocity profiling on the transverse section across the entrance sill (between Yamagawa and Nejime) of the Kagoshima bay from February 7 to 23, 1981.

4-1-2. In summer

A. In June 1980

The time series of the daily mean velocity of the section from 13 to 22 June 1980 in summer are shown in Fig. 11 (a). The inflow in the lower layer and the outflow in the upper layer presented to flow except on 13 and 17 - 22 June in this period. The inflow in the eastern and the outflow in the western both layers appeared on 15 - 16 June 1980.

The strong inflow did not exist during in this period and the strong outflow in the eastern upper layer on 17 June and that the strong outflow lasted until 20 June 1980.

Water temperature section are shown in Fig. 11 (b). Water temperature in the eastern upper layer is higher than that in the other layers in this period. The strong outflow began to the eastern upper layer on 17 June one day after the water temperature began to goes down 1 ℃.

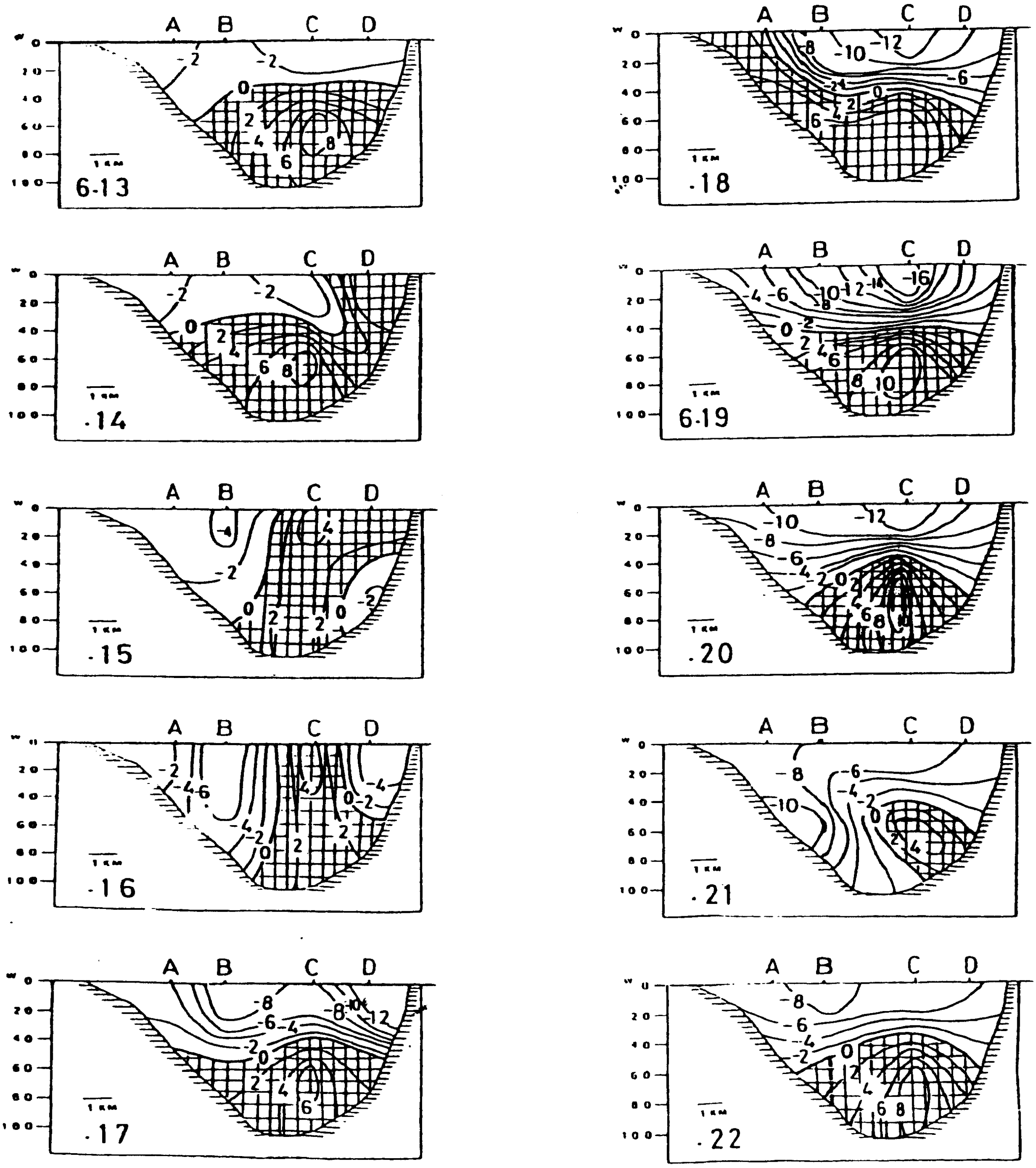

Fig. 11(a). Daily mean velocity profiling on the transverse section across the entrance sill (between Yamagawa and Nejime) of the Kagoshima bay from June 13 to 22, 1980.
(+) inflow (−) outflow

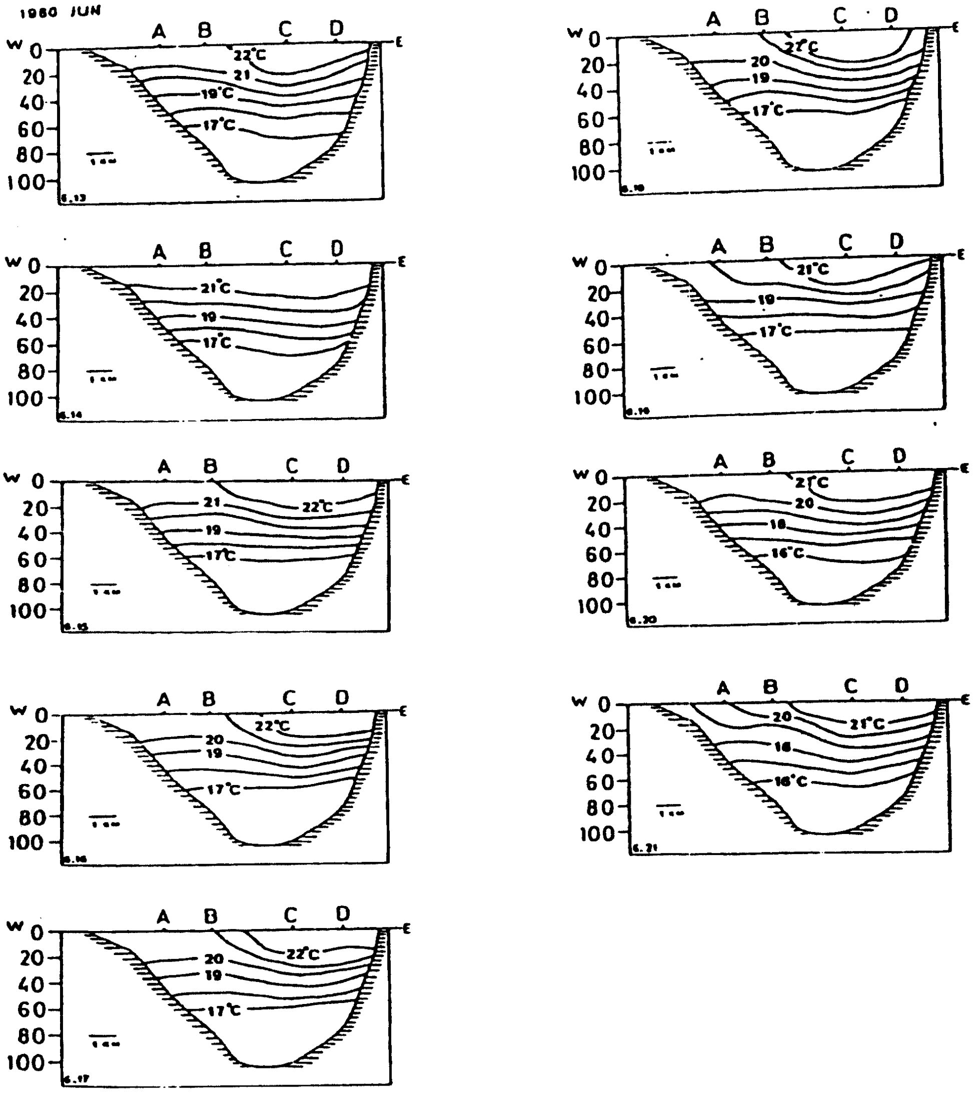

Fig. 11(b). Daily mean temperature profiling on the transverse section across the entrance sill (between Yamagawa and Nejime) of the Kagoshima bay from June 13 to 22, 1980.

B. In June 1981

The time series of the daily mean velocity of the section from 10 to 21 June 1981 in summer are shown in Fig. 12 (a). The inflow in the lower layer and the outflow in the upper layer occurred on 12 - 13 June and 19 - 20 June 1981 that the same motion as in June 1980. The flow direction changed rapidly on 15 June 1981, that is, it shown the inflow in the upper and the bottom layers, and the outflow in the middle layer. This flow pattern lasted until 18 June 1981. The strong inflow occurred on 10 June, 15 - 18 June 1981 at the same time as the strong outflow occurred in the middle layer.

Water temperature section are shown in Fig. 12 (b). Water temperature in the upper layer was about 20 ℃ from 10 to 15 June 1981 but it rapidly increased to 22 ℃ on 16 June one day after the strong inflow in the eastern upper layer began to flow.

The flow pattern in June 1980 and 1981 accounts for 53% of the outflow in the upper layer and the inflow in the lower layer.

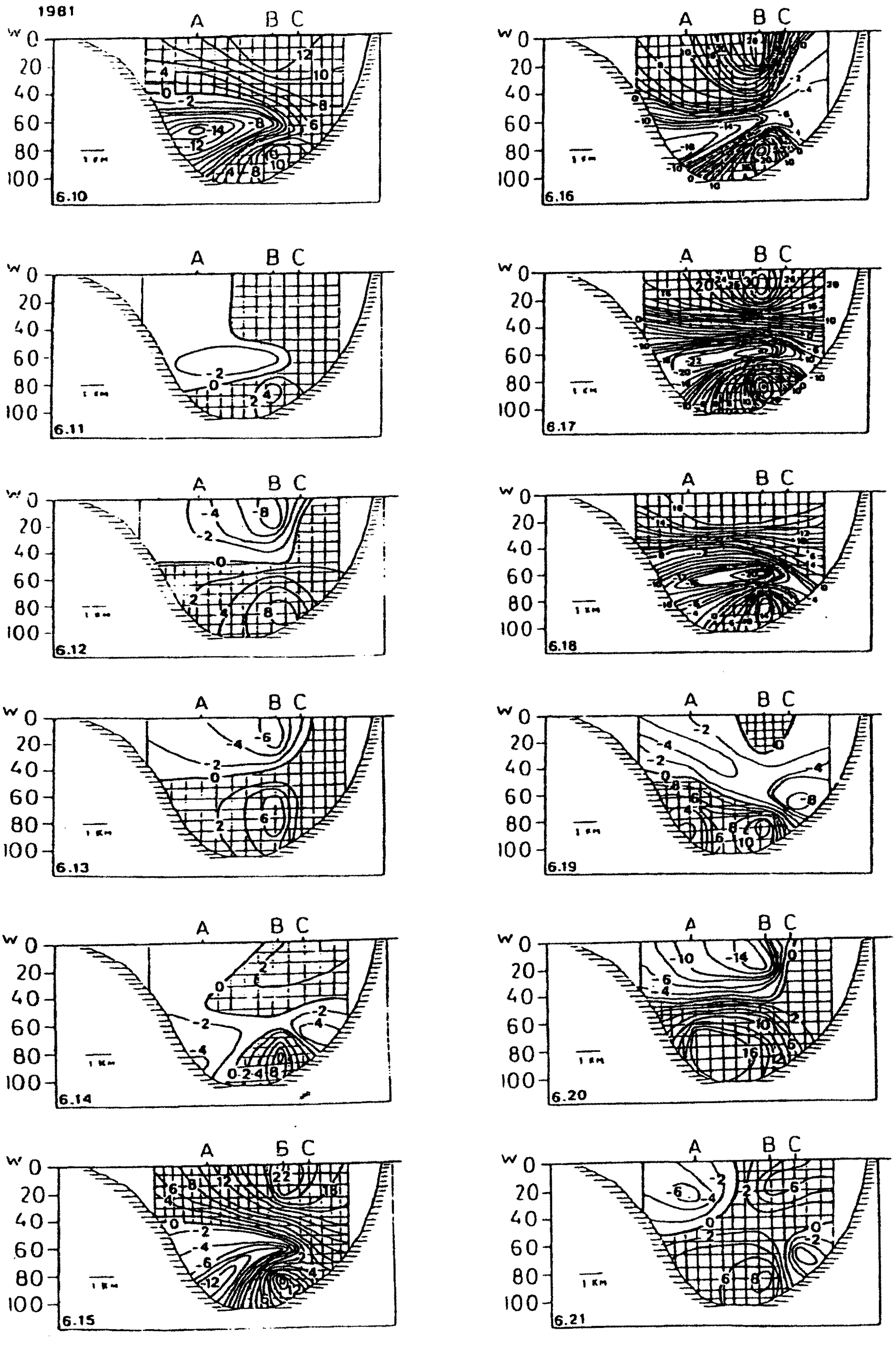

Fig. 12(a). Daily mean velocity profiling on the transverse section across the entrance sill (between Yamagawa and Nejime) of the Kagoshima bay from June 10 to 21, 1981.
(+) inflow (−) outflow

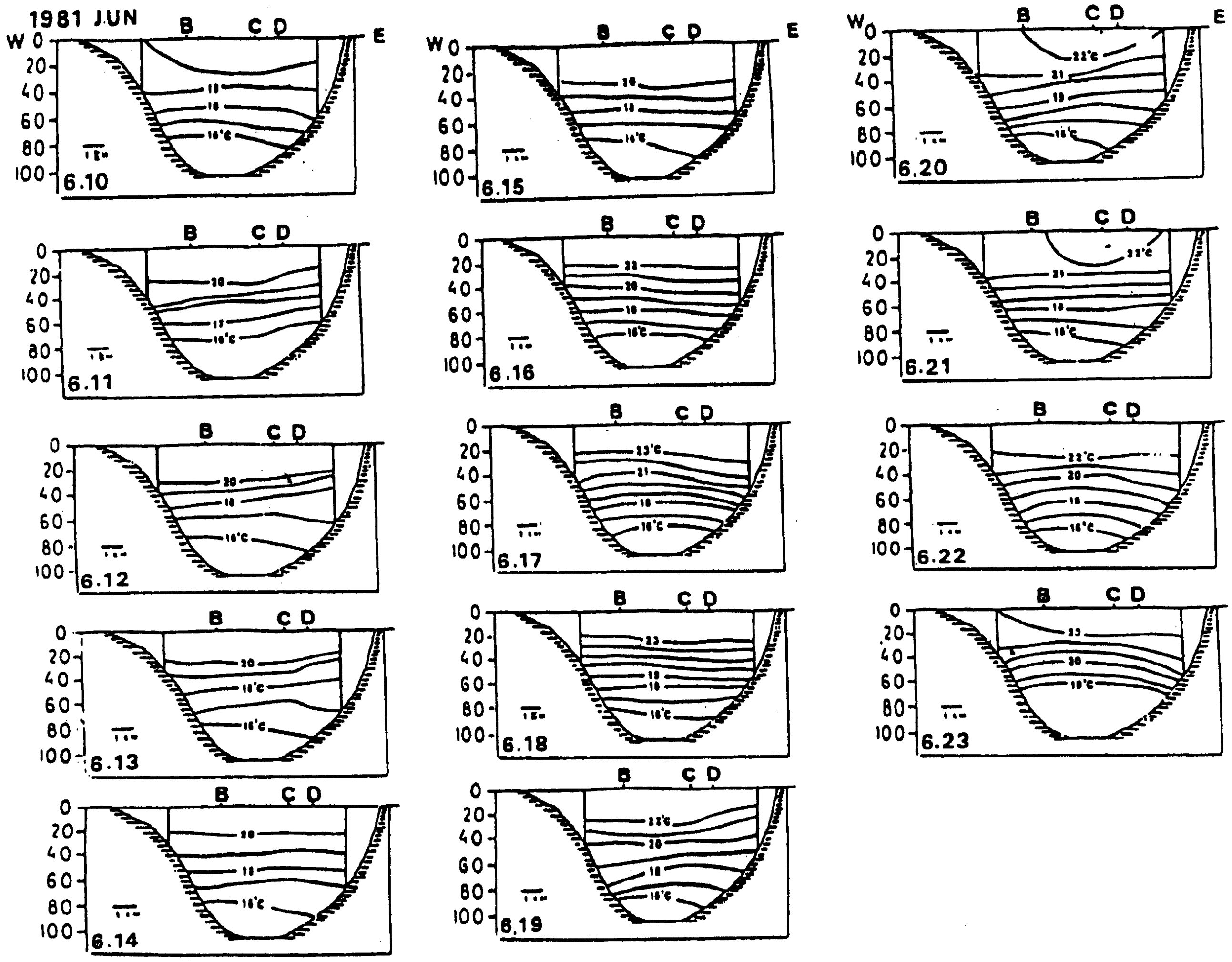

Fig. 12(b). Daily mean temperature profiling on the transverse section across the entrance sill (between Yamagawa and Nejime) of the Kagoshima bay from June 10 to 21, 1981.

4-2. Variation of the volume transport

Daily volume transports of the inflow and the outflow through on the sill were estimated from current velocity profiles.

4-2-1. In winter

The variation of volume transports over the period in February 1980 and 1981 are shown in Fig. 13. Large volume transport of the inflow occurred five times during 30 days in winter 1980 and that is 15, 19, 27 February and 2, 10 March. The maximum value of the inflow was $27 \times 10^8 m^3 day^{-1}$ on 27 February and the minimum was $0 m^3 day^{-1}$ on 6 March. The inflow transport is larger than the outflow transport whole period from 7 to 18 February 1981, therefore net transport is indicated only inflow. The maximum value the inflow transport was $27 \times 10^8 m^3 day^{-1}$ on 16 February and the minimum one was $3 \times 10^8 m^3 day^{-1}$ on 12 February 1981. The peak of the inflow transport correspond to that of the outflow transport through in winter for two years in 1980 and 1981 and the net transport fluctuated for a period of 5 to 7 days. Furthermore the large inflow transport corresponded to the strong northward velocity in the eastern upper layer.

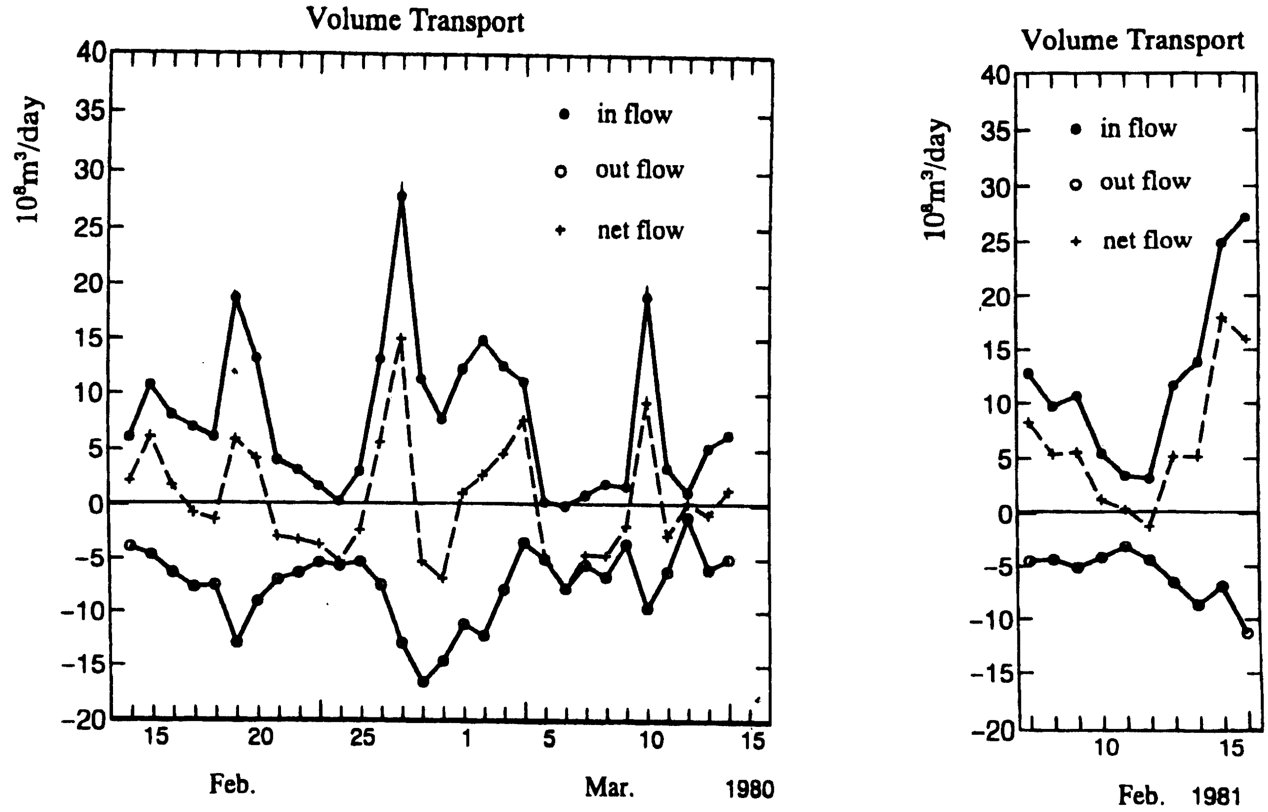

Fig. 13. Variation of daily mean volume transport on the transverse section across the entrance sill February 1980 (Left) and 1981 (Right).

4-2-2. In summer

The variation of volume transports over the period in June 1980 and 1981 are shown in Fig. 14. The outflow transport predominate in June 1980 during the observation, and the maximum value is 28.5×10^8 m^3day^{-1} on 19 June 1980. The maximum inflow transport value is $14\times10^8m^3day^{-1}$ on 14 June and its fluctuate with a period of 5 days in June 1980.

It is predominant that the inflow transport is strong in June 1981 which is against tendency in June 1980. The variation of the inflow transport has the period of 7 days in June 1981. and the maximum one is $47.7\times10^8m^3day^{-1}$. The peak of the inflow transport corresponded to that of the outflow transport. The strong inflow current velocity showed in the eastern upper layer when the peak of the inflow transport.

We see from results that the volume transport of the dominant inflow relates to the dominant of the northward current speed increased in the eastern upper layer.

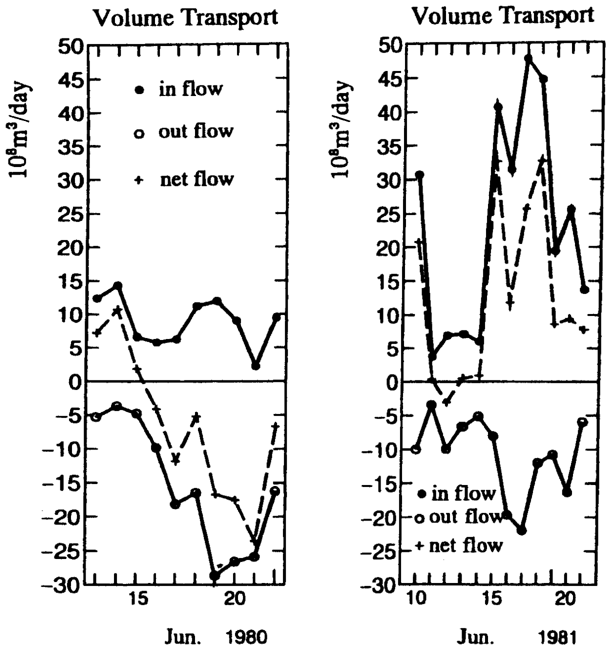

Fig. 14. Variation of daily mean volume transport on the transverse section across the entrance sill June 1980 (Left) and 1981 (Right).

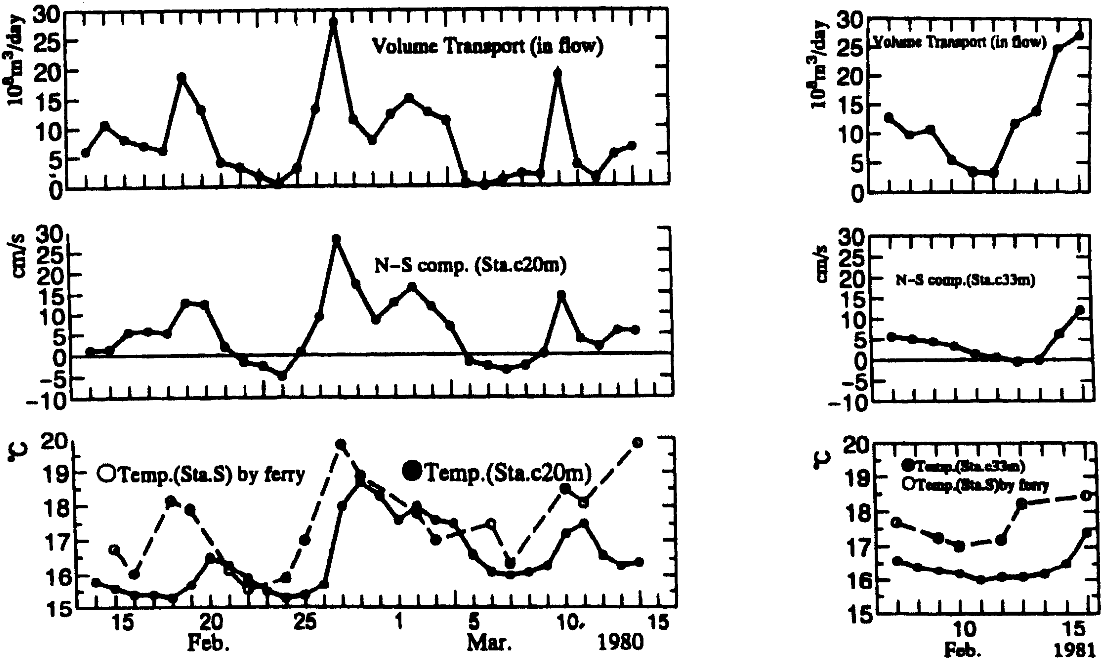

Fig. 15(a). Time variations of the inflow transport and daily mean north component velosity and water temperature at Sta. C1. Period in February 1980 (Left) and 1981 (Right).

The flow pattern in June 1980 and 1981 accounts for 55 % of the outflow in the upper layer and the inflow in the lower layer.

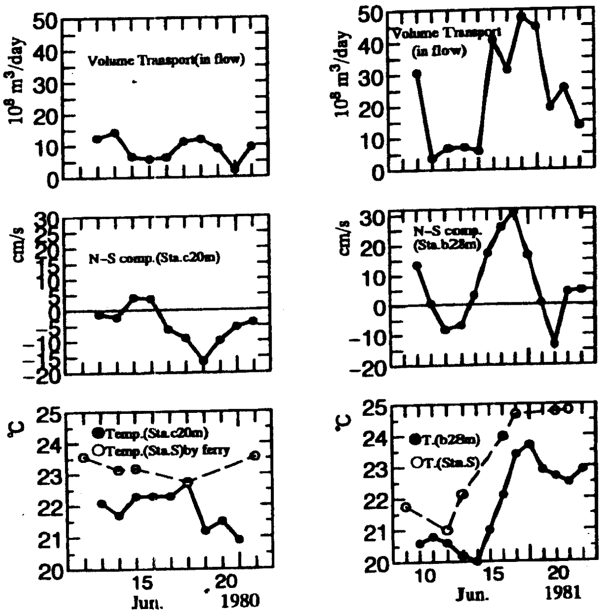

Fig. 15(b). Time variations of the inflow transport and daily mean north component velosity and water temperature at Sta. C1. Period in June 1980 (Left) and 1981 (Right).

5. Discussion

5-1. Relation between northward volume transport and the current velocity and water temperature in the eastern upper layer.

Fig. 15 (a), (b) the time variations of the inflow transport and daily mean north component current velocity and water temperature at Sta.C1. The fluctuating pattern of the inflow transport show a similar tendency northward current velocity and the water temperature. However, the peak of water temperature appears one day after the peak of the inflow transport. The outflow transport is large than the inflow transport in the whole section in June 1980, then the strong southward velocity flowed and a low water temperature existed during this period at the Sta. C1. (Fig. 15 (b) upper).

It is suggest that the cold water mass is extrusion from the bay when the outflow transport is strong in

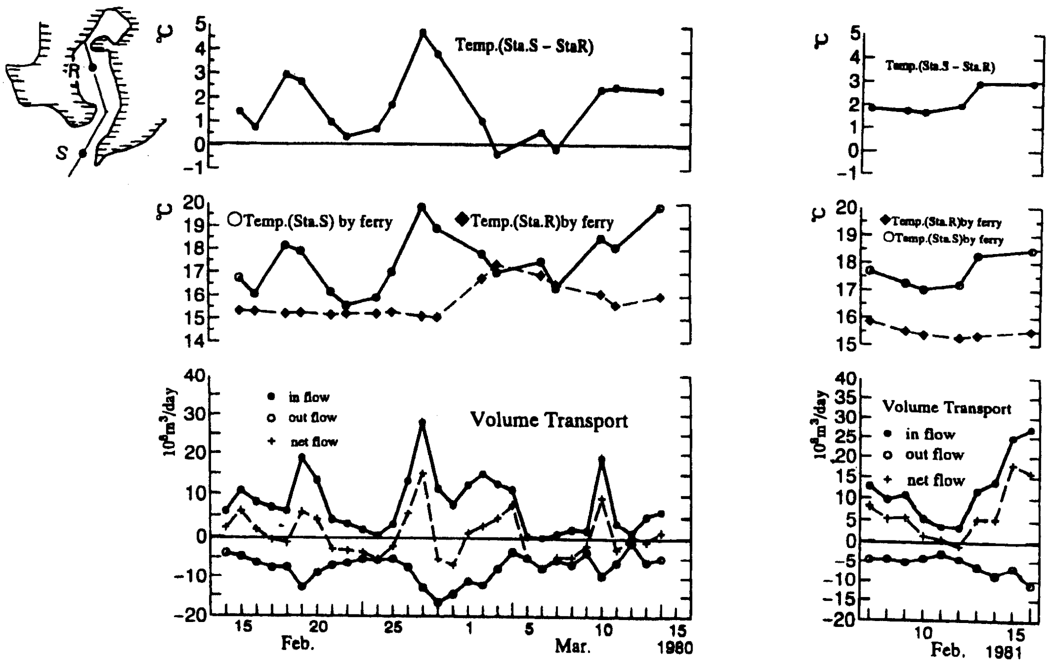

Fig. 16(a). Time variations of (Sta. R-Sta S) temperature and volume transport in February 1980 (Left) and 1981 (Right).

this section.

A one of the study project the Kuroshio Exploitation and Utilization Research, the Kagoshima Prefecture Fisheries Observatory installed a temperature sensor on board the ferry and recorded intervals of 15 minutes. A ferry boat "Emerald-Amami" voyage between Kagoshima and Naha. the ferry leaves at Kagoshima Harbor at 18 : 00 every second day and two days after return to kagoshima Harbor at 8 : 00.

One of them the Point S located at the west of Satamisaki. The characteristic of the variation of time series at Point S are similar to that the northward current velocity and the inflow transport, and the strong inflow transport when the sea surface temperature (SST) go up at Point S. It is indicate that large variation of water temperature occurred in the near bay mouth, some time after, the northern region Sta. C1 is large variation inflow transport.

5-2. Relation between the volume transport and SST

We tried to find a correlation between the SST variations and the inflow and the outflow transport. In Fig. 16 (a), (b) shows SST at two point, namely Point R is the northern part in the central portion and

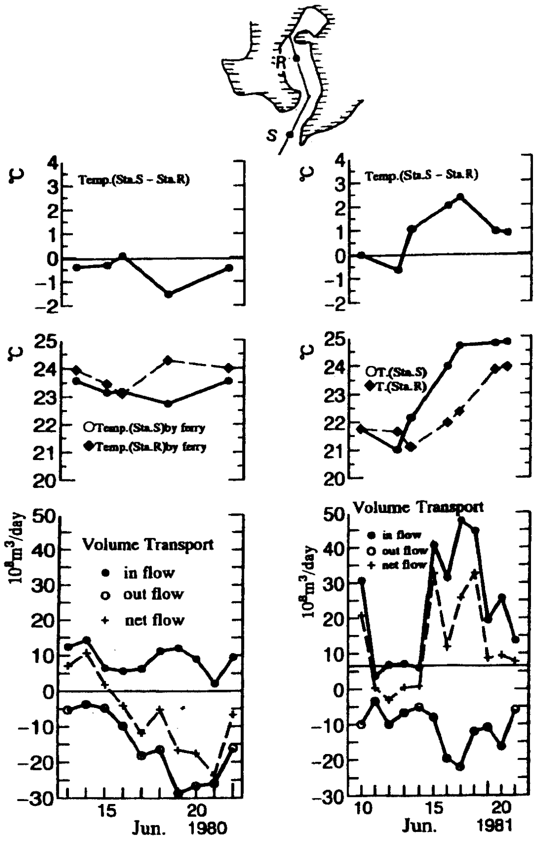

Fig. 16(b). Time variations of (Sta. R-Sta S) temperature and volume transport in June 1980 (Left) and 1981 (Right).

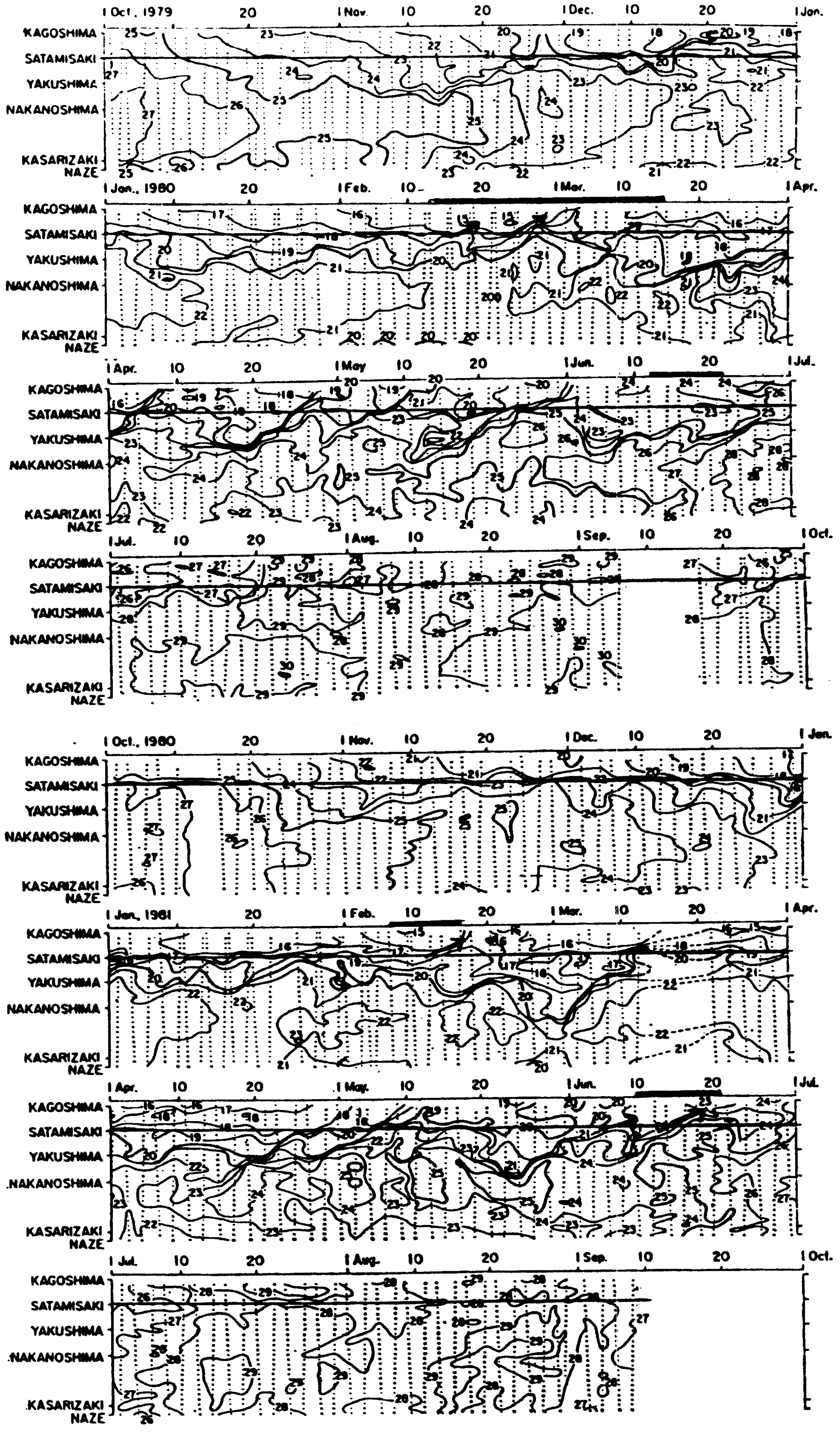

Fig. 17. Space-time diagram of the SST distribution from Kagoshima to Amami by Nagata and Takeshita (1985).

Point S is west of the Satamisaki. (position of Point R and Point S are the upper figure).

The magnitude of the variation of Point R is much smaller than at Point S, then we may also examine the SST difference of (Point S-Point R).

Nagata and Takeshita (1985) was illustrated that the results of the space - time diagram of the SST distribution from Kagoshima to Amami during in October 1978 and 1981. (see Fig. 17) There are compared Fig. 16 (a), (b) with Fig. 17. The strong water temperature front moved northward and approaches near the Satamisaki when both of the peak of inflow transport and large difference of (Point S-Point R) on 19 February 1980, on 27 February 1980, on 10 March 1980, on 16 February 1981 and on 17 June 1981. But the front moves southward of Yakushima when in the upper layer was the outflow in the bay in June 1980. We found that the dominant variation of the inflow transport equivalent to temperature front is approach and inrush in to the bay.

The inflow events occurred five times during 62 days that is, in 16 - 20 February 1980, in 24 February - 5 March 1980, in 9 - 11 March 1980, in 13 - 16 February 1981 and in 15 - 19 June 1981. and it's total events are 28 days. (see Fig. 18).

Total inflow volume transport by the events are 455×1010^8 m^3 and that transport except the events are 34 days and are 260×10^8m^3. Inflow volume transport by the events are stronger than except the events. Inflow volume transport by the events average values over 28 days were 16.2×10^8m^3 and other inflow average value over 34 days were about 7.7×10^8m^3.

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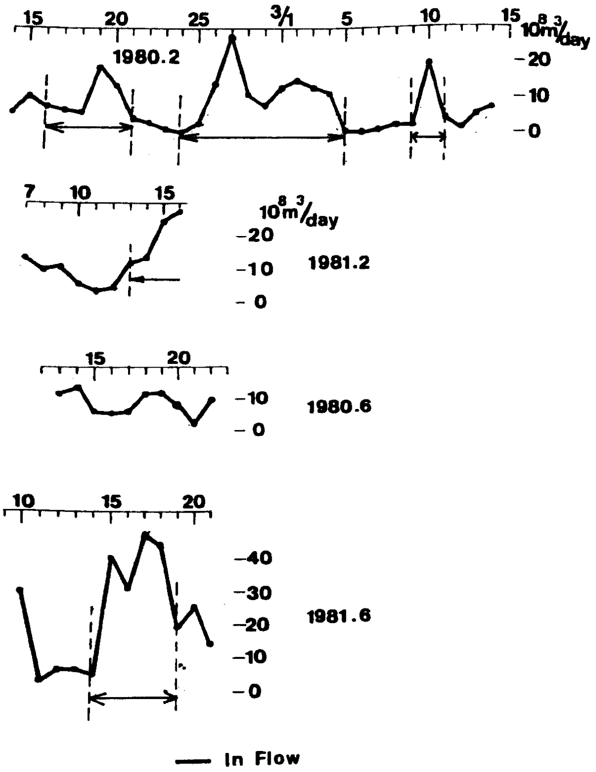

Fig. 18. Inflow events (arrow line).

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