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Vertical Distributions of Temperature, Salinity and Density in Owase Bay

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Abstract

Hydrographic conditions of Owase Bay are characterized by two effluents of thermal water from thermal electric power plant and fresh water from hydroelectric power plant. Constraction of the third thermal electric power plant in June 1987 induced total volume of thermal water effluent to increase from less than 31.6 m^3 sec^{-1} to 53-55 m^3 sec^{-1}, while the effluent of fresh water varies with a range of 0-25 m^3 sec^{-1} up to now. Vertical distributions of temperature, salinity and density in Owase Bay along three observational lines are presented in this paper by using observational data in thirteen periods from April 1986 to September 1991. It is shown that there exist significant changes in hydrographic structure depending on tidal periods: effluents of thermal and fresh water spread to a center of the bay or to a baymouth during the periods of ebb and low water. However, two effluents are confined to an innermost of the bay and the effluents expand vertically during the periods of flood and high water. This tendency is most prominent along southernmost observational line. It is also shown that the difference in temperature distribution occurred depending on the volume of effluent of fresh water: effluent of thermal water spreads in upper layer in period of weak fresh water effluent, while it intrudes below the less saline water in period of large fresh water effluent.

1 Introduction

Location and geometry of Owase Bay in Kii Peninsula are shown Fig. 1. Hydrographic conditions of Owase Bay are characterized by two effluents of thermal and fresh water. Thermal water is discharged into the river mouth of Yano-River, while fresh water is discharged along Naka-River (Fig. 1). Horizontal distributions of temperature and salinity in Owase Bay have been studied in Part 1 of this study[1]. Main results of Part 1[1] are summarized as follows:

(1) Hydrographic condition in the layer shallower than 3 m significantly changes with tidal periods. In period of constant effluent of fresh water, less saline water expands in relatively large area in ebb and low water periods, and expansion tends to be confined to an innermost of the bay in the periods of flood and high water. In period of variable effluent of fresh water, expansion of less saline water depends on the volume of effluent of fresh water.

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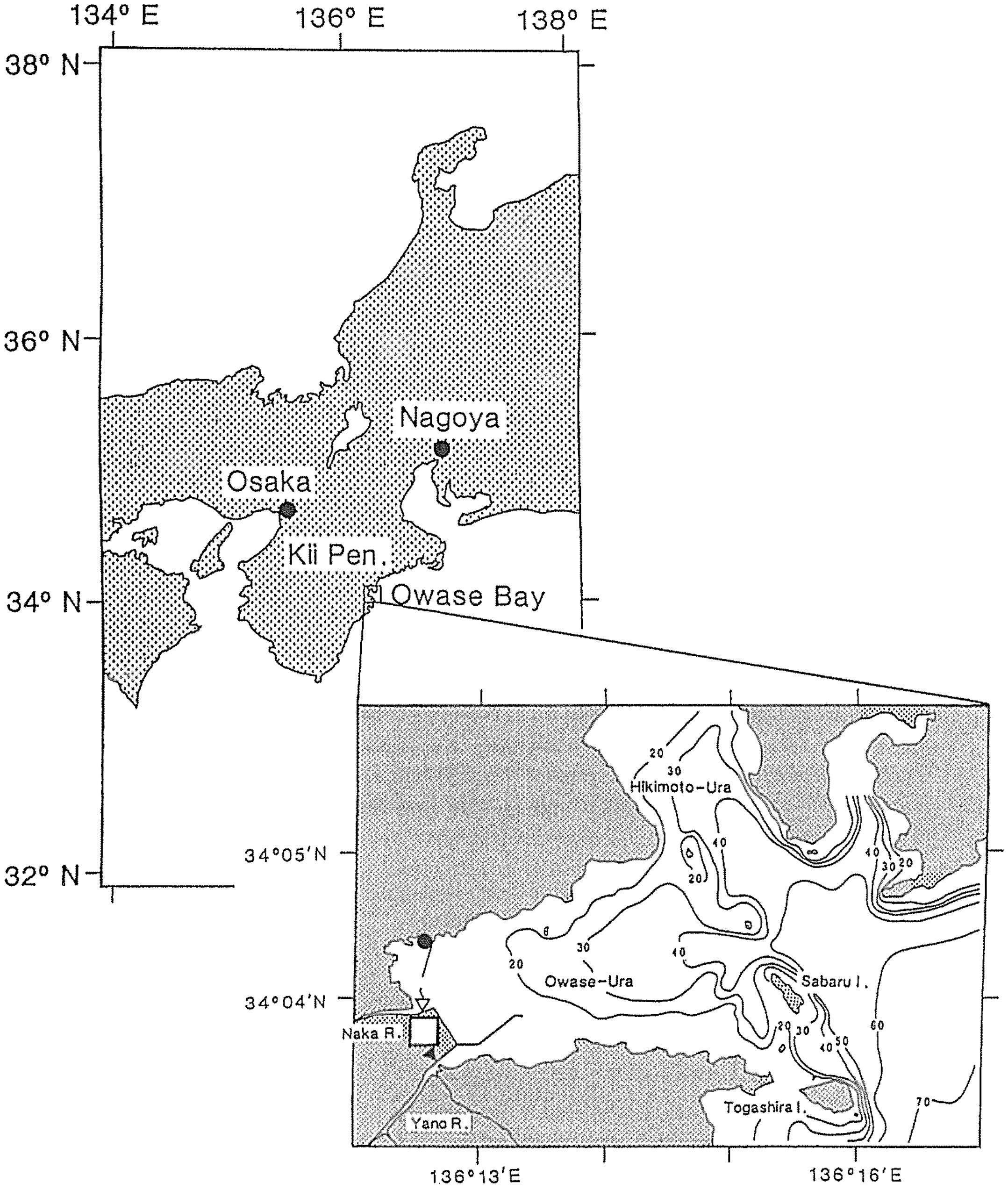

Fig. 1. Location and geometry of the western part of Owase Bay and its depth contours (in meter). Open large square near innermost of the bay means the location of thermal electric power plant. Open and closed triangles at rivermouth of Naka-River and Yano-River mean the location of inflow and outflow of sea water used in thermal electric power plant. Closed circle shows the location of Owase Tide Station.

(2) Expansion of two effuluents is mainly confined to a layer shallower than 3 m. On the whole, it is concluded that the hydrographic conditions of Owase Bay depend on the volume of thermal and fresh water effluents and on the tidal periods.

However, since the discussion is based on horizontal distrbutions of temperature and salinity, details of vertical distributions have not been well discussed in Part 1[1]. Therefore, vertical structure in Owase Bay is presented in the present study.

2 Observations

Locations of observational points of temperature and salinity are shown in Fig. 2. Three observational lines, A-, B- and C-lines, were set to see the vertical distribution. Details of the observations are given in Table 1, in which volume of effluents of thermal and fresh water averaged over three hours before each observation are also shown. Sea level changes at Owase Tide Station (Fig. 1) are shown in Fig. 3. Larger sea level change of 1.5 m is observed in spring tides and sea level change is relatively small (0.5 m) in neap tides.

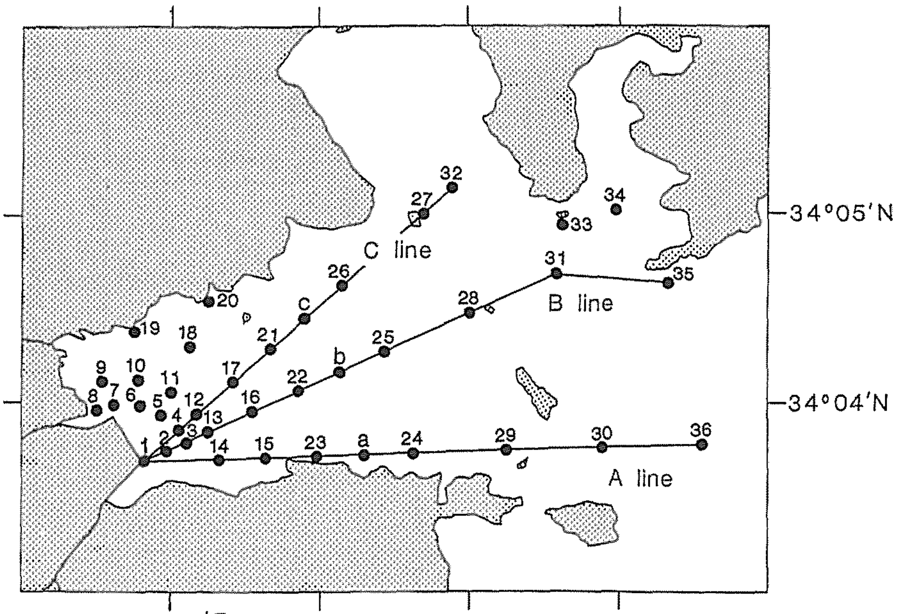

Fig. 2. Locations of observational stations for temperature and salinity.

As for each observational period, four times observations of temperature and salinity have been carried out in different tidal periods. Temperature and salinity are observed by EIL Salinometer (MC5/2). Density (σ_t) is calculated from temperature and salinity data. Salinity at all stations on 25 April 1986 (86API-IV) and salinity on eastern half of three observational lines on 20 and 28 August 1990 (90AGI-VIII) were not observed.

Same as in Part 1[1], we classify the observational conditions into four cases based on the difference in season and volume of effluents of thermal and fresh water (Table 2). We do not show the results on 25 April 1986,

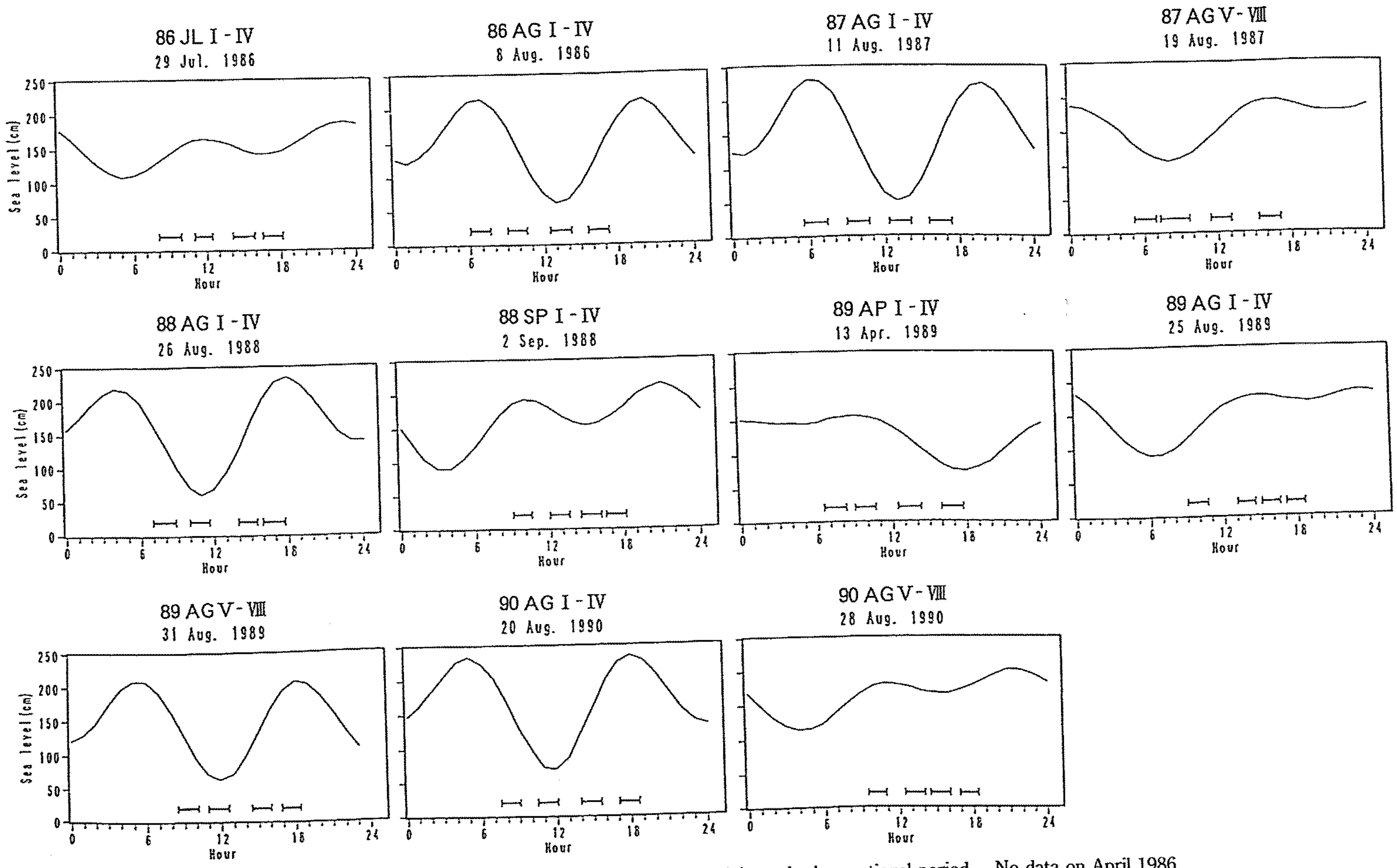

Fig. 3. Sea level changes at Owase Tide Station (Fig. 1) in each observational period. No data on April 1986 and on September 1991 are available. Bars suggeste observational period.

Table 1. Details of observations. N.D. means no data.

Observations	Date	Tide	Effluent (m^3 sec^{-1})	
			Thermal water	Fresh water
86API	25 Apr. 1986	Ebb	N.D.	13.0
86APII		Low water	N.D.	0.3
86APIII		Flood	N.D.	0.0
86APIV		High water	N.D.	0.3
86JLI	29 Jul. 1986	Flood	31.6	0.0
86JLII		High water	31.6	16.4
86JLIII		Ebb	31.6	16.8
86JLIV		Low water	31.6	8.1
86AGI	8 Aug. 1986	High water	31.6	0.0
86AGII		Ebb	31.6	0.3
86AGIII		Low water	31.6	16.4
86AGIV		Flood	31.6	24.8
87AGI	11 Aug. 1987	High water	38.8	0.0
87AGII		Ebb	38.8	8.3
87AGIII		Low water	38.8	16.4
87AGIV		Flood	38.8	24.2
87AGV	19 Aug. 1987	Ebb	54.6	0.0
87AGVI		Low water	54.6	0.0
87AGVII		Flood	54.6	8.4
87AGVIII		High water	54.6	16.3
88AGI	26 Aug. 1988	Ebb	46.0	24.7
88AGII		Low water	50.0	24.8
88AGIII		Flood	52.0	24.7
88AGIV		High water	53.0	24.8
88SPI	2 Sep. 1988	High water	48.5	23.6
88SPII		Ebb	53.0	23.7
88SPIII		Low water	53.5	23.7
88SPIV		Flood	53.5	23.8
89API	13 Apr. 1989	Flood	N.D.	0.0
89APII		High water	N.D.	15.9
89APIII		Ebb	N.D.	16.0
89APIV		Low water	N.D.	24.0
89AGI	25 Aug. 1989	Flood	50.5	23.9
89AGII		High water	53.5	24.0
89AGIII		Ebb	54.3	24.0
89AGIV		Low water	53.5	24.1
89AGV	31 Aug. 1989	Ebb	54.6	24.6
89AGVI		Low water	54.6	24.6
89AGVII		Flood	54.6	24.5
89AGVIII		High water	54.6	24.5
90AGI	20 Aug. 1990	Ebb	54.6	0.0
90AGII		Low water	54.6	9.5
90AGIII		Flood	54.6	23.9
90AGIV		High water	54.6	7.6
90AGV	28 Aug. 1990	Flood	54.6	24.1
90AGVI		High water	54.6	24.1
90AGVII		Ebb	54.6	23.8
90AGVIII		Low water	54.6	23.9
91SPI	2 Sep. 1991	Flood	N.D.	24.8
91SPII		High water	N.D.	24.8
91SPIII		Ebb	N.D.	24.7
91SPIV		Low water	N.D.	24.8

Table 2. Classification of observation in view of water effluence

Group	Observational season	Water effluence		Corresponding observation (Figures)	
		Thermal water	Fresh water		
I	Spring	No data	No data	89API-IV	(Fig. 4)
II	Summer	Small	Variable	86JLI-IV	(Fig. 5)
				86AGI-IV	(Fig. 6)
				87AGI-IV	(Fig. 7)
III	Summer	Large	Variable	87AGV-VIII	(Fig. 8)
				90AGI-IV	(Fig. 9)
IV	Summer	Large	Constant	88AGI-IV	(Fig. 10)
				88SPI-IV	(Fig. 11)
				89AGI-IV	(Fig. 12)
				89AGV-VIII	(Fig. 13)
				90AGV-VIII	(Fig. 14)
				91SPI-IV	(Fig. 15)

because no observation of salinity was carried out. Because of the constraction of third thermal electric power plant in June 1987, the effluent of thermal water increased from less than 31.6 m^3 sec^{-1} to 53–55 m^3 sec^{-1}. Observations on 11 August 1987 were carried out after the constraction of third thermal electric power plant, effluent of thermal water is less than 50 m^3 sec^{-1} (Table 1). Therefore, this observation is classified into Group (II).

3 Results

Vertical distributions of temperature, salinity and density along A-, B- and C-lines are shown in Figs. 4–15. In case of the Group (I), vertical temperature change on 13 April 1989 is weak except for an innermost of the bay (Fig. 4). A water warmer than 18°C expands gradually as the lapse of time. This tendency is relatively clear in A- and B-lines. There is significant difference of salinity distributions in each tidal period: less saline water than 33 psu spreads to a baymouth in the layer shallower than 2 m during the periods of flood and high water. However, less saline water expands vertically to a depth of 3 m in an innermost of the bay during the periods of ebb and low water. Although an effluent of fresh water started during high water period (Table 1), less saline water than 30 psu appears in ebb period. The less saline water spreads in the layer shallower than 2 m in low water period. This tendency is relatively prominent in C-line.

In case of the Group (II), a water warmer than 26°C spreads to a center of the lines in the layer shallower than 2 m in the period of flood on 29 July 1986 (Fig. 5). However, a warm water expands vertically to a depth of 4 m on and after high water period. Similar change is also detected in salinity distribution. Less saline water than 31 psu spreads to a baymouth in the layer shallower than 3 m in flood period. Although fresh water effluent began during the observation in high water period (Table 1), less saline water is confined to relatively inner area of the bay in the period of ebb and low water. Small expansion of less saline water is supposed to be due to neap tides in this observational period (Fig. 3). Less saline water than 28 psu is observed in the layer deeper than 2 m of stn. 4 on C-line in ebb period, details of this less saline water is unclear.

Because tidal changes have a common phase in 8 August 1986 (Fig. 6) and 11 August 1987 (Fig. 7), similar

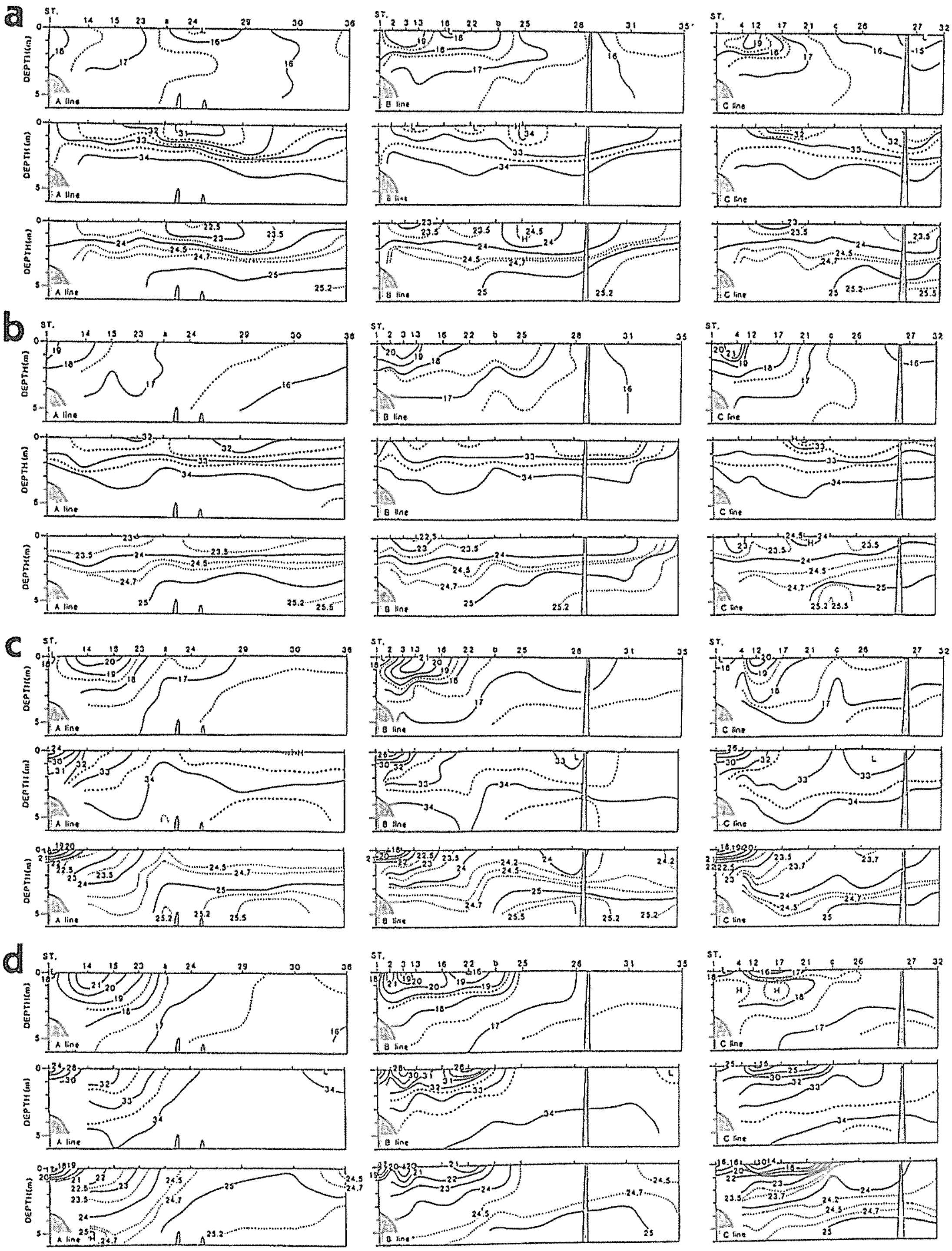

Fig. 4. (a) Vertical distributions of temperature (top), salinity (middle) and density (σ_t) (bottom), along A-line (left), B-line (center) and C-line (right) in flood period on 13 April 1989. (b) Same as (a) but for high water period. (c) Same as (a) but for ebb period. (d) Same as (a) but for low water period.

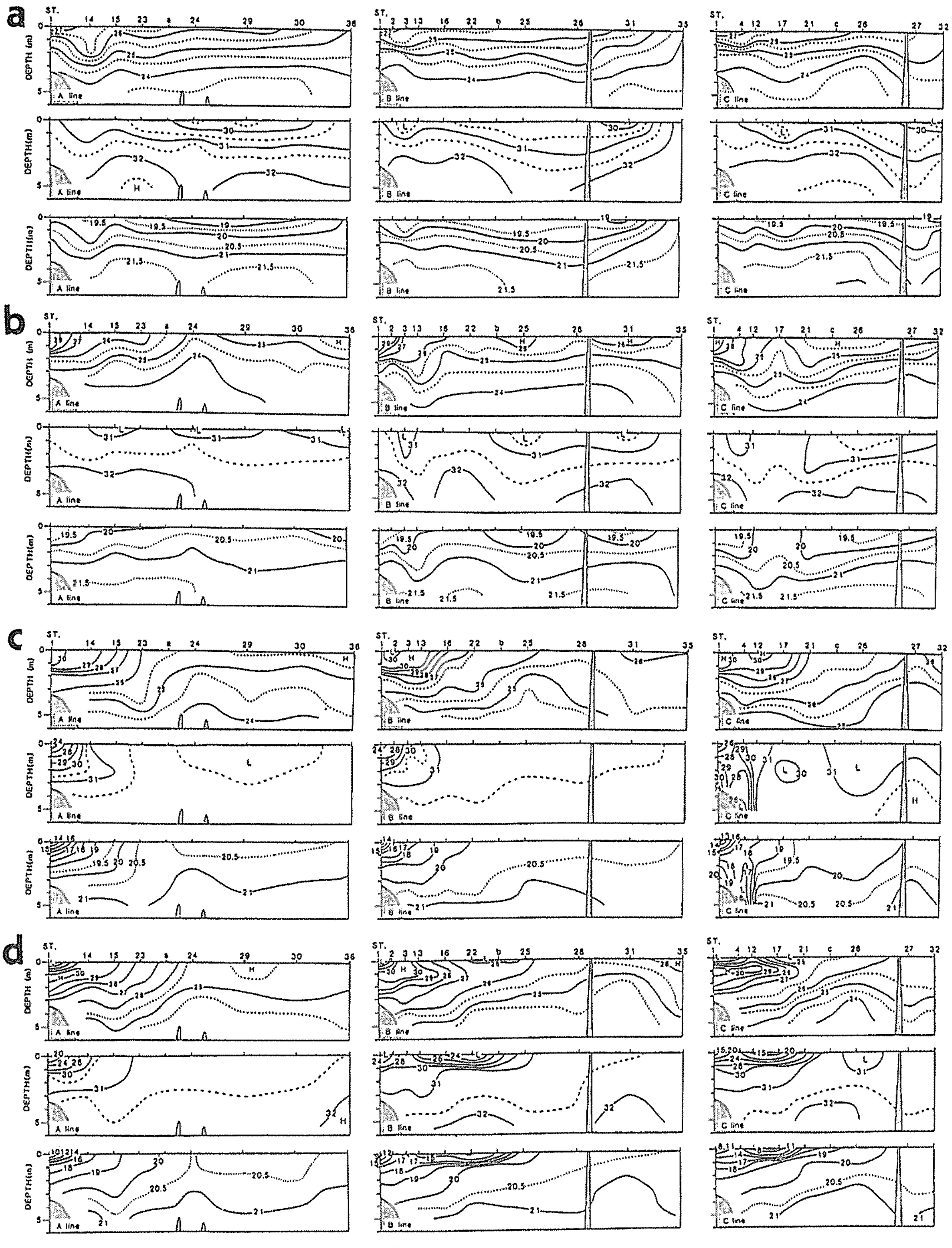

Fig. 5. (a) Same as Fig. 4(a) but for in flood period on 29 July 1986.
(b) Same as (a) but for high water period.
(c) Same as (a) but for ebb period.
(d) Same as (a) but for low water period.

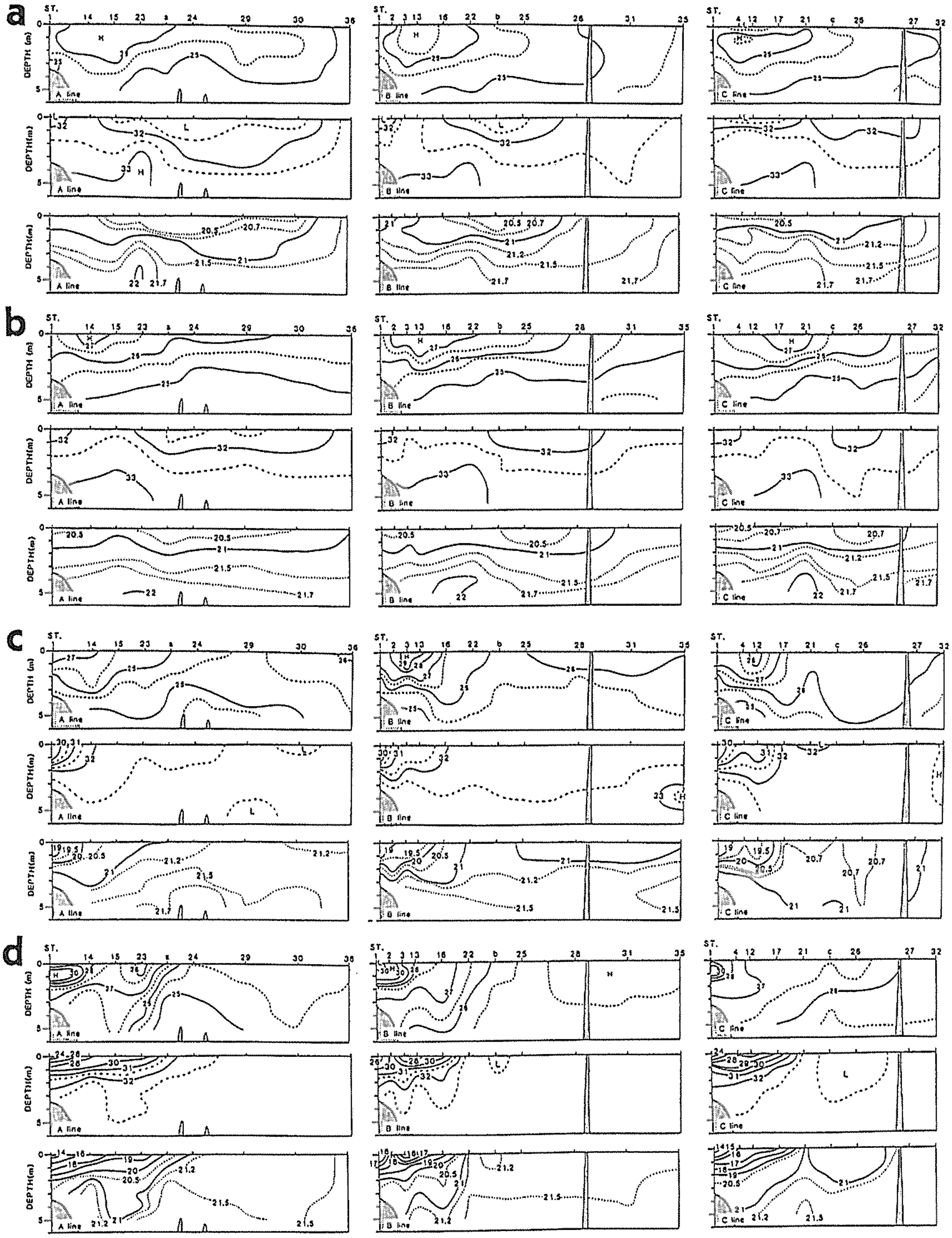

Fig. 6. (a) Same as Fig. 4(a) but for in high water period on 8 August 1986.
(b) Same as (a) but for ebb period.
(c) Same as (a) but for low water period.
(d) Same as (a) but for flood period.

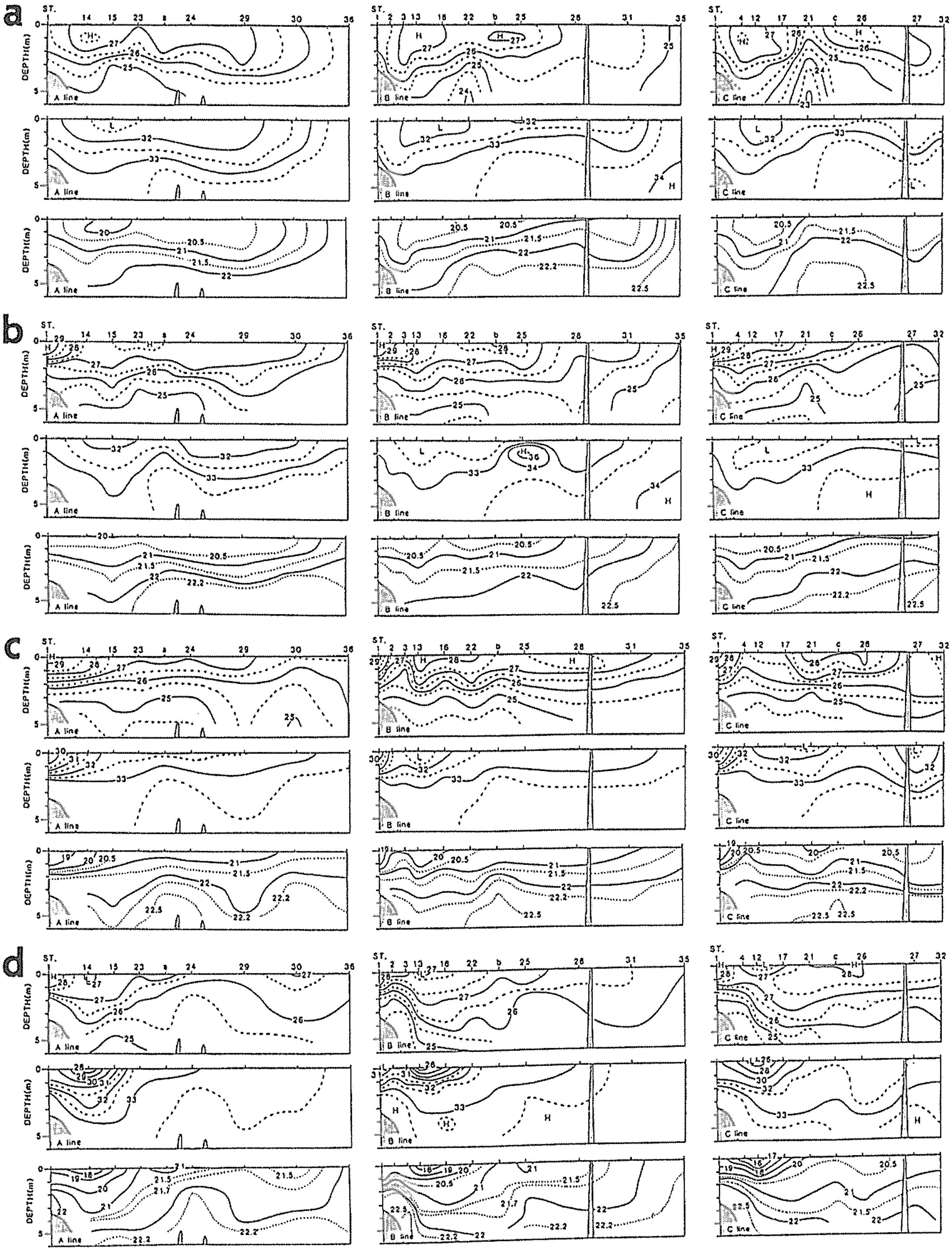

Fig. 7. (a) Same as Fig. 4(a) but for in high water period on 11 August 1987.
(b) Same as (a) but for ebb period.
(c) Same as (a) but for low water period.
(d) Same as (a) but for flood period.

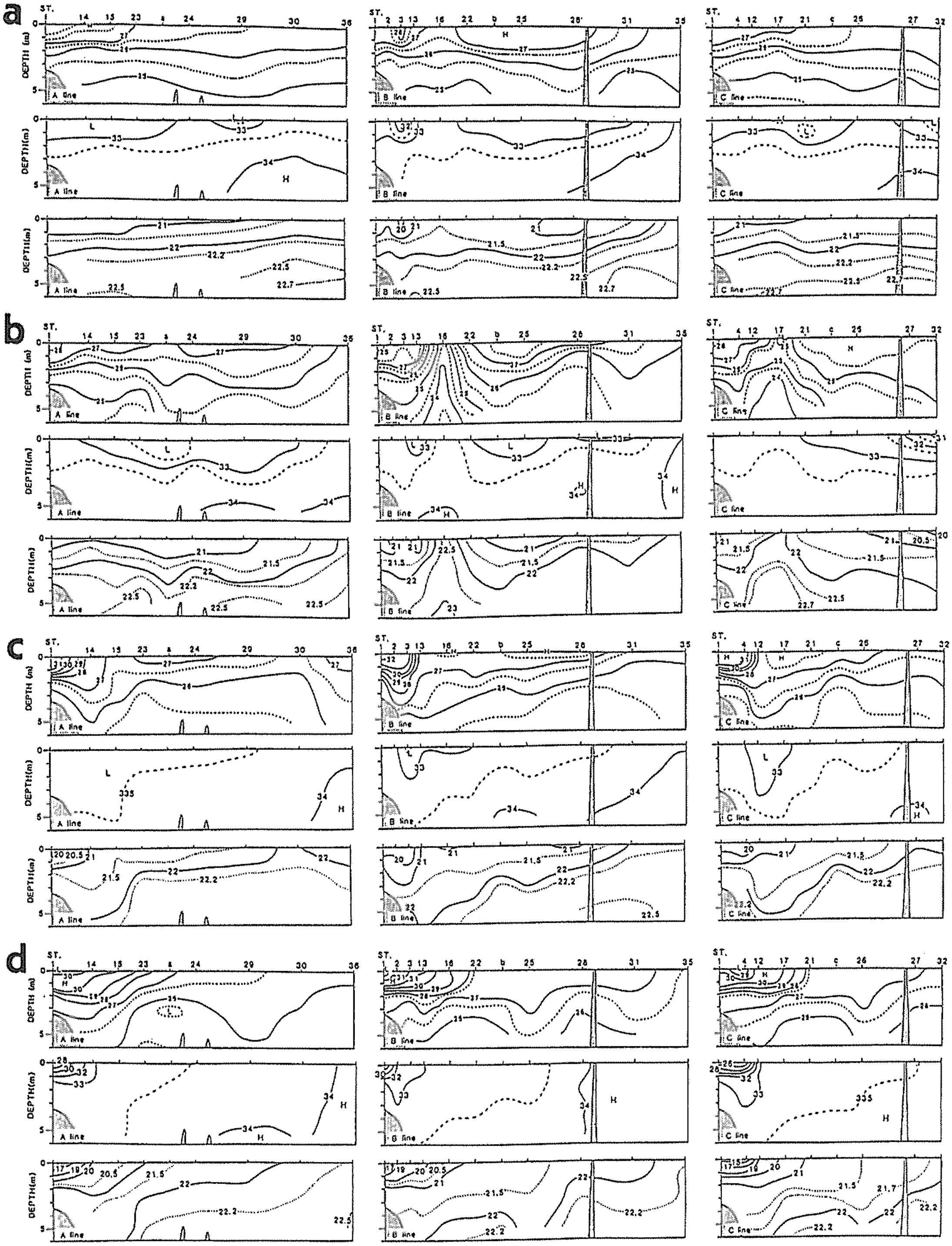

Fig. 8. (a) Same as Fig. 4(a) but for in ebb period on 19 August 1987.
(b) Same as (a) but for low water period.
(c) Same as (a) but for flood period.
(d) Same as (a) but for high water period.

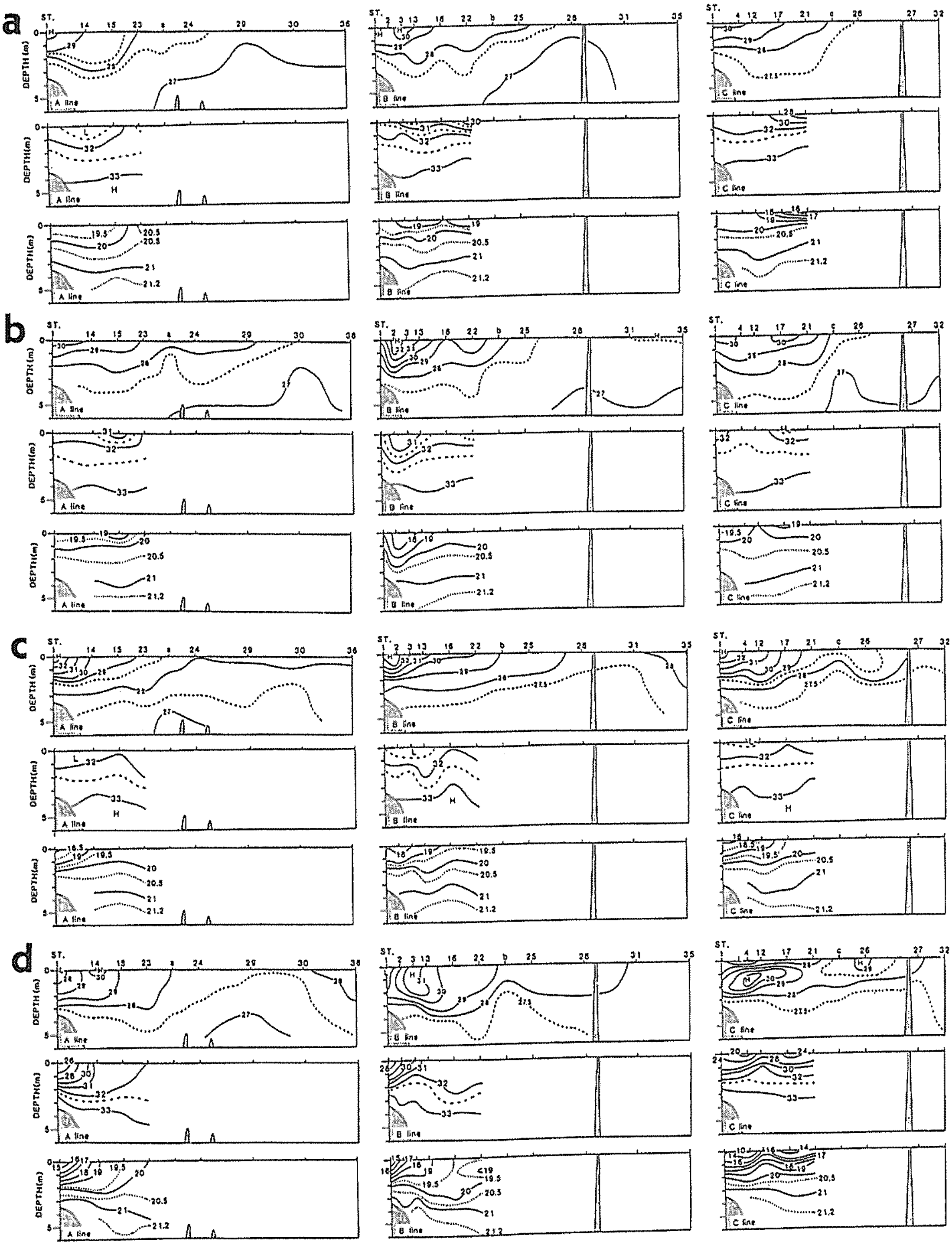

Fig. 9. (a) Same as Fig. 4(a) but for in ebb period on 20 August 1990.

(b) Same as (a) but for low water period.

(c) Same as (a) but for flood period.

(d) Same as (a) but for high water period.

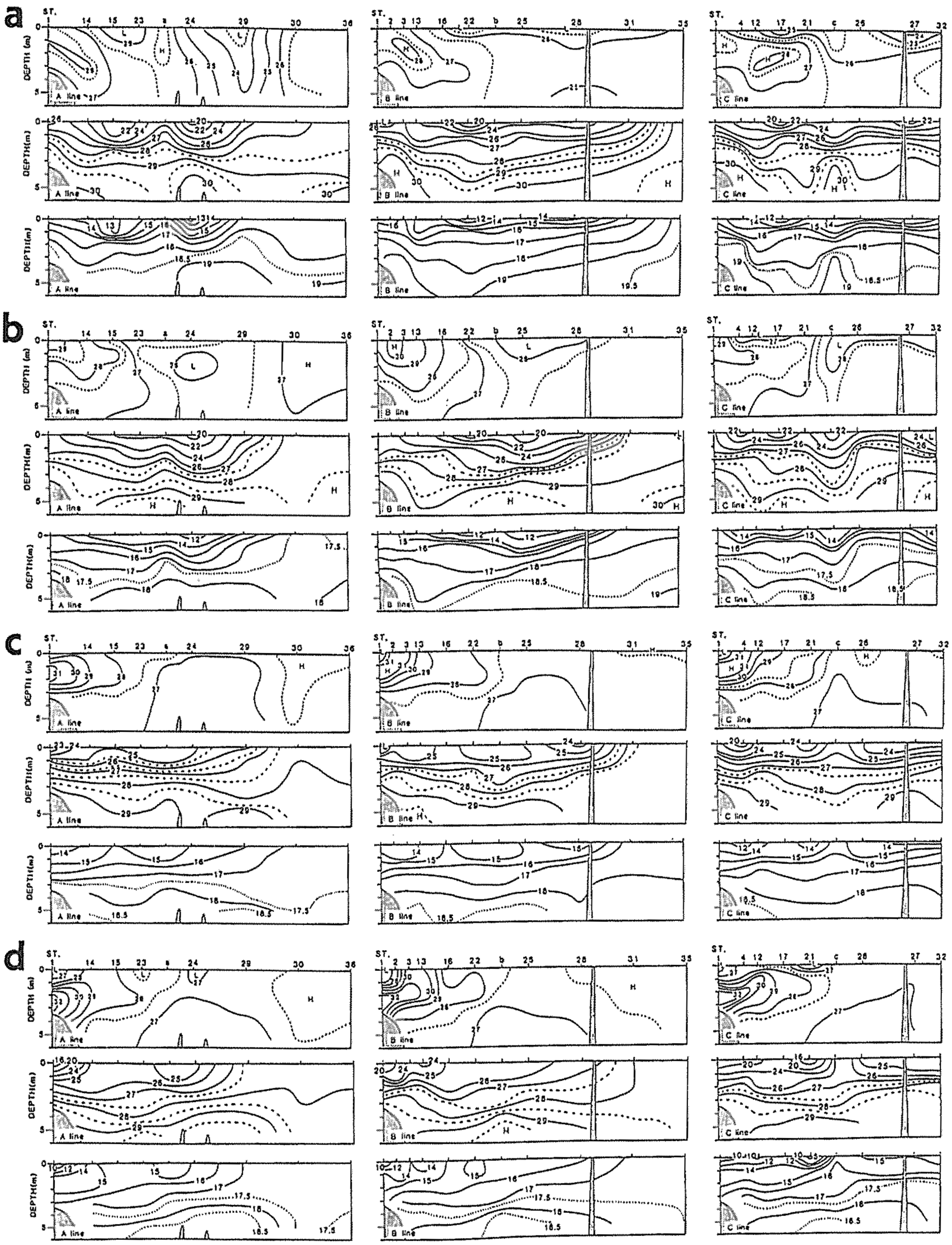

Fig. 10. (a) Same as Fig. 4(a) but for in ebb period on 26 August 1988.
(b) Same as (a) but for low water period.
(c) Same as (a) but for flood period.
(d) Same as (a) but for high water period.

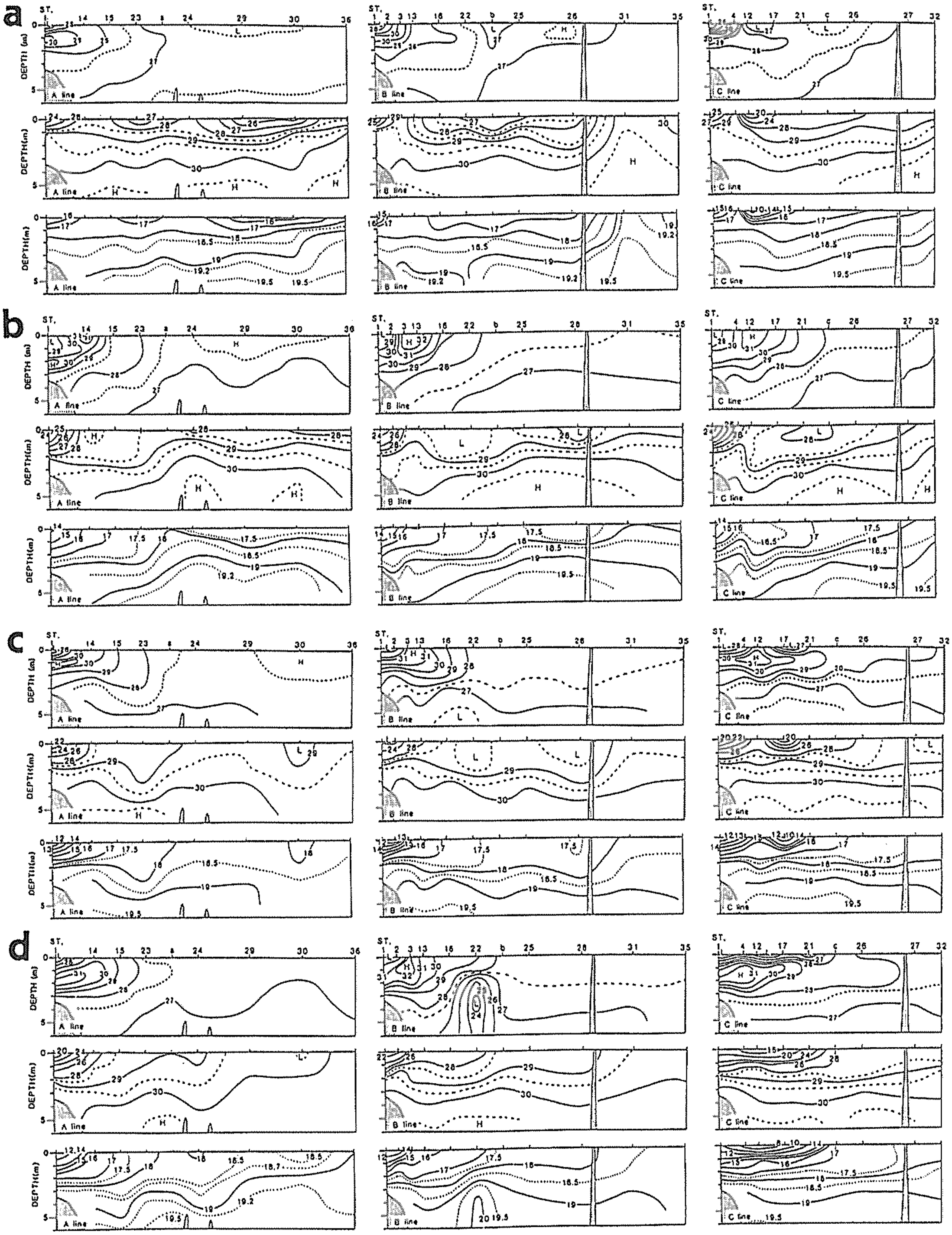

Fig. 11. (a) Same as Fig. 4(a) but for in high water period on 2 September 1988.
(b) Same as (a) but for ebb period.
(c) Same as (a) but for low water period.
(d) Same as (a) but for flood period.

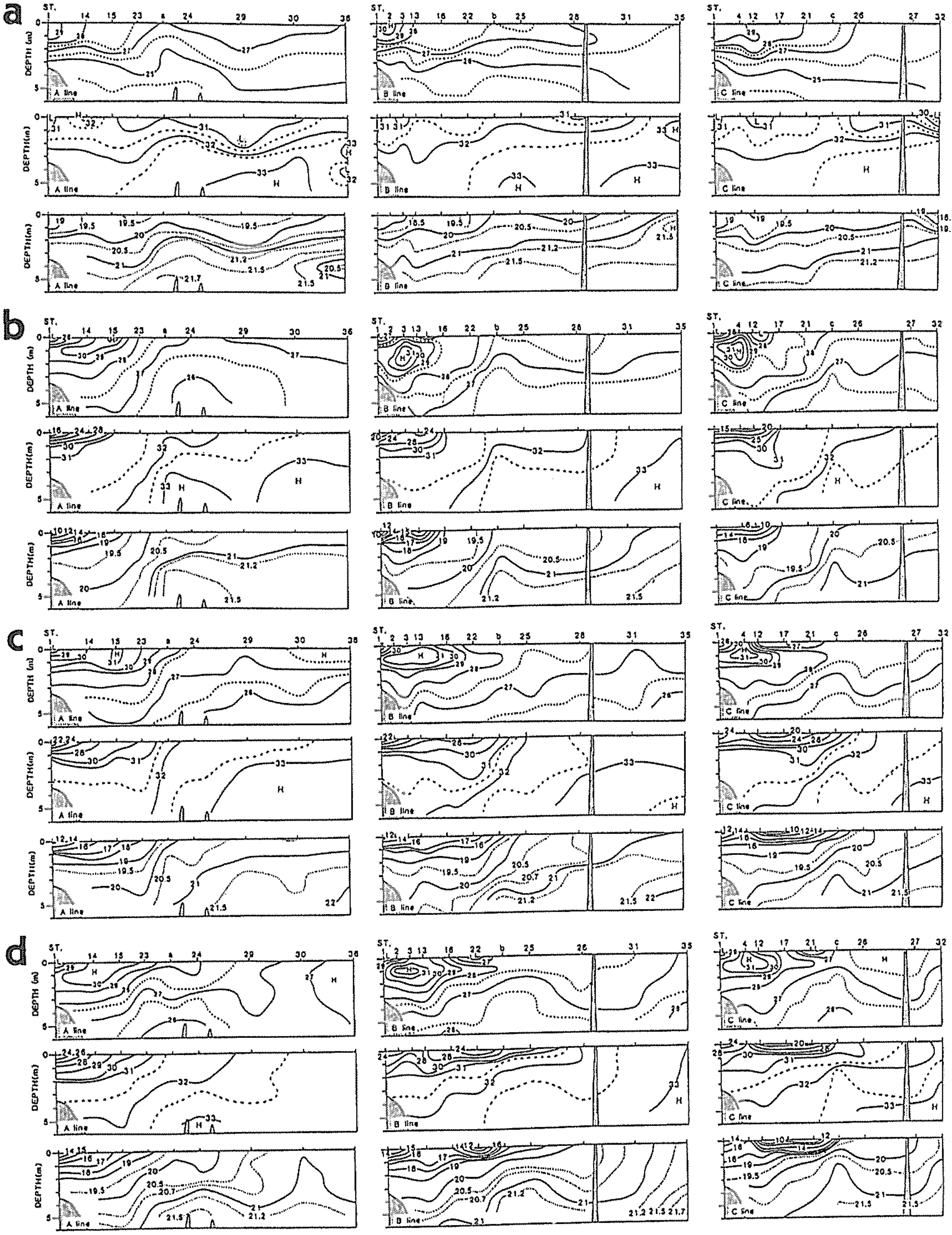

Fig. 12. (a) Same as Fig. 4(a) but for in flood period on 25 August 1989.
(b) Same as (a) but for high water period.
(c) Same as (a) but for ebb period.
(d) Same as (a) but for low water period.

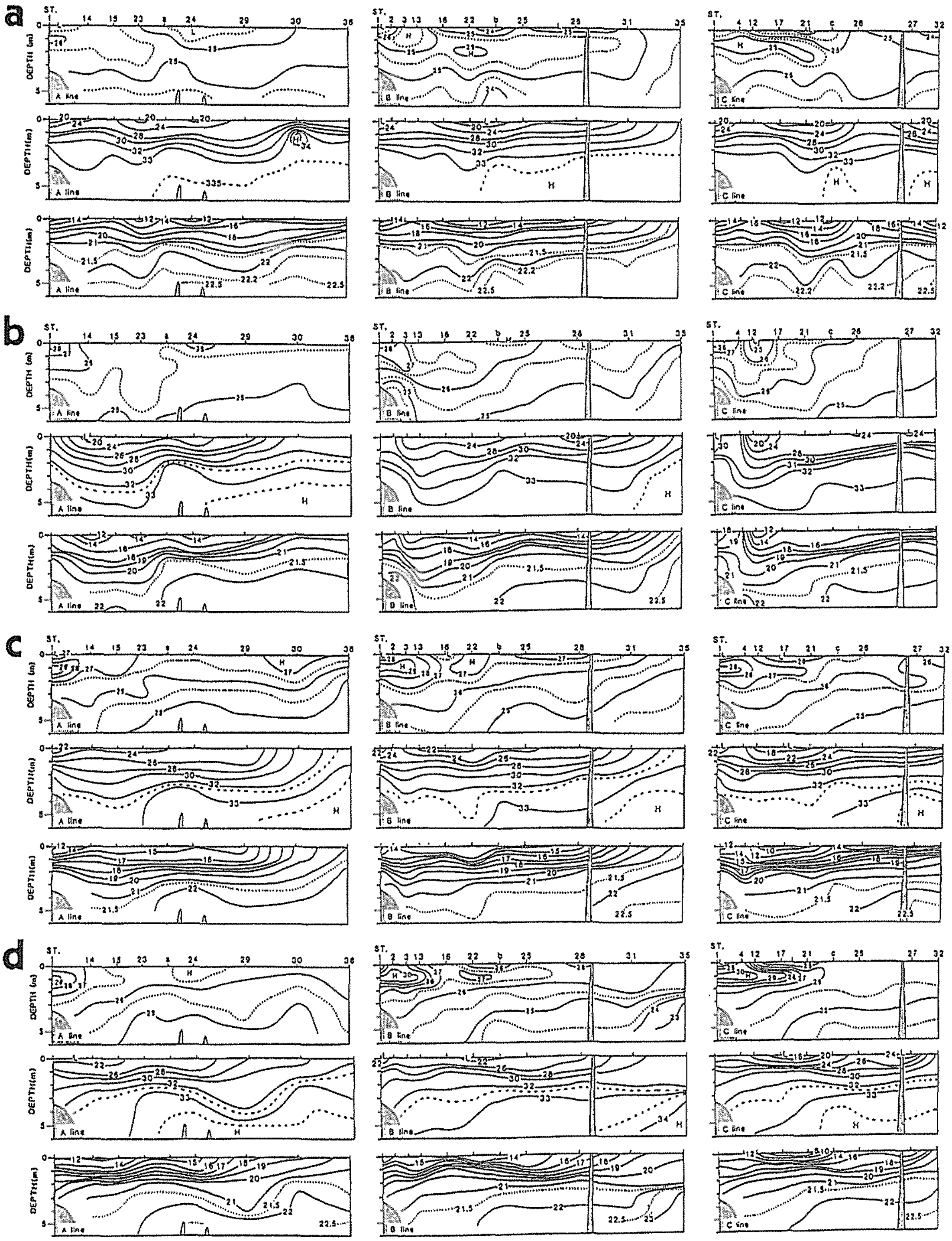

Fig. 13. (a) Same as Fig. 4(a) but for in ebb period on 31 August 1989.
(b) Same as (a) but for low water period.
(c) Same as (a) but for flood period.
(d) Same as (a) but for high water period.

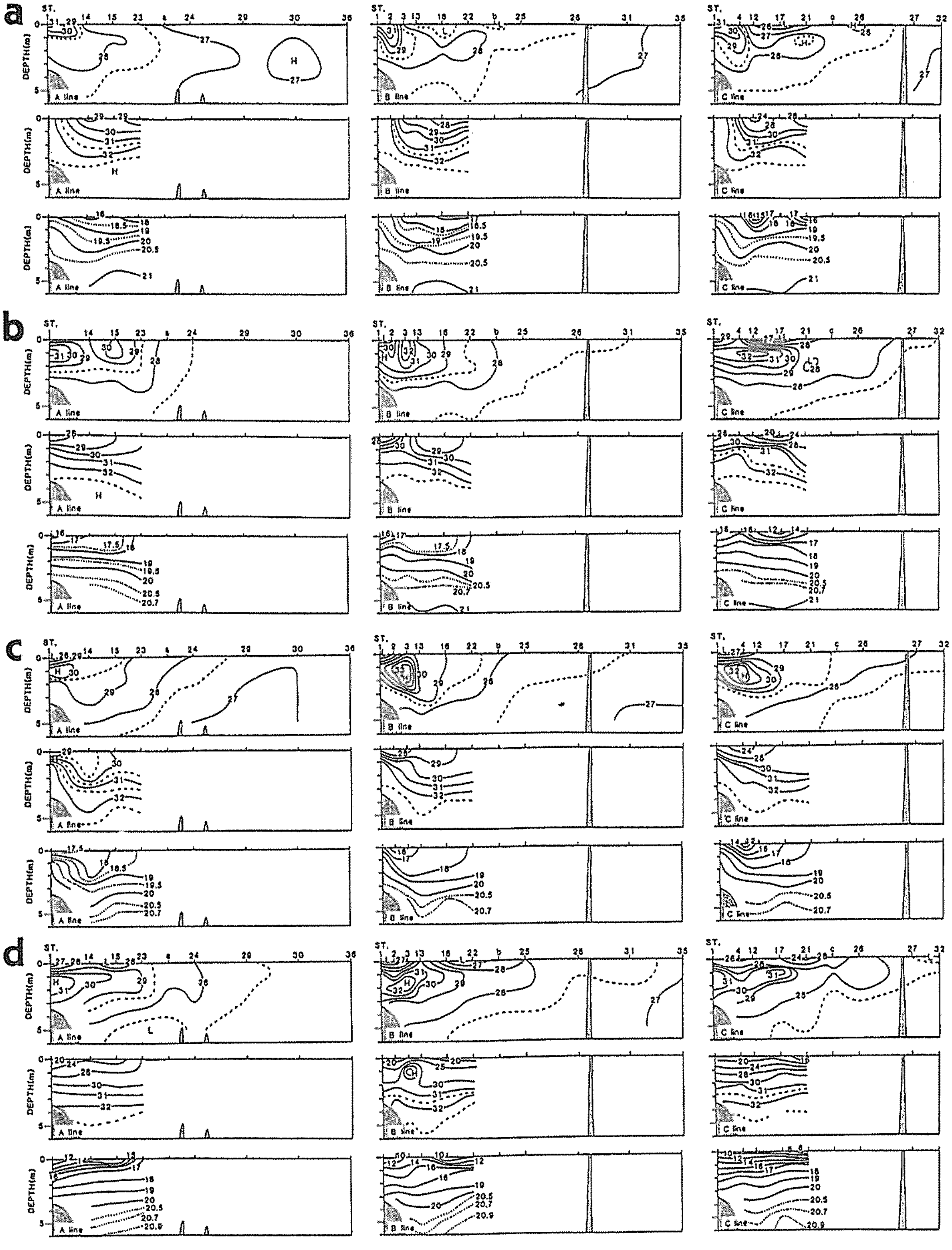

Fig. 14. (a) Same as Fig. 4(a) but for in flood period on 28 August 1990.
(b) Same as (a) but for high water period.
(c) Same as (a) but for ebb period.
(d) Same as (a) but for low water period.

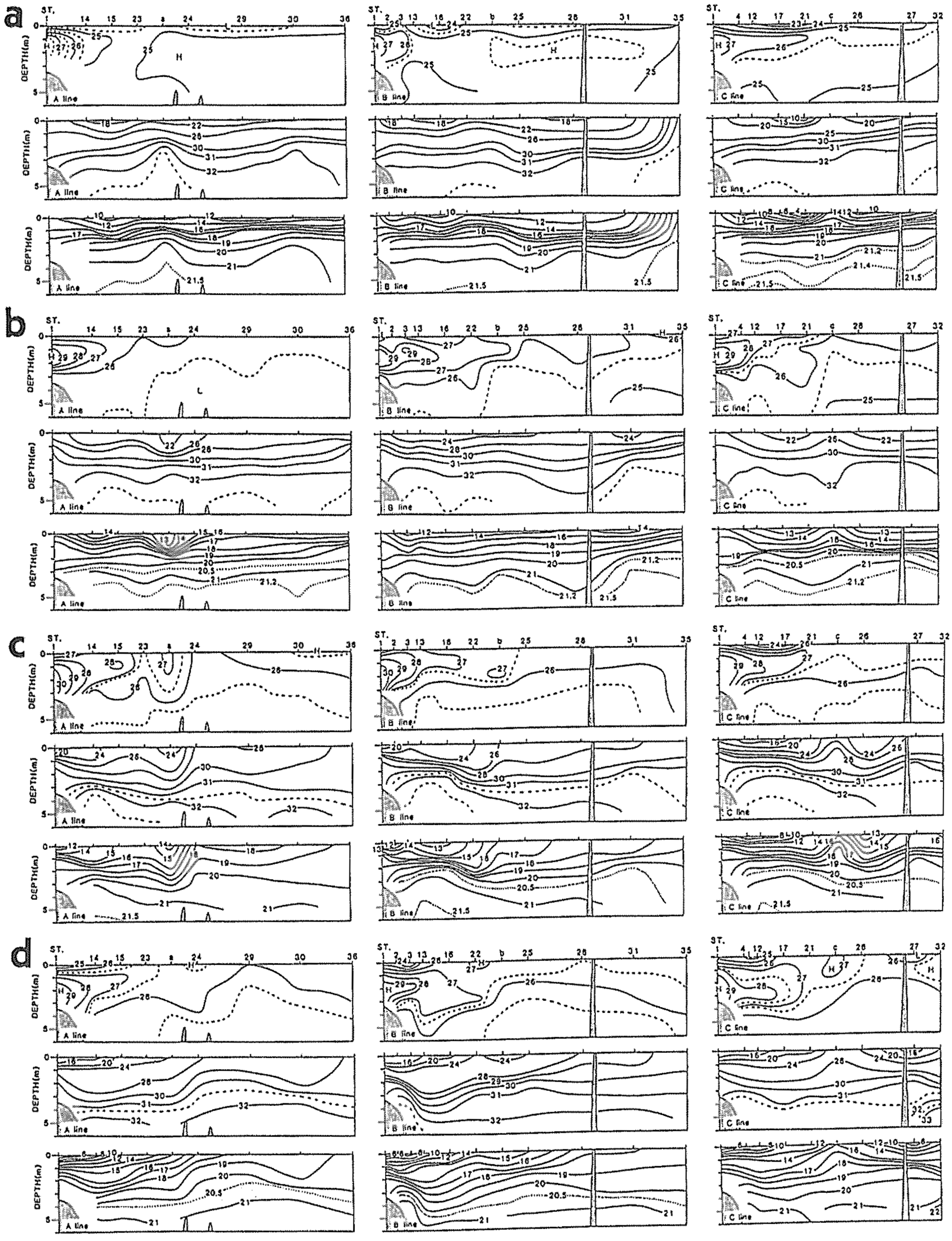

Fig. 15. (a) Same as Fig. 4(a) but for in flood period on 2 September 1991.
(b) Same as (a) but for high water period.
(c) Same as (a) but for ebb period.
(d) Same as (a) but for low water period.

temperature and salinity change are observed: on A- and B-lines, a water warmer than 26°C spreads to a center of the lines in the layer shallower than 2 m in ebb period, and warm water expands vertically in flood period. Especially on 8 August 1986 (Fig. 6d), a warm water reaches to a depth of 5 m. However on C-line, a warm water expands horizontally and vertically as the lapse of time. It is noted that temperature inversion occurs at the surface of the innermost of the bay in flood period. This phenomenon seems to be resulted from intrusion of thermal water effluent below less saline water. Salinity change depending on tidal period has a common phase to temperature.

In case of the Group (III), the two observations, on 19 August 1987 (Fig. 8) and 20 August 1990 (Fig. 9), have a common change in temperature. A water warmer than 27°C (Fig. 8) or 28°C (Fig. 9) spreads in the layer shallower than 2 m in low water period, and the warm water on A-line expands rather vertically to a depth of 3 m in high water period. However, the warm water on C-line continues to expand holizontaly and verticaly as the lapse of time. Temperature inversion occurs at the surface layer of the innermost of the bay in high water period (Figs. 8d and 9d). It is found that salinity is relatively high even at the surface in the innermost of the bay on each observation except for high water period.

In case of Group (IV), significant decrease in salinity was commonly observed except for 25 August 1989 (Fig. 12). Especially, less saline water than 30 psu is detected even at a depth of 5 m on 26 August 1988 (Fig. 10). It is suggested that notable decrease of salinity in the upper layer results in intrusion of effluent of thermal water. However, three different changes in temperature and salinity are observed, depending on the tidal period. Firstly, the two observations, on 26 August 1988 (Fig. 10) and 2 September 1988 (Fig. 11), have a common change in salinity: less saline water than 24 psu (Fig. 10) or 29.5 psu (Fig. 11) spreads to a center of each line or to a baymouth in periods of ebb and low water, but less saline water is suppressed to an innermost of the bay in flood period. This phenomenon is rather conspicuous on A- and B-lines. However, it is detected that temperature distribution is independent on tidal periods. A significant cold water than 24°C is observed at a depth of 3–4 m of B-line on 2 September 1988 (Fig. 11d). As this cold water is detected at only one observational point, details of this cold water is unclear.

Secondly, as for the results of 25 August 1989 (Fig. 12) and 2 september 1991 (Fig. 15), salinity distribution differs from previous two obseravations of Group (IV). Less saline water than 32 psu (Fig. 12) or 26 psu (Fig. 15) spreads to a baymouth in the upper layer in flood period, and less saline water is suppressed to an innermost of the bay in ebb period. Less saline water expands vertically to a depth of 5 m in an innermost of the bay on and after high water period on 25 August 1989 (Fig. 12). Simillar change is also found in temperature distribution: a water warmer than 27°C spreads in the layer shallower than 2 m in period of flood, and warm water expands vertically to a depth of 4 m on and after high water period. Since sea level change on 25 August 1989 is relatively small due to neap tides (Fig. 3), dependence on tidal periods is relatively small. In contrast to this, a water warmer than 26°C expands horizontally as the lapse of time on 2 september 1991 (Fig. 15).

Thirdly, it should be noticed that temperature distributions on 31 August 1989 (Fig. 13) on 28 August 1990 (Fig. 14) show no dependence on tidal periods, although the former (latter) obserbational period is in spring (neap) tides (Fig. 3). A water warmer than 26°C (Fig. 13) or 28°C (Fig. 14) expands horizontally and vertically as the lapse of time. Less saline water than 30 psu spreads in the layer shallower than 2 m to a baymouth in ebb period, and less saline water is rather suppressed to a center of A- and B-lines in flood period on 31 August 1989 (Fig. 13).

4 Summary and discussion

As an initial phase of the hydrographic condition of Owase Bay, the vertical distributions of the observed temperature, salinity and density have been presented in the present paper. The main results are summrized as follows.

(1) It is detected that hydrographic condition of Owase Bay signifgicantly depends on tidal period: effluents of thermal and fresh water tend to spread to a center of the bay or to a baymouth in ebb and low water periods. In contrast to this, expansion of effluents tend to be confined to an innermost of the bay, and effluents expand vertically in flood and high water periods. This suggests that advection of tidal current is important for the expansion of effluents. This tendency is more significant on A-line.

(2) During constant large effluent of fresh water, low density water due to low salinity spreads in a surface layer. Effluent of thermal water intrudes below the less saline water. From this view point, volume of fresh water effluent is important for the total feature of hydrographic condition in Owase Bay.

Uplift of saline water near the outflow of thermal water is perceived in some observations: in low water period on 8 August 1986 (Fig. 6c), in three periods on 11 August 1987 except for low water period (Fig. 7), in ebb period on 26 August 1988 (Fig. 10a) and in low water period on August 1989 (Fig. 13b). There is a possibility that the uplift is caused by the vertical entrainment of saline water due to the strong effluent. The dynamical discussion on this process is needed for the future study.

Together with the horizontal distributions of temperature and salinity1), general features of hydrographic structure of Owase Bay have been presented. Hydrographic structure of Owase Bay associated with effluents of fresh and thermal water and tidal conditions will be examined statisticaly and quantitatively in a succeding paper.

Acknowledgments

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尾鷲湾内部の水温・塩分・密度の鉛直分布について

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尾鷲湾の海況は火力発電所からの温排水と水力発電所からの淡水の流入により特徴づけられる。1987年7月に火力発電所3号機が増設され，温排水量は最大で 31.6 $m^3 sec^{-1}$ であったのが 53 $m^3 sec^{-1}$ から 55 $m^3 sec^{-1}$ に増加した。一方，淡水放水量は今日まで 0 $m^3 sec^{-1}$ から最大 25 $m^3 sec^{-1}$ の間で変化している。本論文では1986年4月から1991年9月にかけて13回行われた3測線におけるデータを用いて，水温・塩分・密度の鉛直分布を示した。全体として潮時に依存する顕著な水温・塩分・密度の変化があることが示された。温排水と淡水の排水は共に下げ潮時と干潮時において湾中央部から湾口にまで広がる。しかし，上げ潮時と満潮時には湾奥に閉じ込められ鉛直方向に広がる。この傾向は最も南寄りの測線において顕著である。また，水力発電所からの淡水放水量により水温構造が異なることが示された。淡水放水量が少ない場合は温排水は海面を広がるが，多い場合は湾の最奥部から温排水は低塩分水の下に貫入する。