

Graduate School of Frontier Sciences, The University of Tokyo

Department of Socio-cultural Environmental Studies

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Master's Thesis

Spatial distribution and its temporal variation of hypoxic
water mass and phytoplankton bloom around Sumida river
estuary, Odaiba, Tokyo Bay

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**Spatial distribution and its temporal variation of hypoxic
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**A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
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ABSTRACT

Water quality deterioration often causes hypoxia and phytoplankton bloom in estuarine and coastal system, but the mechanism that controls hypoxia and phytoplankton bloom vary among estuaries and often difficult to distinguish. A series of automated water column time series observation has been established around Sumida river estuary, Odaiba, Tokyo Bay. The time series data obtained from the three fixed observation stations at the outer and inner part of Odaiba during the period of June to September 2011 reveal the occurrence of episodic surface phytoplankton bloom followed by hypoxic events. The goal of the present study was to indentify and clarify the mechanism of hypoxic events and phytoplankton blooms in relation to hydrographic and environmental factors to mitigate the adverse effect on the estuary natural ecosystem. Five hypoxic events and phytoplankton blooms occurred during the summer observation period around the estuary in summer 2011.

Spatial and temporal variations in dissolved oxygen and chlorophyll-a concentration and the current severity of phytoplankton blooms were higher in the eutrophicated and stratified outer part (station 1) of the estuary than that of inner part (station 2 and 3). In contrast hypoxia were pronounced at the inner part than that of outer part of the estuary. In the inner part of the estuary, the main factor explaining dissolved oxygen and chlorophyll-a concentration variations were stratification, a floating fence on the surface water with a dominant effect on oxygen consumption processes and transport of phytoplankton towards the enclosed area of the estuary. In contrast, in the outer part of the estuary, the main factor explaining dissolved oxygen and chlorophyll-a concentration variations were tidal circulation, input of river discharge and direct source of phytoplankton from downstream directed ebb tidal currents suggesting that the effect of oxygen production and accumulation of phytoplankton through transportation were stronger than that of inner part. The outer part of the estuary showed strong water-column stratification and very high tidal flushing, and ventilation processes through the water column were more important than oxygen production or consumption processes.

Most hypoxic events were developed at the three stations with the increase of discharge followed by precipitation, north wind, ebb tide directed to downstream, light limitation coincided with low solar radiation and breakdown of each hypoxic event followed the opposite hydrographic and environmental phenomena. However, the most dominant factors to occur hypoxic events were summer stratification induced by north wind. Higher concentration of dissolved oxygen concentration in subsurface layer of the water column could be observed at the outer part (station 1) corresponding well with the distribution of chlorophyll-a concentration as because at the inner part (station 2 and 3) of estuary correspond with low dissolved oxygen concentration with low chlorophyll-a concentration compared to outer part of the estuary.

Phytoplankton biomass was concentrated more at the station 1 than those of station 2 and 3 as station 1 was more influenced by river water as well as sea water which are the dominant of source phytoplankton accumulation around the estuary. In the other sense, there was a significant difference in chlorophyll-a concentration between station 2 and 3 as a floating fence was positioned on the surface water which may restrict/hinder the horizontal transport of chlorophyll-a from station 2 towards 3. Thus the highest concentration of chlorophyll-a was found at the outer part (station 1) and second highest concentration was observed at station 2 and the lowest concentration of chlorophyll-a was found at the station 3. The observed phytoplankton bloom exhibited with several environmental and hydrographic factors such as south wind forcing, light availability and river discharge structures, current direction and relatively stable water column. However, the most dominant factors to occur phytoplankton bloom in this area were summer solar radiation and transport of high chlorophyll-a water from the upstream to the downstream region around the mouth of the river.

HADCP data result shows that downstream directed along river currents can force to accumulate high chlorophyll-a concentration water around the estuary that caused phytoplankton bloom more at station 1 than those of station 2 and 3. Conversely, intrusion of salt water from the bay by tidal circulation of upstream directed currents can force hypoxic water mass around this area rapidly with significant implications for water quality. The effects were intensified by the prevailing south wind that accumulated high concentration of chlorophyll-a water around the estuary and low dissolved oxygen water mass were developed at the onset of north wind associated with spring-neap tidal modulation that possibly enhanced the estuarine circulation. Peak along river velocity was noted at the end of ebb, when the river discharge and tidal discharge combined into one flow. Similarly weak velocity was observed at the end of flood phase.

The observations from summer 2011 suggest that the hypoxic events and phytoplankton blooms have close correlation with predominant wind, seasonal water column stratification, fresh water discharge and tidal circulation. Based on these findings, it can be projected into future years the time when summer blooms and hypoxia are most likely to occur around this area which will initiate long-term estuarine monitoring to investigate the adverse effect of water quality deterioration on estuarine ecosystem.

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CHAPTER 1: INTRODUCTION

1.1 General

Estuaries are of immense importance to many communities. It has been estimated that 60 to 70% of the commercial marine fishery resources depend on estuaries for part of or all of their life cycle (Klen, 2006). The coastal waters are one of the most valuable and vulnerable of Earth's habitat, despite their limited area. Human being is largely dependent on them for various aspects, such as food, energy, transportation, recreation and livelihood. The intense variability of the coastal and estuarine regimes is closely associated with their rich and variegated structure of the ecosystem. Due to their immense importance concerning biodiversity estuarine regimes are considered to be indispensable to the life on earth. An estuary is a semi-enclosed body of water, which has a free-connection with the sea and is thus strongly affected by tidal action. The characteristics of estuarine flow and transport process are important as they play a critical role in the functionality and health of this system. Coastal waters and estuaries present the world with a bounty of tangible and intangible benefits. People rely on the coastal waters and estuaries for recreation, livelihoods, and social and economic wellbeing. Estuaries represent only a tiny proportion of the world's surface waters, but they are among the most productive ecosystems in nature. Rivers drain into estuaries, bringing in nutrients from uplands thereby plants use these nutrients, along with the sun's energy, carbon dioxide and water to manufacture food. Thus these waters provide critical habitat for various life stages of commercial fish and shellfish and support popular recreational activities. This mixing of fresh and saline water creates a unique environment that brims with life of all kinds, such as birds, mammals, fish and other wildlife.

However, most riverine pollutants empty into estuary. Dredged materials, industrial discharge and wastes are the primary point sources to estuaries. Urban runoff and agricultural activities are often the major nonpoint sources. Thus estuaries face similar pollution problems due to over enrichment of nutrients and alteration of fresh water inflow. In addition to these problems in estuaries the other key characteristics of coastal and estuarine waters include sharp horizontal and vertical gradients of salinity and other hydrodynamics and water quality variables. The sharp salinity gradients results from the freshwater inflows and the mixing of saline waters from sea. In additions, in the estuarine region wind forcing and tidal circulation affect the gradient of salinity, temperature and other water quality variables such as dissolved oxygen and chlorophyll-a concentration. These problems results in harmful phytoplankton blooms, oxygen depleted waters, beach and shellfish bed closings, fish kills and a variety of other environmental

problems. Thus, the importance of estuarine research is very significant to mitigate the adverse effect on estuary natural ecosystem

The wind driven current is generated by a southerly wind in the summer. Normally stratification in Tokyo Bay strengthens in summer and weakens in autumn and winter. A northerly wind prevails over the bay in autumn, winter and spring, and a southerly wind dominates in summer (Unoki et al., 1980). These conditions induce a gravitational circulation at the mouth of the bay in the upper layer and into the bay in the lower layer. Moreover, 13 rivers empty into Tokyo Bay and the density driven current is accompanied by an estuarine front in the west bank of Tokyo Bay where large rivers discharge. The inflow of the seaward water drives circulation within the embayment and can transport bottom hypoxic water in many coastal regions. In a tributary estuary of Chesapeake Bay the combined motion due to wind-forced oscillation and internal tidal oscillation cause intrusion of heavy and hypoxic water from below the pycnocline of the main stem bay (Stanford and Biocourt, 1990; Breitburg, 1990). Similarly wind and tidal forcing drive heavy hypoxic waters into other estuaries and onto the near-shore continental shelf (Falkowski et al., 1980; Swanson and Parker, 1988). Tidal forcing regulates the frequency and quantity of sea water that enters an estuary, and tidal waves are often modified when the tide propagates through an estuary. Frictional effects can produce tidal harmonics that vary with factors such as depth, shape and length of the estuary (Pugh, 1987; Prandle, 1991). Salinity or density distribution within an estuary is controlled by the vertical and horizontal mixing between the sea and fresh water; occurring at time scales ranging from those of turbulent motions through to seasonal scales (Peters, 1997).

Tokyo Bay is located in the center of main island of Japan, southern Kanto region of Japan. The Bay is surrounded by the Boso peninsula (Chiba Prefecture) to the east and the Miura Peninsula (Kanagawa Prefecture) to the west. In a narrow sense, Tokyo Bay is the area north of the straight line formed by the Cape Kannon on the Miura Peninsula on one end and Cape Futtsu on the Boso Peninsula on the other hand. This area covers about 922 km². In average, the bay is about 1000 km² in area, have average depth of around 17 m, width of around 20 km, length of around 60 km and narrow mouth of about 7 km.

Tokyo Bay is one of the most eutrophic semi-enclosed embayment in the world having degraded water quality, decreasing in fishery landing and frequent occurrence of phytoplankton bloom and depletion of dissolved oxygen (DO) concentration in the water column in stratified

season. Extensive spring and summer phytoplankton bloom and associated oxygen depletion in the lower layer of the water is thought to be one of the most important factors in reducing the capacity of the bay and the estuary area to support economically important fishery resources. These characteristics are partly attributed to the topographic setup of the bay that restrict the water exchange between the bay and outer sea (Miyata and Hattori, 1986). The phytoplankton bloom can be easily occurred by the abundance of the nutrient discharge from the surrounding rivers which flow through heavily urbanized and industrial metropolitan area and receive a variety of industrial and municipal effluents (Koibuchi and Isobe, 2007; Sohma et al., 2008). Extensive researches have been carried out in the Tokyo Bay including the general biogeochemical properties in terms of phytoplankton activities (Koibuchi & Isobe, 2007) as well as the hypoxic water behavior (Yagi et al., 2007; Sohma et al., 2008). Oxygen-depleted waters in stratified season are also a serious environmental problem in inner Tokyo Bay. The development of this water is due to the substantial oxygen consumption to decompose large amount of organic materials that are internally produced and received from the surroundings of Tokyo Metropolitan and nearby cities associated with the stratification of the water column (e.g. Koibuchi and Isobe, 2007; Sohma et al., 2008). The overall circulation and water quality of Tokyo Bay was found to greatly affect the tributary estuaries (Suzumura et al., 2004; Pokavanich et al., 2008; 2009; Yagi et al; 2008; 2009).

Thus, water quality deterioration often causes hypoxia and phytoplankton bloom in estuarine system but the mechanisms that controls hypoxic events and phytoplankton bloom vary among estuaries are often difficult to distinguish.

1.2 Research Motivations

The coastal and estuarine areas are strongly affected by tidal action and a dynamic natural complex is formed as land, river and sea merge. Estuaries rank along with tropical rainforests and coral reefs as the world's most productive ecosystems, more productive than the rivers and the oceans that influence them from either side (Harvey, 1998). In an estuary, the mixing of lighter fresh water and heavier salt water trap and circulate nutrients in such a way that they are often retained and recycled by benthic organisms to create a self-enriching system. The deterioration and use conflict of these areas are multifaceted, with large extent and multi-level structure and interactive functioning not yet fully understood. Research on the dynamics of their physical process and its interaction, therefore, needs to be addressed accordingly in an integrated and holistic approach. This requires substantial field effort and monetary budget to

obtain spatial and temporal resolution information in terms of water quality parameters specially focusing on the development and fate of oxygen depleted water mass and phytoplankton bloom which could be very lethal and stressful for the aquatic organisms for varying spectrum of scientific discipline. This calls forth for the development of an effective, up-to-date field observation to fill the knowledge gap.

1.3 Background and purpose of the study

The study was conducted around the Sumida river estuary (Figure 3.1), which is one of the most eutrophic basins in Japan. The estuary is located along the west side of Tokyo Bay and is a healthy natural ecosystem supporting many kinds of marine flora and fauna as well as tourism activities are the most prominent features around this area and it is mentionable that this area is traditionally land reclaimed to establish more activities. It is still possible that the changing due to land reclamation might trigger the deterioration of water quality around the estuary causing fetal damage to well function ecosystem or it might yield other detrimental effects to the estuarine-bay ecosystem system. It is actually among the limited natural ecosystems left in the bay after the heavily reclamation programs along the area. Sumida River flows through heavily urbanized and industrial metropolitan area and receive a variety of industrial and municipal effluents. The drainage basin covers wide space of Tokyo Metropolitan and adjacent cities receiving tremendous excess nutrients from waste water and rainfall-runoff discharge from surrounding. Schematic illustration showing the overall estuarine process and functions is given in Figure 1.1.

Although previous researches have pointed out that the residual current in Tokyo Bay has a strong seasonal variations corresponding to meteorology, river discharge and wind affecting the material transport (e.g. Asad et al., 2006, Guo and Yanagi, 1996, 1998; Yanagi et al., 2003), effects of oceanic water intrusion (e.g. Fujiwara et al., 2000; Fujiwara and Yamada, 2002; Yagi et al., 2003; Yagi et al., 2008; Pokavanich et al., 2009). Yet, the detailed discussion on the combined effect of wind forcing and intrusion of bay water to estuary and the transport of hypoxic water mass and chlorophyll-a around the estuary area by continuous time series observation has not yet been documented or forecasted around the Sumida river estuary.

Extensive summer phytoplankton bloom and associated oxygen depletion is though to be one of the most important factors in reducing the capacity of the coastal and estuaries to support the economically important fisheries and other activities. The concentration of dissolve oxygen is

an important water quality parameter in estuarine environment because low DO concentration can be physically stressful or lethal to aquatic organisms (Breitburg et al., 1997). Hypoxic and anoxic condition can have a severe impact on the behavior of marine animals and on the structure and function of benthic communities including micro-invertebrates (Diaz and Rosenberg, 1995). Since, Tokyo Bay and Sumida river estuary physical process are closely related, the effects of changes in the estuary might substantially contribute to the alteration of the bay system. Moreover, it was found that inflow of oceanic water greatly alter the physical transport process about the Tama river estuary and largely affect the movement of hypoxic water around this area (Fujiwara and Yamada, 2002; Yagi et al., 2008 and Pokavanich et al., 2009).

This study which has final goal to understand the tidal circulation and water quality characteristics in terms of hypoxic water mass and phytoplankton blooms to mitigate the adverse effects on the estuary natural ecosystem. Due to strong linkage between Tokyo Bay and Sumida river estuary, the present study aimed to investigate and examine the complex interactions of water circulation associated with the interaction with hypoxic water and chlorophyll-a and water quality process as well as understanding the dynamic behavior of hypoxic water and phytoplankton bloom mechanism. However, the general characteristics of water quality and the highly fluctuating mechanism on the development and fate of hypoxic water and phytoplankton bloom associated with stratification in response to environmental factors around this estuary has not yet been adequately addressed or documented by continuous time series observation. At present or currently, available information by continuous time series on spatial and temporal resolution is limited on this area and therefore little is known about the mechanism on the occurrence of hypoxia and phytoplankton bloom and their interaction in response to different environmental factors in particular.

To achieve the goal, series of intensive field observation coupled with spatial and temporal dimension were used to investigate the water quality characteristics with particular reference to the occurrence of hypoxia and phytoplankton bloom around Sumida river estuary in summer 2011. The summer was chosen for field data analysis as this was assumed to be the season with the greatest potential for chronic degraded water quality due to river flow and high thermal stratification within the estuary. The findings from the study would better serve scientists, decision makers and managers in their attempts to address the cause of hypoxia and bloom in estuaries located in heavily populated areas such as Odaiba. In addition, the fundamental

understanding from the present study will then be very useful to issue the management strategy to tackle the possible adverse effect to the natural ecosystems in this area.

1.4 Objectives:

As outlined previously, the main objective of this study is to clarify the mechanism on the development and fate of phytoplankton bloom and hypoxic water of shallow estuarine systems by utilizing field data. In this process, this study first collected a set of hydrodynamic and water quality data from a shallow estuary like odaiba, Sumida river estuary, Tokyo Bay, Japan during June to September, 2011.

The specific objectives of the study are as follows:

- To provide a detailed description of the patterns and mechanism on the occurrence of the hypoxic events and phytoplankton bloom in response to physical forcing and environmental factors.
- To describe the spatial distribution and its temporal variation of the hypoxic events and phytoplankton blooms.
- To characterize the variability in the flow velocity field and corresponding transport process of the Sumida river estuary under a variety of forcing conditions.

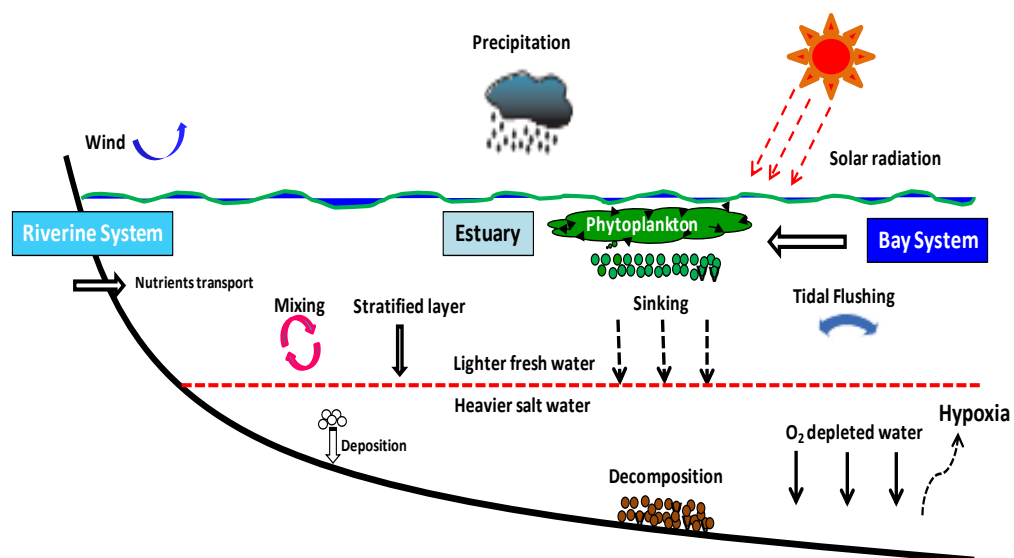


Fig .1.1 Schematic illustration of overall estuarine processes and function in Sumida river estuary, Tokyo Bay, Japan.

1.5 Organization of Thesis:

All chapters in this thesis are self contained with figures, tables and references. The thesis layout is organized in the following manner, following Chapter 1.

In Chapter 2, it summaries the literature review on water quality characteristics in Tokyo Bay, tidal mixing and estuarine circulation, physical stratification and low dissolved oxygen studies, phytoplankton bloom studies, physical studies of wind driven circulation and physical studies of river discharge that have been extensively used in this studies and also briefly described in this chapter.

The previous chapter provides the background, literature review and framework for the study to be done. Chapter 3 outlines the methodology involved in the study and is divided into three parts. The first section of this chapter outline the description of the study area and the second section of this chapter describes the field observation techniques and third section outlines the calculation of river discharge.

Chapter 4 illustrates the results of field observation using the continuous observation at the fixed point stations can be shown in time of temporal and spatial variation. It outlines the results of the observation in terms of water quality parameters incorporating with hydrographic conditions associated with local atmospheric conditions. This chapter is divided into major components of the study with sections for comparing the spatial distribution of dissolved oxygen and chlorophyll-a concentration around this area by explaining the mechanism of these phenomena.

Chapter 5 involves with the discussion part of the observed results whether the obtained results are corresponded with the previous studies conducted in the same field or slightly deviated of the present study result incorporated. In other sense, this chapter describes, that the obtained results from the present study comply or differ with the previous results. However, this chapter explains the possible interaction of the observed water quality parameters.

Finally, Chapter 6 outlines the conclusions of this study.

CHAPTER 2: LITERATURE REVIEW

This chapter summarizes the literature review on water quality characteristics in Tokyo Bay, estuarine circulation, physical stratification and low dissolved oxygen studies, phytoplankton bloom studies, physical studies of Tokyo Bay, physical studies of wind driven circulation and physical studies of river discharge that have been extensively used in this study and also briefly described in this chapter.

2.1 Water quality in Tokyo Bay

Nutrient load in Tokyo Bay have decreased remarkably by conducting the marine environmental improvement project (1970's), the sea blue project to improve (1980's) and the Eco-port project (1990's). As a result, both the residence time of sea water and the nutrient load into the bay have decreased, yet the condition of eutrophication remains. The typical phenomena of eutrophication such as red tide, hypoxic water and blue tide still occur in Tokyo Bay. In Tokyo Bay, large scale red tides have repeatedly occurred from spring to early winter every year. The red tide is a kind of phenomena characterized by phytoplankton bloom. Strong stratification due to salinity and temperature gradient occurs in late spring and summer. High oxygen consumption rate by bottom sediment accelerate oxygen depletion in inner Tokyo Bay. The frequency of oxygen depleted water in the bottom layer has almost remained constant at about three to four months per year since the 1980's.

In 2001, Cabinet office, Government of Japan, declared to promote restoration of sea and Tokyo Bay Renaissance committee was formed by local governments. The committee set a goal referring "water Quality". The committee attempted to investigate the dissolved oxygen concentration to clarify the mechanism of spatial distribution of hypoxia in Tokyo Bay (Horie et al., 2009).

2.2 Tidal mixing and estuarine water circulation

The tidal regime of an estuary can greatly influence mixing. Fischer et al. (1979) outlines two ways in which this is done. The most obvious of these is through the back and forth oscillation of the tides, creating a shear near the bed. Maximum mixing in estuaries and lagoons occurs when the estuary is narrow and the tidal period is similar to the time required for cross sectional mixing

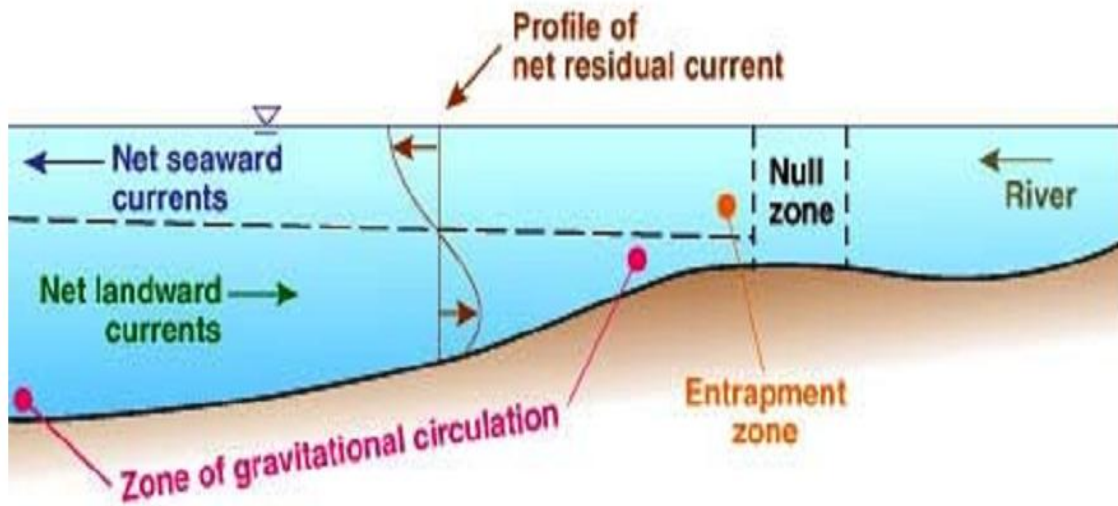


Fig.2.1 Typical estuarine circulation. Diagram demonstrates seaward flowing surface layer due to freshwater discharge, and landward currents flowing bottom layer (H'Trent 2003).

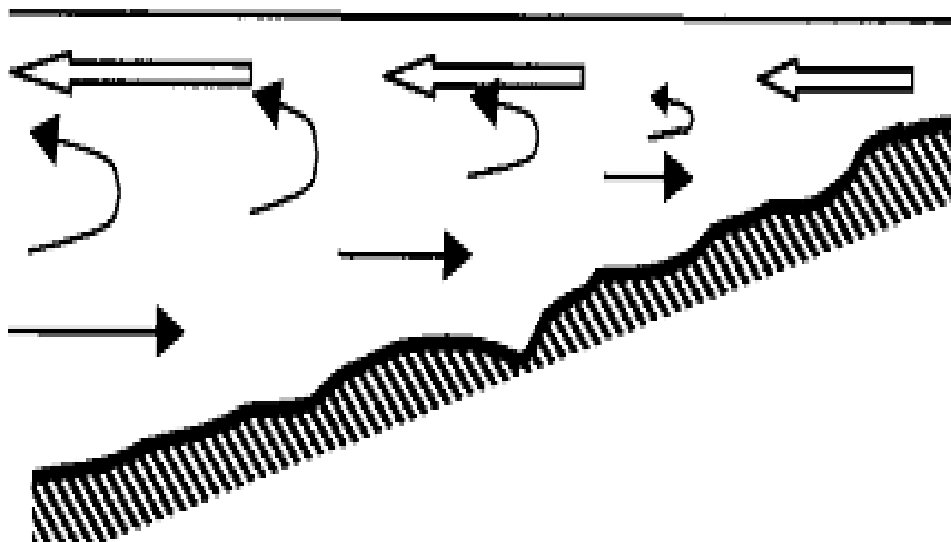


Fig.2.2 Estuarine circulation. Diagram demonstrates seaward flowing surface layer due to freshwater discharge, and landward currents flowing bottom layer (J'Largier 2000).

The second important characteristic of tidal flows is the residual circulation. The loose definition of the residual is the velocity field resulting from averaging the velocity at every point in the estuary over an entire tidal period. This residual current is generally one or two orders of magnitude less than the currents themselves, but can potentially dominate the overall distribution of characteristics such as temperature and salinity (Pugh 1987). The residual current may be caused by bathymetric irregularities, density differences, wind stress, changes in atmospheric pressure or reflection of tidal currents. The classic estuarine circulation pattern is shown in Figure 2.1 and 2.2. It shows the buoyant freshwater layer often evident in estuaries, resulting in a net seaward flow at the surface, and a net landward flow at the riverbed caused by tidal action.

Yanagi et al. (2003) investigated the spring-neap tidal variations of tidal currents, residual flow and clockwise circulation related an estuarine front in Tokyo Bay using observed data. They pointed out a peculiar fortnightly variability of residual flow near the bay mouth resulting from the vertical distribution of shear and viscosity.

2.3 Physical stratification and low DO studies

A direct relationship between the occurrence of stratification and depletion of oxygen below the pycnocline was found throughout the literature for many estuaries. Stratification separated the water column into at least two vertical sections where the bottom layer was effectively cut off from re-aeration due to lack of mixing processes. This separation allowed benthic respiration to deplete DO in the lower layers. Increased benthic respiration and hence DO depletion were directly attributed to eutrophication.

One effect of eutrophication is the supply of excess phytoplankton biomass to the water system. This supply of organic material eventually will be decomposed, absorbing DO in the process. The resultant complete lack of oxygen in the water column was defined as anoxia. Hypoxia is defined as the reduction of DO concentration to less than 4 mg/l for a period lasting 24 hrs or more (Thursby, 1999). The term pronounced or severe hypoxia represented DO values less than 2 mg/l. Various investigators have chosen different oxygen concentrations, usually either 2 mg/l or 3 mg/l, as the criterion for hypoxia. Breitburg et al., (2009) define hypoxia “mechanistically as oxygen concentration that are sufficiently reduced that they affect the growth, reproduction, or survival of exposed animals, or result in avoidance behaviors.” It has become clear that sublethal effects must be considered when assessing the impacts of low DO events on ecosystems.

Development of hypoxia in Japan has been confirmed in the inner part of almost every major bay of Japan on the Pacific Coast from Tokyo southward. Teruaki, 2001 investigated using Mikawa Bay, where Japan's most serious hypoxia occurs, as an example. Although hypoxia basically results from the increase of nutrient load input from water, domestic and livestock sources, the intense reclamation of shallows (including tidal flats) and the large reduction in river flow due to farm land irrigation drastically accelerated dissolved oxygen deficiency. It is suggested that the first thing to do is to restore tidal flats over an extensive area and to recover sufficient water flow, which may be a more urgent imperative than reducing the nutrient load input.

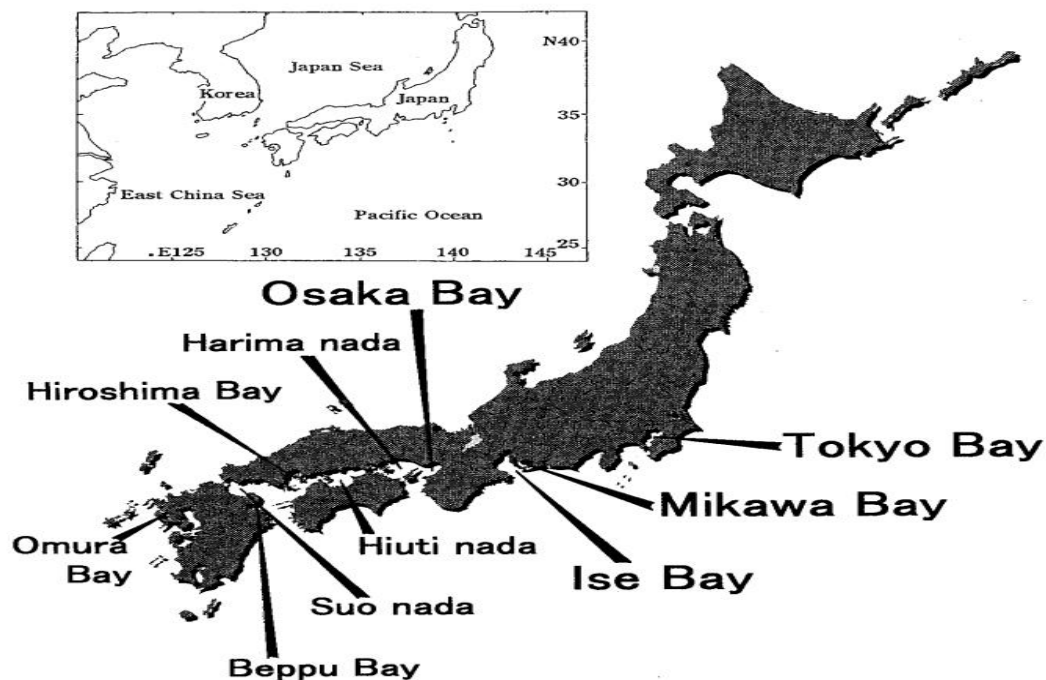


Fig.2.3 Sea areas of Japan where development of oxygen-deficient water masses occurs (Teruaki, 2001).

The inflow of the seaward water drives circulation within the embayment and can transport bottom hypoxic water in many coastal regions. In a tributary estuary of Chesapeake Bay the combined motion due to wind-forced oscillation and internal tidal oscillation cause intrusion of heavy and hypoxic water from below the pycnocline of the main stem bay (Stanford and Biocourt, 1990; Breitburg, 1990). Similarly wind and tidal forcing drive heavy hypoxic waters into other estuaries and onto the near-shore continental shelf (Falkowski et al., 1980; Swanson and Parker, 1988). When the intruding water is oxygenated and lighter than the bottom water, the intruding water occupies an intermediate depth in the bay and hypoxia develops below this depth (Ochi and Takeoka, 1986; Nogami and Matsuno, 2001; Fujiwara et al., 2002). In general,

the inflow has a wide range of timescales, from days to months and also the inflow depth varies depending on the relationship between the density of the inflow water and that of the ambient bay water (Allen and Simpson, 1998). The intrusion induces gravitational circulation and transport within the estuary.

Nikolay et al., (2008) investigated the dissolved oxygen dynamics in the upper Newport Bay, a tidally mixed eutrophic urban estuary in southern California. The environmental factors were identified regulating dissolved oxygen dynamics. Detecting hypoxia is difficult because DO is exceptionally variable short time scales, i.e., less than a day, due to variable rates of oxygen production and consumption, which fluctuate in response to different environmental factors. Hypoxic events occurred associated with a combination of low solar radiation, increased fresh water discharge following precipitation and enhance haline stratification during reduced tidal range periods. Oxygen-rich and oxygen-poor water were transported down estuary by ebb tide, resulting in dissolved oxygen spatial distribution throughout the estuary.

Occurrence of surface phytoplankton blooms followed by subsurface hypoxic events were investigated in the upper portion of Providence river estuary in Narragansett Bay and the connection between surface blooms and sub surface hypoxia and tidal range is attributed to water column stratification and the ability of moderate changes in tidal amplitude to reduce stratification through vertical mixing (Bergondo et al., 2005).

Inflow of oceanic water into Tokyo Bay and generation of subsurface hypoxic water mass accompanying changes in circulation within the bay have been studied by repeated measurement of the longitudinal distributions of hydrographic parameters and oxygen concentration from the bay head to bay mouth (Fujiwara and Yamada, 2002). Investigators concluded that density changes in the upper ocean induce inflow and outflow of oceanic water in the bay so that when water density increased in the upper ocean, heavy saline water intruded into the lower layer of the bay. This inflow forced bottom hypoxic water mass to the bay head and finally lifted it up to a form of subsurface hypoxic water mass.

Spatial distribution of hypoxic water mass based on a monitoring campaign of bay environment in Tokyo Bay was also conducted in 2008 (Horie and Furukawa, 2008). Results showed that the bottom hypoxic water mass dominated in the head of Tokyo Bay, while dissolved oxygen

condition was high condition in tidal flat and in shallow waters, such as Tama river estuary, Sanbanze tidal flat area and the Arakawa river estuary.

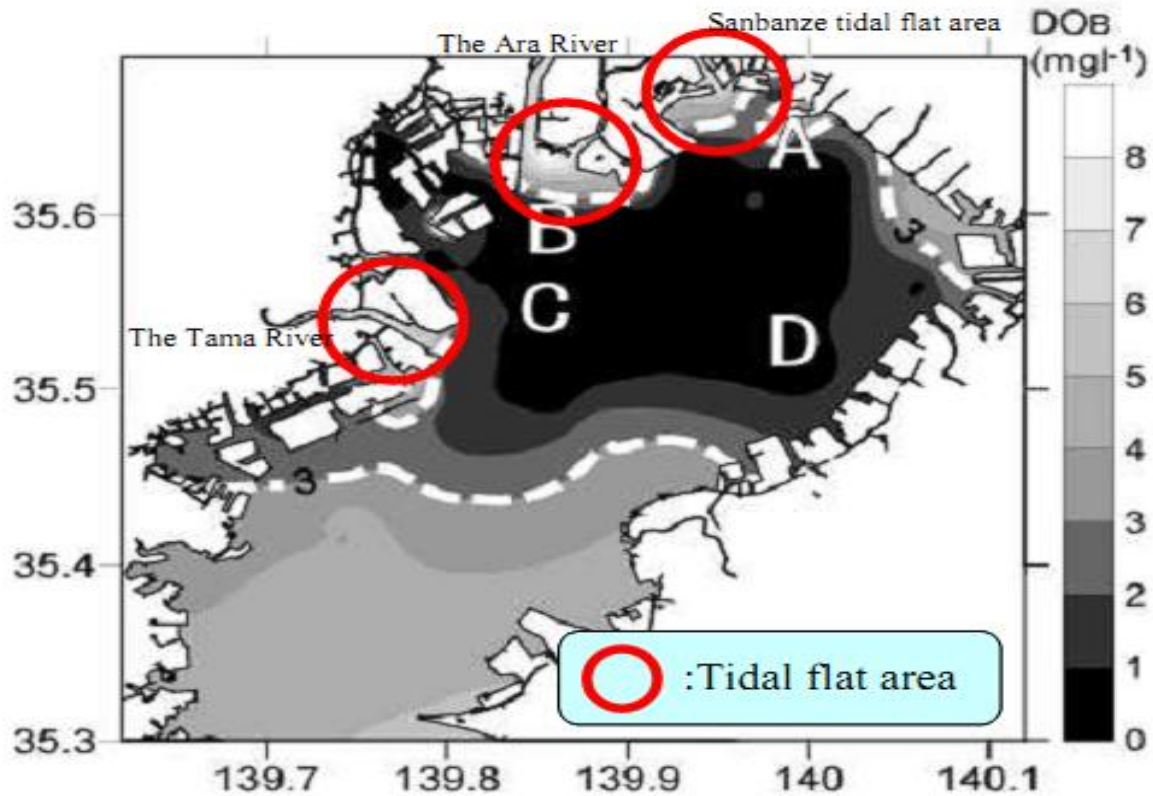


Fig.2.4 Distribution of Bottom dissolved oxygen and the location of tidal flat area on July 2nd in 2008 at inner Tokyo Bay (Horie and Furukawa, 2008).

In temperate eutrophicated body of water, water column stratification in summer can aggravate water quality problems. This phenomenon lessens vertical mixing of water column that onset the immoderate growth of phytoplankton in upper layer of water and cut the dissolved oxygen supply to the lower layers. Highly fluctuating behavior of hypoxic water and anoxic water were observed in Tama river estuary, Tokyo Bay in summer 2006 (Pokavanich et al., 2009). Investigators found that the hypoxic and anoxic water had largely developed around bay head at the end of June from relatively stable water column and increase of dissolved oxygen consumption in the bottom layer. They were transported back and forth along the bay longitudinal axis by the currents driven by prevailing south and north wind.

The development of hypoxic water is due to the substantial oxygen consumption to decompose large amount of organic materials that are internally produced and received from the

surroundings of Tokyo Metropolitan and nearby cities associated with the stratification of the water column (e.g. Koibuchi and Isobe, 2007; Sohma et al., 2008).

In a more temperate region, a 15 years study on salinity and bottom water hypoxia was conducted in the shallow, partially mixed Palmiko River Estuary (Stanley and Nixon, 1992). Investigators concluded that hypoxia developed only when there was both vertical water-column stratification and warm water temperature. They assumed this relationship was a natural feature of the system and not attributed to eutrophication. Furthermore, in Mobile Bay, Alabama and the adjacent shelf bottom waters, oxygen depletion was also demonstrated to be directly related to the intensity of water column stratification (Turner et al., 1987).

Northward, vertical stratification played a major role in the development of hypoxia in the western Long Island Sound. There, the oxycline always coincided with the pycnocline and period of oxygen depletion corresponded with periods of thermally-controlled stratification (Welsh and Eller, 1991). The oxycline also coincided with the pycline in Waquoite Bay, Massachusetts to exacerbate the formation of an anoxic region (D'Avanzo and Kremer, 1994). In that system, however, it was the combination of eutrophication, stratification and solar irradiance that created anoxic water volumes.

2.4 Phytoplankton bloom studies

Eutrophication is a world-wide problem in coastal waters, including those of Japan, especially in Tokyo Bay. Excessive phytoplankton growth or red tides, resulting from eutrophication can cause an increase in detrital flux when the phytoplanktons die. However, the short-term dynamics of phytoplankton community in the inner Tokyo Bay, identifying the factors that control the variability through use of field observations made at near-daily observations (Nakane et al., 2008). They found that oxygen-depleted water forms in the bottom layer during the stratification period, but vertical mixing of the water column due to changing wind and rainfall conditions caused by passing weather fronts, resulting in the breakdown of oxygen-depleted water mass. Finally, this study shows that the short-term dynamics of the phytoplankton community are closely coupled to fluctuations in environmental forcing, and that the degree of coupling is stronger during periods when solar radiation is greater.

Extensive researches have been carried out in the Tokyo Bay including the general biogeochemical properties in terms of phytoplankton activities (Koibuchi & Isobe, 2007) as

well as the hypoxic water behavior (Yagi et al. 2007; Sohma et al., 2008). The investigators concluded that physical conditions associated with meteorological condition such as solar radiation and wind forcing are significant in controlling the levels of blooms in an area affected by eutrophication. Following the phytoplankton blooms, dissolved oxygen concentrations show greater temporal variability through decomposition process of phytoplankton.

Hydrographic patterns and chlorophyll-a concentrations in the Columbia river estuary were compared for the spring and summer period. In both spring and summer, modulation of the spring-neap tidal cycle determined stratification, patterns of mixing and fate of phytoplankton. The Columbia river differs from the more tidally dominated coastal estuaries in the Pacific Northwest by its large riverine phytoplankton production and transfer of this biogenic material to the estuary and coastal ocean. All Pacific Northwest coastal estuaries investigated to date have exhibited advection of coastally derived chlorophyll during the upwelling season (Roegner et al., 2010).

Extensive spring and summer phytoplankton bloom and associated oxygen depletion in the lower layer of the water is thought to be one of the most important factors in reducing the capacity of the bay and the estuary area to support economically important fishery resources. These characteristics are partly attributed to the topographic setup of the bay that restrict the water exchange between the bay and outer sea (Miyata and Hattori, 1986).

The impact of Mississippi river discharge was monitored in Breton Sound estuary (Lane et al., 2007). It was found that chlorophyll-a concentrations were higher in mid-estuary during summer and fall at low discharge events and found lowest during winter and spring at high discharge events.

2.5 Physical studies of wind driven circulation

Wind induced circulation has been investigated in many estuaries and bays. Tidal forcing regulates the frequency and quantity of sea water that enters an estuary, and tidal waves are often modified when the tide propagates through an estuary. Frictional effects can produce tidal harmonics that vary with factors such as depth, shape and length of the estuary (Pugh, 1987; Prandle, 1991). Estuaries that experience strong seasonality in rainfall or those where river inputs almost ceases during the dry season may also sub-tidal forcing to be an important forcing. Therefore, sub-tidal oscillations cannot be disregarded as a forcing mechanism as prolonged

algal blooms have been linked to longer residence times associated with non-tidal forcing (Vieira and Chant, 1993).

`Classic' estuarine circulation, i.e. gravitational circulation, is based on buoyant fresh water entering from the landward end, and dense sea water entering in a lower layer on the seaward side (Pritchard, 1952; Hansen and Rattray, 1965). Salinity (or density) distribution within an estuary is controlled by the vertical and horizontal mixing between the sea and fresh water; occurring at time scales ranging from those of turbulent motions to seasonal scales. Longitudinal density gradients are generally regarded as the dominant contributor to residual circulation in partially mixed estuaries (Uncles, 2002) as proposed originally by Pritchard (1952). Herman et al. (2004) proposed that tidal pumping, not gravitational circulation, dominated circulation in a micro-tidal estuary. Circulation may be influenced, in varying amounts, by barotropic and baroclinic circulation, thus it is important to quantify the dominant transport processes in estuaries where water quality issues are paramount.

Tidal currents with amplitude of about 50 cm/s dominate in Tokyo Bay (Yanagi et al., 2003). Residual flow which consists of tide induced residual currents, wind-driven currents and density-driven current, plays the most important role in the long term material transport in the bay although its speed is relatively small compared to that of the tidal current in Tokyo bay because the tidal current is an oscillatory flow (Unoki et al., 1980; Ikeda et al., 1981 Unoki, 1985). The wind driven current is generated by a southerly wind in summer. Normally stratification in Tokyo Bay strengthens in summer and weakens in autumn and winter. A northerly wind prevails over the bay in autumn, winter and spring, and a southerly wind dominates in summer (Unoki et al., 1980). These conditions induce a gravitational circulation at the mouth of the bay in the upper layer and into the bay in the lower layer. Moreover, 13 rivers empty into Tokyo Bay and the density driven current is accompanied by an estuarine front in the west bank of Tokyo Bay where large river discharge.

In coastal embayment that receive freshwater influence, estuarine gravitational circulation prevails; the low-salinity water flows out the upper layer and in compensation, the high-salinity sea water flows into the lower layer. However, the gravitational circulation is highly sensitive to changes in the seaward conditions (Carter and Prichard, 1988). When the estuarine water is lighter than the bay waters, reverse estuarine circulation (upper inflow) arises.

The Tama river estuary in Tokyo Bay contains natural tidal flats that have biological significance and sustain life of various marine species. Highly fluctuating behavior of hypoxic water mass off Tama river estuary, Tokyo Bay were investigated (Pokavanich and Yagi, 2009). Results suggested that the evolution of hypoxic water mass and other water quality characteristics had close correlation with predominated wind, general water circulation, seasonal water column stratification, light availability and the intrusion process of oceanic water from the bay mouth which can reach the estuary.

Low dissolved oxygen is a common feature of many estuarine and shallow water environments, and is often attributed to anthropogenic nutrients enrichment from terrestrial-fluvial pathways. However, recent investigation on the upwelling wind stress that controlled the timing and magnitude of low DO events, while tidal-modulated estuarine circulation patterns influenced the spatial extent and duration of exposure to low DO water (Roenger et al., 2011). Strong upwelling during neap tides produced the largest impact on estuary based on wind forced supply mechanism.

Wind driven circulation altered the degree of stratification within the estuary. Often, wind speed was sufficiently strong to vertically mix and destratify the water column (Goodrich et al., 1987). In other circumstances, however, wind driven circulation was just strong enough to maintain stratification (de Kreece and Robaczewska, 1989) or when combined with tidal effects, even intensified stratification (valle-Levinson et al., 1998). Finally one typical response to meteorological forcing was the tilting of the pycnocline similar to the thermocline response in stratified lake system. This tilting was also documented in the Chesapeake Bay (Sanford et al., 1990). In that investigation, it was found that wind forced lateral internal oscillations of the pycnocline in the mainstream of the bay resulted in the advection of saline, hypoxic water from below the pycnocline onto the flanks of the bay and into the lower reach of adjoining tributaries’.

2.6 Physical studies of river discharge

An estuary is defined as a semi-enclosed coastal body of water which has a free connection to open sea, extending into the river as far as limit of tidal influence and within which sea water is measurably diluted with fresh water derived from land drainage (Dyer, 1997). Fresh water runoff affects circulation in an estuary by creating both a surface water slope from the head of the mouth of the estuary and a longitudinal density gradient through dilution of saline water. The subtidal circulation within an estuary, termed as estuarine circulation, consists of a two layer flow with fresh downstream flowing water at the surface and saltier, denser upstream flowing water near the bottom. Mixing of two layers may occur along the zone of separating layers, changing the salinity structure both vertically and longitudinally (Stommel, 1953).

Total twelve rivers discharge into Tokyo Bay with major discharge from Tama, Edo and Ara rivers all located along upper western area of the bay. According to the Japan Scientists Association (1979), annually, 10 km^3 of fresh water from rivers drain into the bay. The Edo River (3.4 km^3 of annual fresh water discharge), the Ara River (2.4 km^3), the Sumida River (1.6 km^3) and the Tama River (1.2 km^3) contribute about 90% of the fresh water that arrives in the bay. Hosokawa (2003) also mentioned that the annual inflow of fresh water into Tokyo Bay from its rivers is approximately 10^{10} cubic meter. Radjawane et al., (2001) has mentioned that the monthly mean of the total volume of fresh water discharged into Tokyo Bay was $110 \text{ m}^3/\text{s}$ and it ranged from $75 \text{ m}^3/\text{s}$ to $250 \text{ m}^3/\text{s}$ during the days of August in 1995. For the rivers entering Tokyo Bay the maximum discharge reaches during the rainy season in Kanto region (between July and August) and also during the typhoon season of September and October another high discharge is also expected (Asad, 2006).

Issues on discharge monitoring in main influent rivers into Tokyo Bay was conducted to evaluate discharges at the river mouths through field measurement by ADCP (Nihei et al., 2007). Results suggested that the discharge in the Naka river was larger than that in the Tama river because of large amount of water supply.

Investigation into the axial variability of salinity stratification due to fresh water discharge was conducted in the Delaware estuary. A seasonal relationship was found in that high discharge periods resulted in lower surface salinities and low discharge resulted in higher surface salinities at two locations in the estuary (Wong, 1995). In the Tamar estuary, England, the axial salinity distributions showed that the saltwater-freshwater interface was located closer to the head of the estuary during low runoff and was pushed further downstream during high runoff (Uncles and

Stephens, 1990). Stratification and destratification events in Mobile Bay were related to the relative strengths of the river discharge and winds (Schroeder et al., 1990). Destratification was observed during periods of strong river discharge where it essentially flushed the system, and during wind events. The river flow appeared to be the dominant control in destratification; winds became important in the absence of large river discharge.

In order to successfully conserve and manage the estuary, there are need to better understand the tidal circulation and water quality characteristics with spatial and temporal resolution focusing on the occurrence of oxygen depleted water mass and red tide . The hydrodynamics and the effect of combined sewerage overflow in monthly of biweekly basis of the estuary were described in previous time, but no study with continuous time series has been done since. Although, there have been several studies already been accomplished as reviewed in the literature in many estuaries in the world, those kind of mechanism related in several literature has not been performed. Therefore, the continuous time series observation was made to gain better understand of the estuary water quality characteristics.

CHAPTER 3: MATERIALS AND METHODS

The previous chapters provide the background, literature review and framework for the study to be done. This chapter outlines the methodology involved in the study and is divided into three parts. The first section of this chapter outline the description of the study area and the second section of this chapter describes the field observation techniques and third section outlines the calculation of river discharge.

3.1 Study site

3.1.1 General description

Tokyo Bay which is located at the central part of main island (Honshu) of Japan. The bay stretches 50 kilometers north to south, 20 kilometers east to west and its average depth is 18 m with the western side being deeper than the east. Its size (960 km²) is forth in Japan and nearly 20 percent of Japan's industrial and economic activity is concentrated around the area of this bay (Furukawa, 2003). This results in a severe population pressure of 26 million people living in the drainage basin of the bay. As a result, Tokyo Bay is a classic example of an estuary suffering profoundly due to urbanization and rapid development in its surrounding areas. The human as well as industrial activity around the bay area causes a huge amount of pollutant and pathogen load into the bay.

For the rivers entering Tokyo Bay, the maximum discharge reaches during the rainy season in Kanto region (between July and August) and also during the typhoon season of September and October another high discharge is also expected (Asad, 2006).

The field observation stations at Odaiba are a narrow channel with two openings to canals at the mouth of the Sumida River. The depth is generally shallower than 5m except in a single narrow shipping lane and around the openings to the canals where the depth is about 8-9 m. The channel curves southward and extends upto the drowned river valley. The estuary is confined to a steep sided channel and there is a little intertidal area along the last 2 km of the estuary. In most of this region, river water depths are less than 6 m at low tide. The estuary is dominated by the semi-diurnal M2 tide and the range is micro-tidal, between 0.5 to 2 m. The area is separated from Pacific Ocean by the Tokyo Bay which has been developed into a marina with no natural wetland area remaining. Odaiba is classified as eutrophic because it is subject to both point and

non-point nutrient sources discharged from surrounding urbanized areas (Islam, 2009), This area is warm basin during summer period and warm waters are associated with low oxygen concentration and intensive respiration and organic matter decomposition rates. Circulation in this area is primarily tidally controlled, through non-tidal circulation induced by winds and fresh water inputs can exert considerable influence on shorter temporal and spatial scales. The observation stations are at station 1 located in the outer part of Odaiba and station 2 and 3 are located at the inner part of Odaiba. Station 1 is profoundly influenced by tidal (sea water) regime and also represented as the deepest observation point among the three observation points. Station 2 represents the shallowest observation location followed by station 3, both of which become exposed during all low tides. The study site is the upper area of Tokyo Bay (Figure 3.1).

3.1.2 Climate

The climate of Odaiba is largely controlled by its temperate location and proximity to the Tokyo Bay. Seasonal weather pattern for coastal Odaiba is primarily influenced by two systems; the Arakawa river to the north and the Tokyo Bay to the south. During winter and spring northerly winds are dominant, with northeasterly winds occurring most frequently, whereas during summer period southerly winds become dominant, with southeasterly winds occurring most frequently.

3.1.3 Hydrology

Sumida river estuary, Odaiba is meteorologically forced and a narrow steep tidal channel. Water movement through the channel is driven by tides, wind and precipitation run-off. Seasonal water level in the channel exhibits a bimodal distribution with maximum levels occurring in the spring and summer, due to precipitation, runoff and thermal expansion basically in summer. The natural hydrology of the channel has been altered by human activities such as land reclamation and as a result channel becomes steep and narrow. Major fluvial input of freshwater is coming from the Arakawa river as this channel has been originated from this river. As being shallow depth and narrow channel, Sumida river estuary is subject to intrusion of bay bottom high salinity and low dissolved oxygen (hypoxic water) and provides efficient conduits for the transport of materials out of the channel water.

On the other hand, Tokyo Bay is a classic example of an estuary suffering profoundly due to urbanization and rapid development in its surrounding areas. The human as well as industrial activity around the bay area causes a huge amount pollutant load into the bay. The apparent overall effect of these activities has been decrease to deteriorate of water quality of the area, thereby decreasing the sustainable natural ecosystem area of the channel.

3.2 Field observations

3.2.1 Data Acquisition

All observations and measurements were carried out at the three fixed stations at Odaiba during summer 2011 (June to September). Three primary data types were determined to be necessary for understanding the estuary dynamics: 1) Temperature and Salinity (T/S) data to understand halocline stratification 2) Dissolved oxygen and chlorophyll-a concentration to understand the development and fate of hypoxic events and phytoplankton bloom mechanism within the estuary and; 3) Current-velocity data to gain a better understanding of the relative contribution of tidal exchanges, and river discharge to exchange processes in the estuary. Details on the instruments and deployment setup have been provided in this section.

3.2.1.1 YSI and Alec Data

A commercially available multi-parameter water quality sensor (Yellow Spring Incorporated-model 6600) with Specific Conductivity, Temperature, Salinity, Dissolved Oxygen concentration, Chlorophyll-a concentration was configured to measure water quality condition in the surface and bottom layers water columns. Data parameters for YSI included date (dd:mm:yy), time (hh:mm:ss), battery voltage (V), temperature ($^{\circ}\text{C}$), Specific conductivity (ms/s), Salinity (psu), turbidity (NTU), dissolved oxygen (mg/l), and chlorophyll-a ($\mu\text{g/l}$). The hydrographic conditions (e.g. water level, water temperature, salinity), water quality condition (e.g. chlorophyll-a and DO concentration) were monitored in every 10 minutes interval by two Yellow spring Incorporated (YSI-6600) sensors at station 1. The deployment depths of bottom sensors were 7 m and 3 m for the surface sensor respectively. Instrumented buoys were moored at other two stations at inner part of Odaiba (Figure 3.1). Each buoy consisted of a more than 1 m diameter foam discus with a water tight chamber that housed the data logger. Aquadome, a telemetric sea condition monitor buoy system (Alec Electronics) were suspended from each buoy at depths 0.5 m below the surface and 0.5 m above the bottom. The deployment depths of bottom sensors were 4 m for buoy 1 and buoy 2 respectively. Every 10 minutes the sensors measured temperature, salinity, dissolved oxygen and chlorophyll-a concentrations. Data were collected from each buoy site at the inner part of Odaiba when exchanging of instruments were done and data were transmitted from outer part of Odaiba(YSI deployment location) through wireless signal/wi-fi at every 10 minutes interval to a computer established in the laboratory.

3.2.1.2 H-ADCP Data

To continuously record the along river (North-South component) and across river (East-West component) current velocity across the cross section of the river, an Acoustic Doppler Current Profiler (H-ADCP; Workhorse 300 kHz; RD Instruments) was positioned 1 m above the river bed during the observation period at outer part of Odaiba indicated by station 1 (Figure 3.1).

H-ADCP was stationary on the river bed and emits acoustic beams from a transducer across river. The beams are scattered by small particles, phytoplankton and zooplankton moving with the currents and reflected beams measured by the sensors. The H-ADCP measures the beams at discrete levels throughout the cross section in both east/west and north/south directions. The bins were located at intervals of 1 m throughout the cross section of the channel and current velocities of north/south and east/west components were recorded every 10 minutes from the fixed measurement point below the bottom of the river. Currents in the north and east directions are measured as negative and currents following towards south and west measured as positive velocities. H-ADCP averaged 120 pings to 40 layers of velocity profiling at every 10 minutes and provided observations of current magnitude and direction at different layers to the across river distance (Figure 3.7). The recorded velocity data were transmitted via wireless signal to the computer established in the laboratory. Then the data was processed using RD instruments Win ADCP, and exported as text files for processing in MATLAB. As the YSI and ALEC data was collected while the H-ADCP was operating at the same location, some comparison of two data sets are enabled for the study. The major purpose of the measurement of current velocity was to map the basic current field and horizontal transport of chlorophyll-a distribution and movement of hypoxic water mass associated with density stratification from downstream to estuary and upstream to bay. List of the sensors, setups and deployed locations are given in Table 3.1.

3.2.2 Measurement Strategies

Three stations around Sumida river estuary, Odaiba, Tokyo Bay were designated for hydrographic data collection from surface to bottom during all the year round of 2011 to till date. All observations were conducted using various instrumentations that were prepared in the laboratory before each field observation and deployment. The station 1 was chosen at the outer part of Odaiba which is directly influenced by fresh water discharge and more open for the sporadic intrusion of bay water during high tide and other two stations were selected at the inner part of Odaiba which are generally enclosed by land and a little bit away from the main channel to observe the significant differences in terms of water quality characteristics within the three

stations. In addition to that bio-fouling was the primary source of data changes in the deployed sensors. Unlike H-ADCP sensors (where a significant amount of biofouling is needed to weaken the acoustic signal appreciably) even small amount of bio-fouling can have significant impact on YSI and Alec sensors. As a result, large segment of salinity and chlorophyll-a concentration data were deemed unsuitable for the analyses and explanation. Current velocity data through the cross-section of the river were measured using a horizontal Acoustic Doppler Current Profiler (H-ADCP) manufactured by RD Instruments. The 300 kHz H-ADCP was boom mounted and positioned 1 m below the river bed in in-house designed stainless steel frames. The H-ADCP measured flow velocities through the cross section of the channel by transmitting sound at a fixed frequency and recording the echoes that have been Doppler shifted returning from sound scatterers in the water. It was programmed to provide data by every 10 minutes intervals. Since, the estuary channel is relatively narrow, the velocities along river directions of maximum and minimum variance at all depths were essentially the along channel and across channel velocities, respectively. However, all subsequent analyses in this study have been carried out using the along channel velocity (North-South) components only. Schematic of H-ADCP are shown in Figure 3.2.

3.2.3 Processing of Data

During each field visit both the data sensor and their associated housings were physically cleaned using brushes and sensor batteries and antifouling coating were replaced during preparation of instruments in the laboratory. Each data file was labeled and saved by month, day and site according to the deployment date and provided consistency and quality control during file maintenance. Sensor data was stored in the YSI 6600 data logger as a comma delimited (comma separated values) text file and downloaded directly to a personal computer and then the raw file directory were converted to Microsoft Office Excel workbook file (xls) and manipulated for analysis by using MATLAB.

Table 3.1: Sensors, measurement setting and deployment locations

Parameters	Instruments	Intervals (Min)	Location	Deployment
Multi-parameters	YSI-6600	10	Stn.1	Surface & Bottom
Chlorophyll-a, Temperature	Alec Compact-CLW	10	Stn.2, Stn.3	Surface & Bottom
Salinity, Temperature	Alec Compact-CTW	10	Stn.2, Stn.3	Surface & bottom
Dissolved Oxygen, Temperature	Alec Compact-DOW	10	Stn.2, Stn.3	Surface & Bottom

All the time series data obtained from YSI and Alec water quality sensors were processed using MATLAB, for determination of the factors influencing temperature, salinity, dissolved oxygen and chlorophyll-a distribution. In contrast, HADCP data was analyzed using RD Instruments Win HADCP and exported as text files for processing in MATLAB. During summer months when biofouling rates were relatively rapid at Odaiba, the automatic data logging sensors (YSI, H-ADCP, Alec- CLW, Alec CTW and Alec DOW) were inspected, checked for drift or biofouling and by swapping the surface and bottom sensors with clean and recently prepared sensors. At the end of each deployment, the data were examined to determine if post-deployment correction were needed to account for sensor drift or biofouling. General setup and overall field observation program snapshot are given in Figure 3.2.

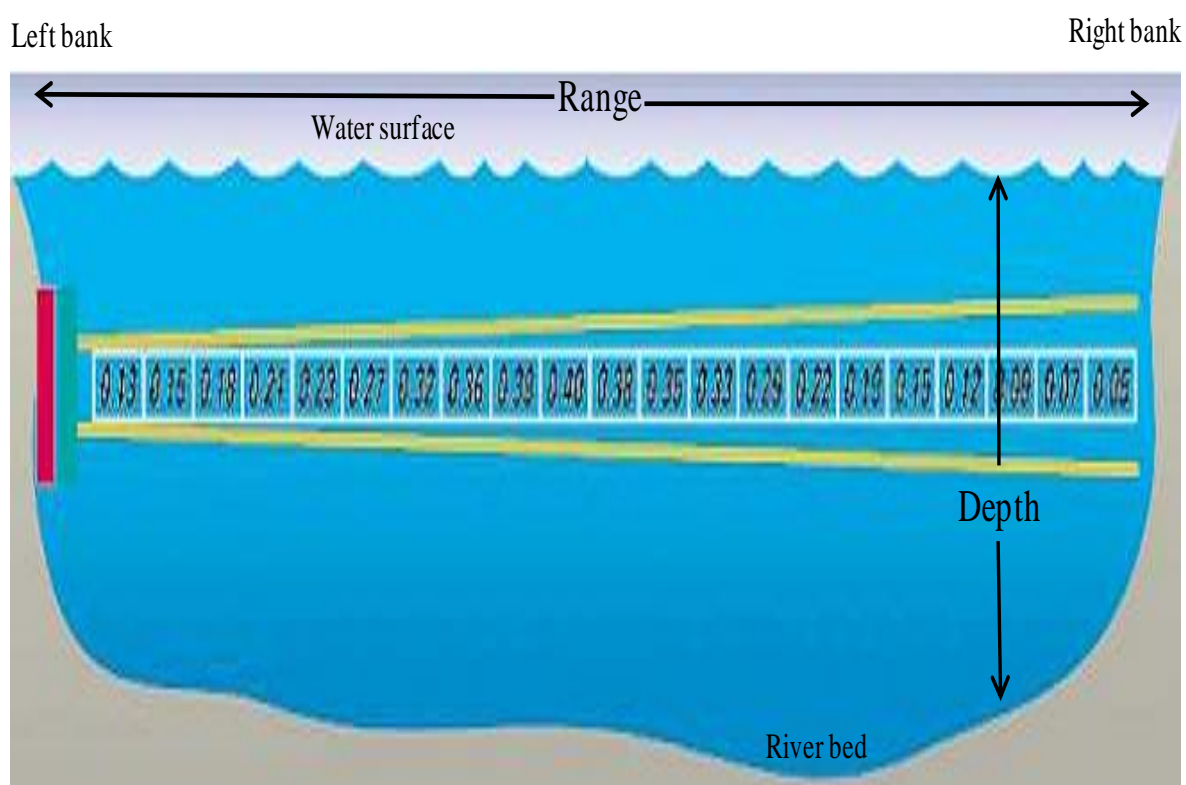


Fig.3.2 Schematic of H-ADCP current velocities across section, Numbers are velocity at cells.
(Adapted from Haugh, H., 2005)



Moorage system



H-ADCP



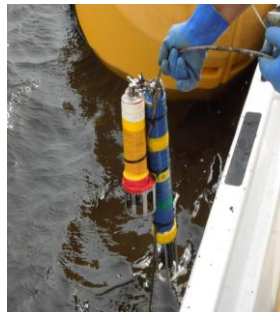
YSI



Alec water quality instrument



Newly YSI deployment



Newly CT and Alec instrument deployment



Mobile surveying unit



Alec water quality instrument

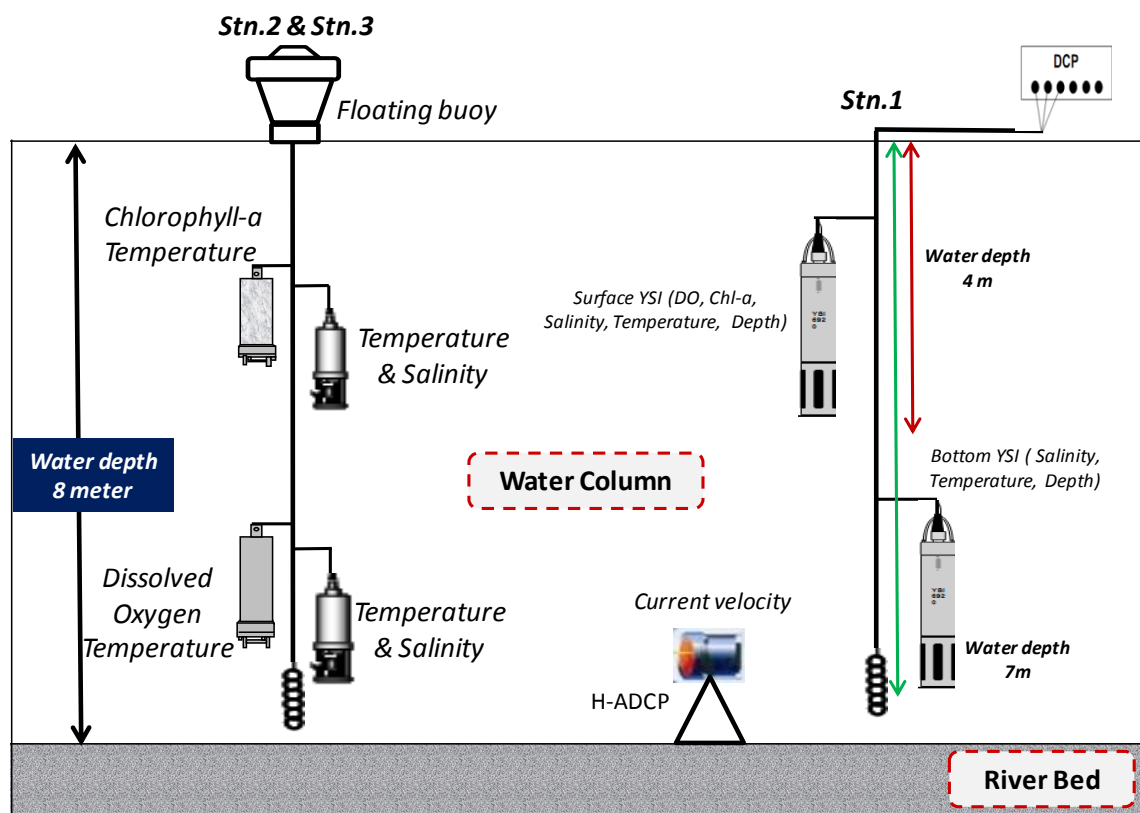


Fig.3.3 Schematic illustration showing the overall of field observation techniques and snapshots during the field surveys.

3.2.4 Meteorological Data

During the observation period, daily and hourly meteorological data such as precipitation, wind speed/direction and solar radiation at the Haneda Meteorological Observatory Station were obtained from the website of Japan Meteorological Agency (JMA). The station was located near the northern side of west bank of Tokyo Bay and approximately 10 m above the sea level.

3.2.5 River discharge

3.2.5.1 Estimation of river discharge using H-Q function at Upstream

Daily flow rates of Sumida river estuary (Sugama observation point) were obtained from the tables of river discharge (Ministry of Land, Infrastructure and Transport, River Bureau). Daily observation of discharge from the Sumida river at upstream point during 2011 were determined from a linear relationship of measured river discharge and water level data. The water level data were recorded during this time at a upstream location of Sugama observation point located near the junction of Ara river. Water level and river discharge data of the same year that means of the year 2001 were correlated to get the H-Q function. Both observed water level and calculated discharge of 2001 were used to plot the scatter diagram. Based on H-Q diagram on 2001 water level and discharge data and this function was applied to determine the discharge of 2011 using water level data of 2011. Calculation of river discharge from Sugama Observation Point using the river discharge data of 2001 and water level data of 2011 are illustrated in Figure 3.4 and Figure 3.5.

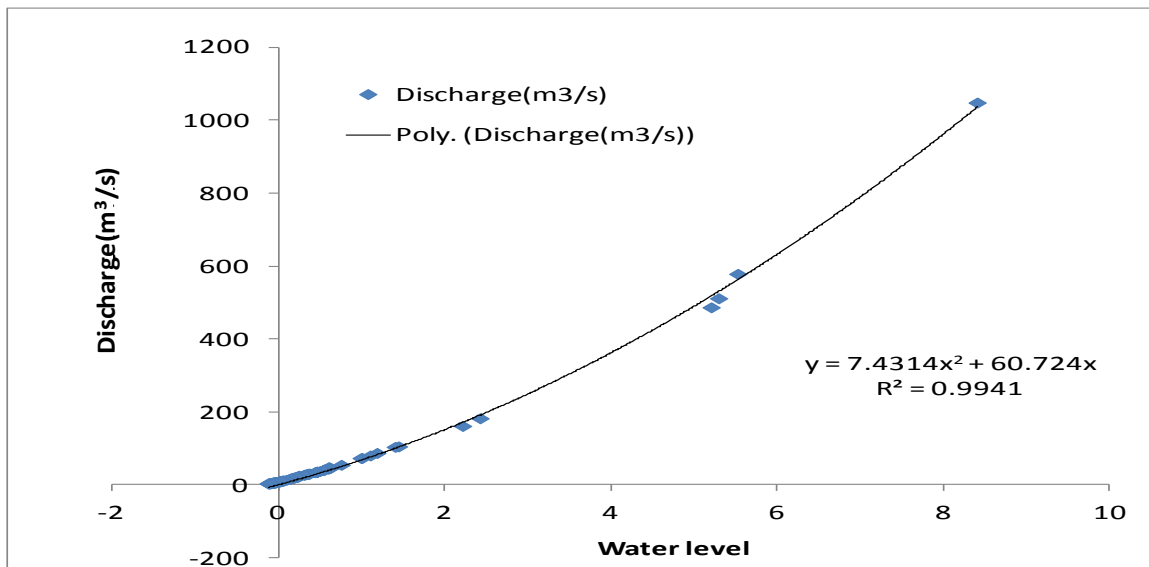


Fig.3.4 Correlation between water level and estimated river discharge of 2001 at Sugama Observation Point of Arakawa River.

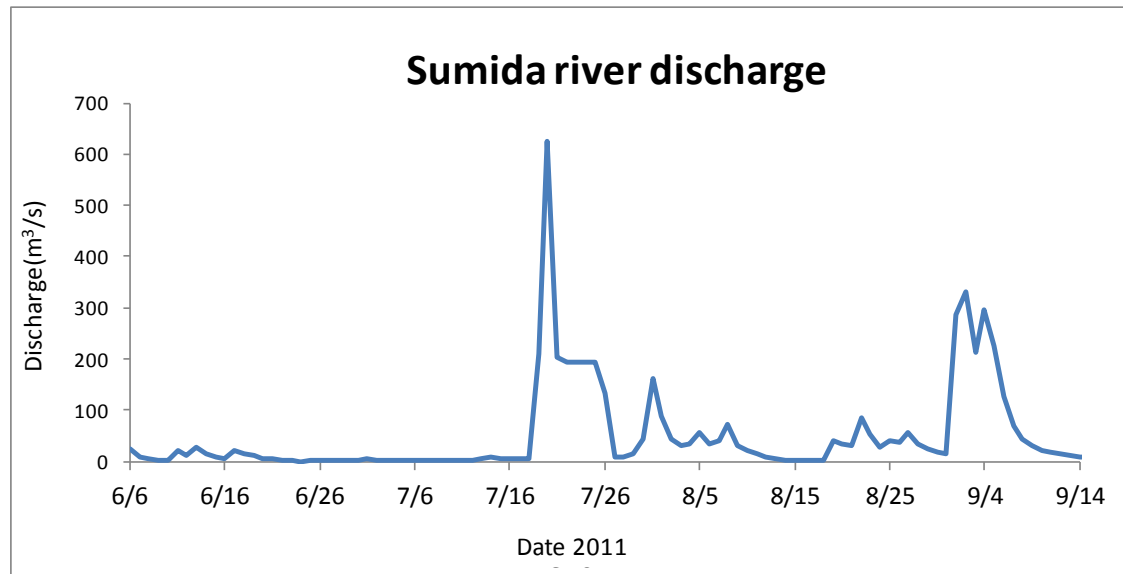


Fig.3.5 Estimated daily discharge of Sumida river at upstream from water level data of 2011 at Sugama observation point of Arakawa river.

3.2.5.2 Estimation of river discharge using H-ADCP velocity data at downstream

River discharge is an important property and is frequently measured along many of the major rivers and streams. Discharge from the downstream point of Sumida river was measured episodically using a horizontal Acoustic Doppler Current Profiler deployed in the discharge channel located at the outer part of Odaiba (station 1). The instrument collected 10 minutes interval velocity and water elevation data. However, the discharge can not be measured directly in a river or stream and it is distributed across too large of a cross section. Thus the discharge (Q) must be calculated from the average stream velocity (V) and cross sectional area (A).

$$Q=VA$$

Where Q is the river discharge (flow), V is the average flow velocity and A is the cross sectional area perpendicular to flow. Because of complex variation in velocities that occurs naturally in stream/ rivers, it has become a well established practice to subdivide a river cross section into several parts of several layer of velocity data to the along river through the cross section of the river. The velocity profile in this study to calculate discharge along the channel is depicted in Table 3.2. For measuring the across river velocity, a horizontal acoustic doppler current profiler was positioned 1 meter above the river bed on the left bank of Sumida river. The depth of the channel is 8 m and the deployment depth of H-ADCP is 7 m which is set 1 m above the river bed. Averaging along river velocities from layer 20 to layer 40 within each layer at a particular cross section and discharge was calculated by averaging all the layer between layer 20

to 40 and water level where H-ADCP acoustic beam range was about 204 m (Figure 3.7). As the H-ADCP was positioned 1 m above the river bed, the measured water elevation by H-ADCP was then added by additional 1 m for each water height. Assuming the width of the channel as 500 m, the area was calculated by multiplying the total depth and width of the cross section. The resulting value of area of the cross section was then multiplied by the averaged along river velocities to estimate river discharge, which was thought to be a more accurate estimate of river discharge at this point (Table. 2). Figure 3.6 shows the calculated river discharge using H-ADCP velocity data at the downstream point of Sumida river.

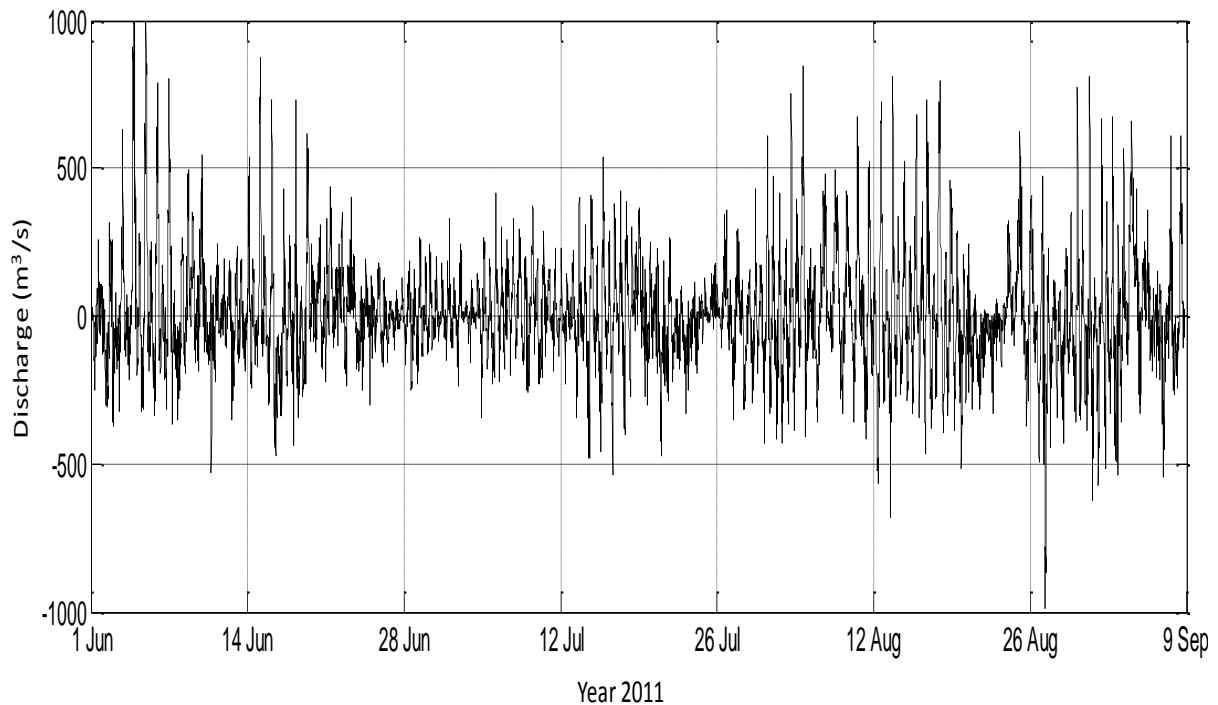


Fig.3.6 Estimated river discharge using along channel current velocity and water elevation data measured by Horizontal Acoustic Doppler Current Profiler around Sumida river estuary (station 1) during 1 June to 9 September, 2011.

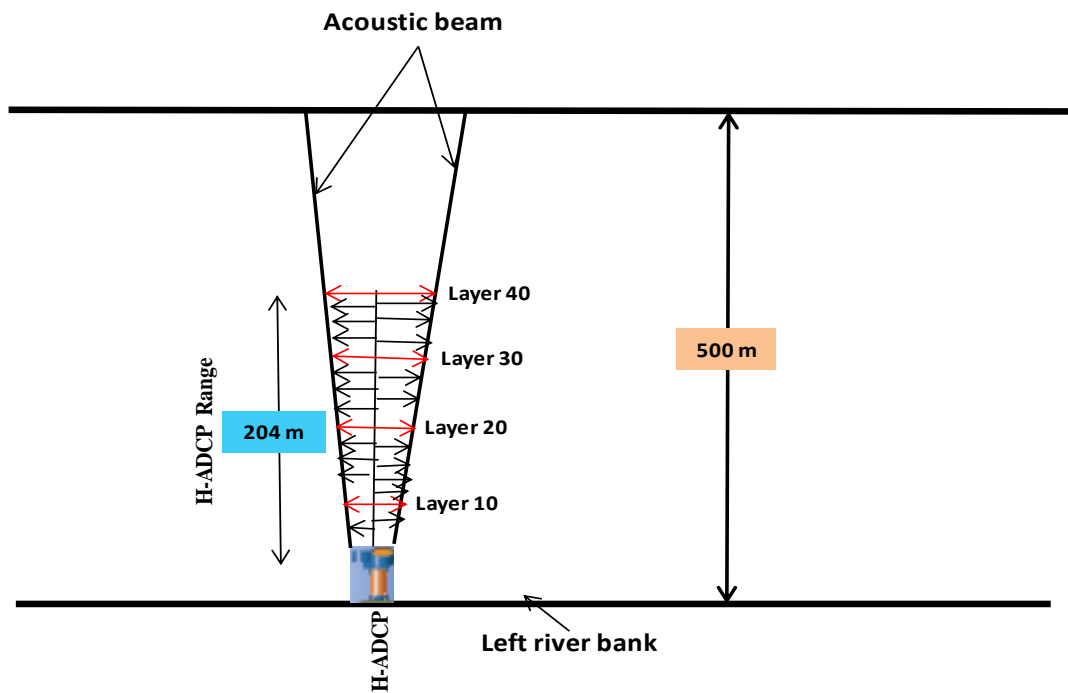


Fig.3.7 Schematic representation of H-ADCP set up through the cross section and velocity profiling along the river, numbers are velocities at layer.

Table 3.2: An example of discharge estimation using along channel velocity component and water level

Depth (m)	Velocity (m/s)	Total Depth (m)	Width of river (m)	Area (m ²)	Discharge (m ³ /s)
5.35	0.03	6.35	500	3176	95.28
5.37	0.01	6.37	500	3189	32.64
5.41	0.007	6.41	500	3206.5	24.43
5.45	0.01	6.45	500	3225.5	33.02
5.47	0.0006	6.47	500	3239.5	2
5.51	-0.0002	6.51	500	3256.5	-0.93
5.54	0.0004	6.54	500	3272.5	1.4
5.58	0.0019	6.58	500	3290	6.4
5.61	-0.00009	6.61	500	3307.5	-0.31
5.64	0.009	6.64	500	3322.5	29.9

CHAPTER 4: RESULTS

4.1 Observation results

Results of field observation using the continuous measurement at the fixed point stations can be shown in temporal and spatial variation as followed.

4.1.1 Weather conditions

Solar radiation levels recorded at the Tokyo Meteorological Observatory station from June 2011 to September 2011 were fairly high during the observation period as this period is characterized as the summer period (Figure 4.1). Transient decreases in solar radiation were recorded in June, July and August due to the onset of precipitation, wind events and passing weather fronts. Solar radiation was recorded high in mid July (24-26 MJ/m²/day) and minimum in late June and mid August (5-7 MJ/m²/day). Figure 4.1 shows the time evolution of observed wind speed and direction at Haneda weather observatory station. It is seen that the prevailing winds were southerly from June to August 2011 with a daily mean velocity of 3 m/s, northerly to northwesterly from the early September with gusts of more than 4 m/s. There was a strong northerly wind with a daily mean velocity 11.9 m/s between 18 to 23 July (maximum 14 m/s) associated with a high rainfall of >200 mm/day on 18 July (Figure 4.1. and Figure 4.2). There was a strong southerly wind with a daily mean velocity 10 m/s between July 1 to 17 July (maximum 14 m/s) associated with strong solar radiation. During south wind solar radiation was found to be high. Conversely, solar radiation was low during north wind.

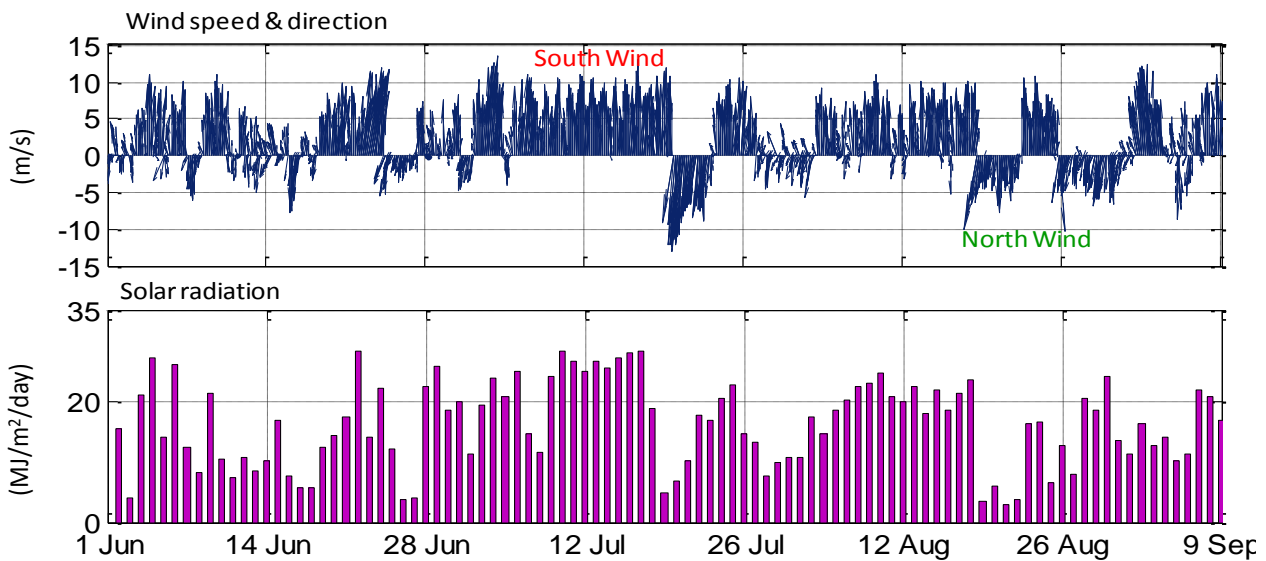


Fig.4.1 Solar radiation and wind condition during the observation period.

4.1.2 River discharge

Figure 4.2 shows the comparison of upstream and downstream discharge of Sumida river during June to September, 2011. Sumida River ranged from 0 to 627 m³/s at the upstream point. Discharge was divided into three categories: low flow (<20 m³/s), medium flow (20-60 m³/s) and high flow (>60 m³/s). Sumida river flow increased rapidly from 40 m³/s to above 600 m³/s after mid July and remained above more than 100 m³/s until 12 August and flow steadily decreased for a few days and again began to rise from August 20 to the rest of the period. Most of the discharge in summer 2011 occurred between mid July to at the beginning of September, with flows peaking at 627 m³/s on July 19 due to a high rainfall of about 200 mm/day on July 18 and decreasing to 50 -80 m³/s of the rest of the period until an another flow peaking at 330 m³/s on September 1 with several rainfall events that continued to the rest of the period at the upstream parts and same pattern of discharge was followed at the downstream point except some peaks at the middle of June and in late July to early September at times upstream point didn't have significant discharge events suggesting that estuary region was more influenced by incoming tide and outgoing discharge. There was no water discharge or a little water discharge at the start of June to mid July at the upstream point. In this period discharge decreased and maintained relatively constant (~20 m³/s), with short interruptions of <10 m³/s flow. Peaks in river flow reflected (with a shorter time lag) the precipitation events as followed by the Figure 4.2.

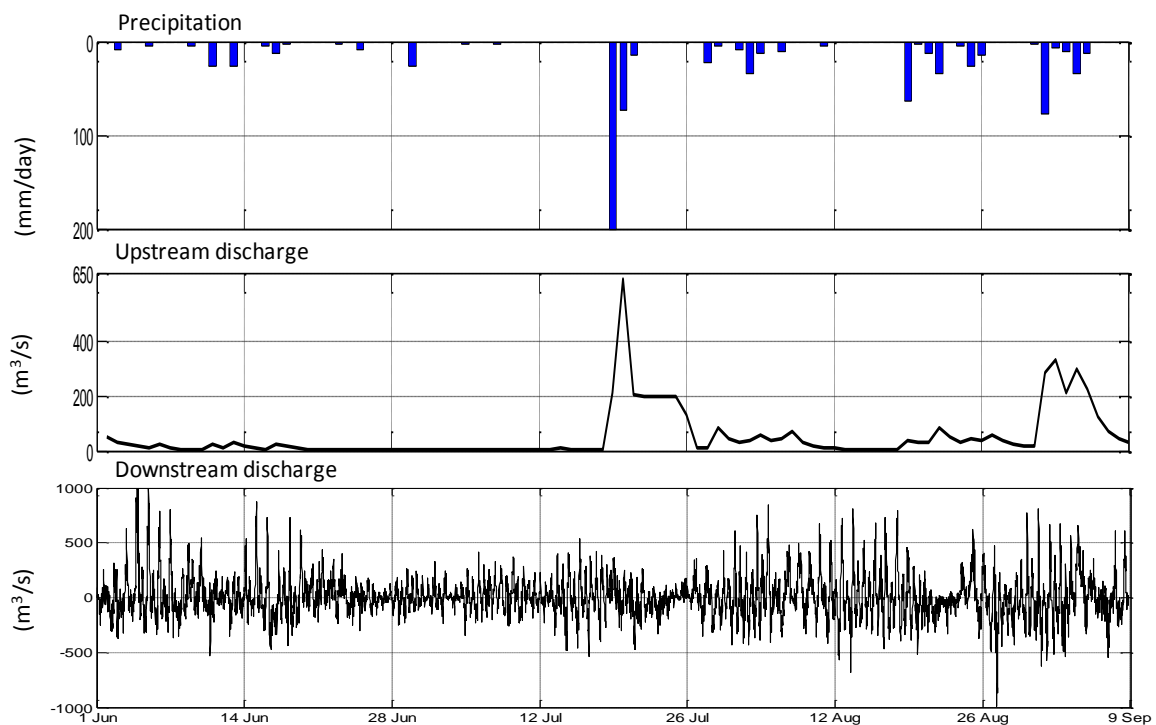


Fig.4.2 Comparison of upstream and downstream discharge of Sumida river during June to September, 2011.

4.1.3 Hydrographic properties temporal and spatial variations

Time series of wind speed, tidal elevation, solar radiation, precipitation, river discharge, water temperature, salinity, dissolved oxygen and chlorophyll-a concentration at station1, station 2 and station 3 during June to September, 2011 are shown in Figure 4.3, Figure 4.4 and Figure 4.5 respectively. The onset of high discharge ($200\text{--}630\text{ m}^3/\text{s}$) on 18th July to 28th July and 31st August to 9th September suggesting a water residence time assuming of approximately 2 weeks during peak and moderate discharges. The seasonal discharge structure followed by rainfall events shows this period with the greatest stratification. Salinity influenced stratification more than temperature indicating pronounced halocline stratification and this stratification was persistent until early September and it exhibited prompt responses to discharge which further regulated density stratification. Figure 4.3, 4.4 and 4.5 show the time series of observed water temperature and salinity at the depth close to water surface and close to the bottom from station 1, 2 and 3. It is seen that the water column was stratified since the beginning of July when the water temperature and salinity of the surface and bottom layer were the most deviated. Results suggested that the water column were stratified more from July to September and water column mixed more towards the beginning of June. Notice that at times, surface and bottom water temperature and salinity abruptly drift up and down regardless to the heat exchange at the water surface and river discharge. On the other hand, July to September there was a clear difference that observed for surface and bottom water temperature and salinity which indicates a clear stratification influenced by surface heat exchange and moderate to high river discharge.

Results from the water hydrographic properties and along channel current velocity obtained from station 1 were interpolated and shown in Figure 4.36. It is seen that hydrographic properties such as water temperature and salinity as well as the flow velocity varied substantially from the Sumida river estuary. The outer and inner part water temperature and salinity distribution displayed strong temporal and spatial distribution and variations corresponding to the flow velocity and river discharge. It is seen that the water columns were in stratified condition from the beginning of July at the three stations in which the inner part stations (station 2 and 3) were more stratified than that of the station 1 since the heat exchange were more prominent and persistent at inner part than the outer part of Odaiba. The stratification were not so strong at the beginning of June and at times water column specially at the bottom layer rapid switch to well-mixed and vice versa. This suggests that there were some mechanism around this area that could mix the water column in the rapid manner. Abrupt increasing and decreasing of surface and bottom temperature and salinity at station 1 rather than station 2 and

station 3, signaled the influences of intrusion of bay water and incoming fresh water flow from the river during high tide and low tide as seen in Figure 4.3, 4.4 and 4.5 respectively. Since at high tide, the outer part (Station 1) is filled with cool, salty sea water and the inner area (station 2 and station 3) is filled with warm salty water. Similarly, at low tide, low salinity water spreads seawards from the river and high salinity water moves out from the outer part. The warm salty water moves seaward and expands to fill the outer part. On the next incoming tide, this water and thermohaline structure from outer part (station 1) is pushed landwards and compressed into the inner part again (station 2 and 3) as shown in the Figure 4.3, 4.4 and 4.5.

The typical halocline structure is also noted by the temperature and salinity patterns observed during stronger river flow of $630 \text{ m}^3/\text{s}$ and $330 \text{ m}^3/\text{s}$ on 19 July and 1 September respectively (Figure 4.3, 4.4 and 4.5). The common theme consists of two hydrographic regimes in the Sumida river estuary: low salinity water and low temperature in the outer part and high salinity water and comparatively high water temperature in inner part. It is referred to a bay regime in the outer part of estuary waters that are primarily from sea and dominantly influenced by river inflow. Conversely in the inner part, it is referred to enclosed estuary regime water that are diluted little by river inflow, but that are warm owing to retention in the shallow depth.

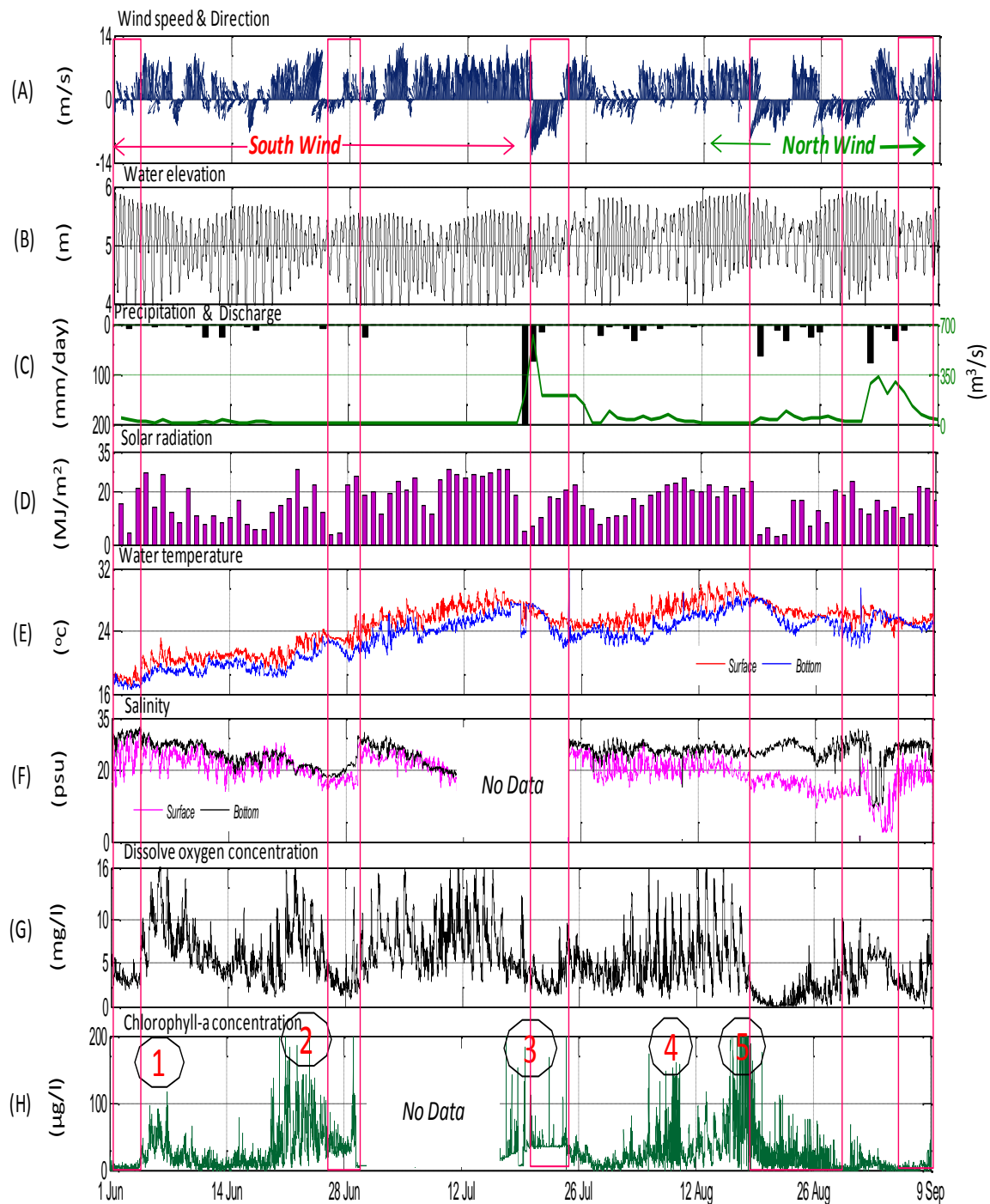


Fig.4.3 Time series of (A) Wind speed and direction (B) Water elevation (C) Daily Precipitation and Discharge (D) Solar radiation (E) water temperature (F) Salinity (G) Dissolved Oxygen concentration and (H) Chlorophyll-a concentration at Station 1 during summer 2011. The vertical red colored rectangular indicates five hypoxic events and black circle indicates five phytoplankton blooms. The mechanism on the development and fate of hypoxic events and phytoplankton blooms has been discussed in the section 4.2.1 and 4.2.2 respectively.

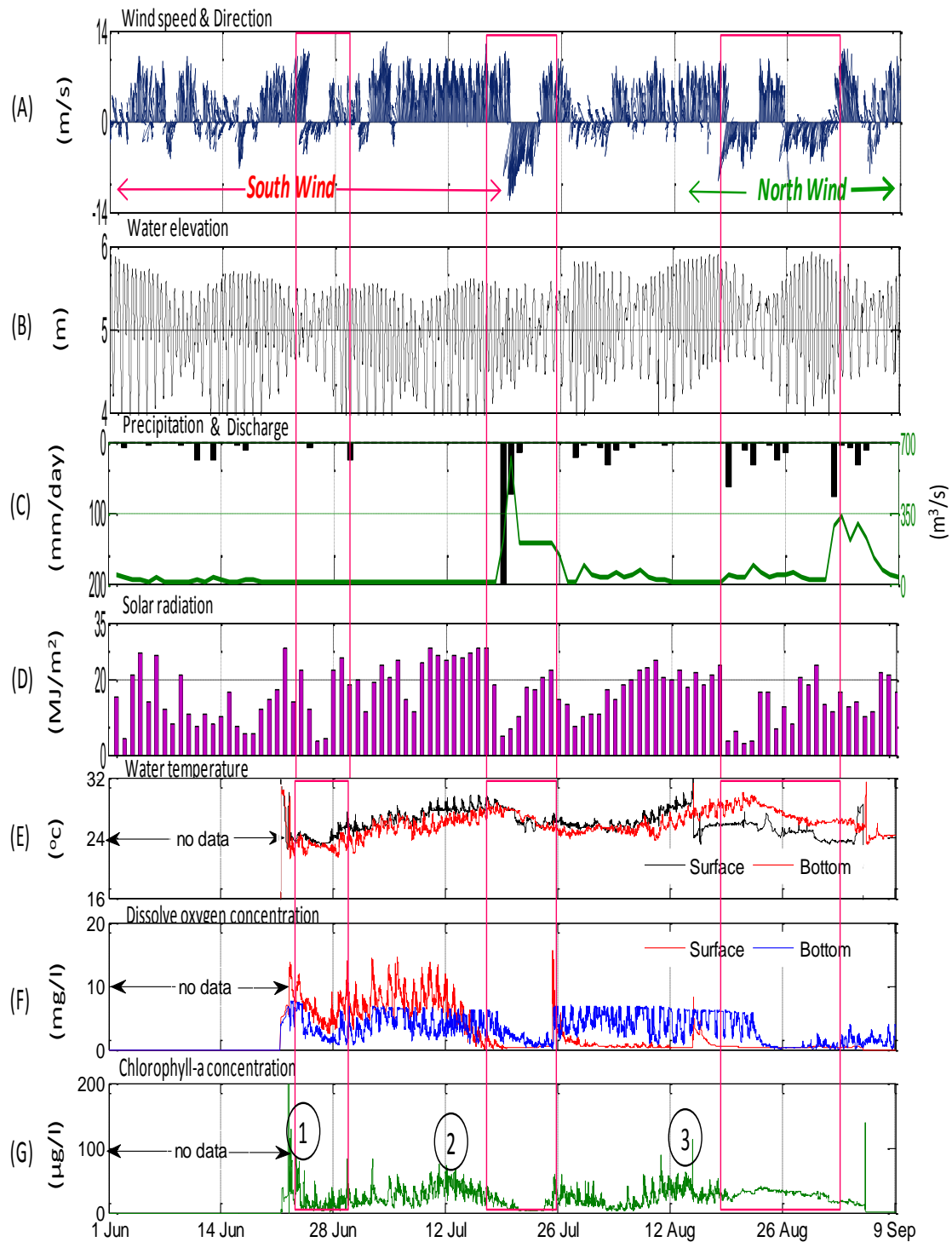


Fig.4.4 Time series of (A) Wind speed and direction (B) Water elevation (C) Daily Precipitation and Discharge (D) Solar radiation (E) water temperature (F) Dissolved Oxygen concentration and (G) Chlorophyll-a concentration at Station 2 during summer 2011. The vertical red colored rectangular indicates three hypoxic events and black circle indicates four phytoplankton blooms. The mechanism on the development and fate of hypoxic events and phytoplankton blooms has been discussed in the section 4.2.1 and 4.2.2 respectively.

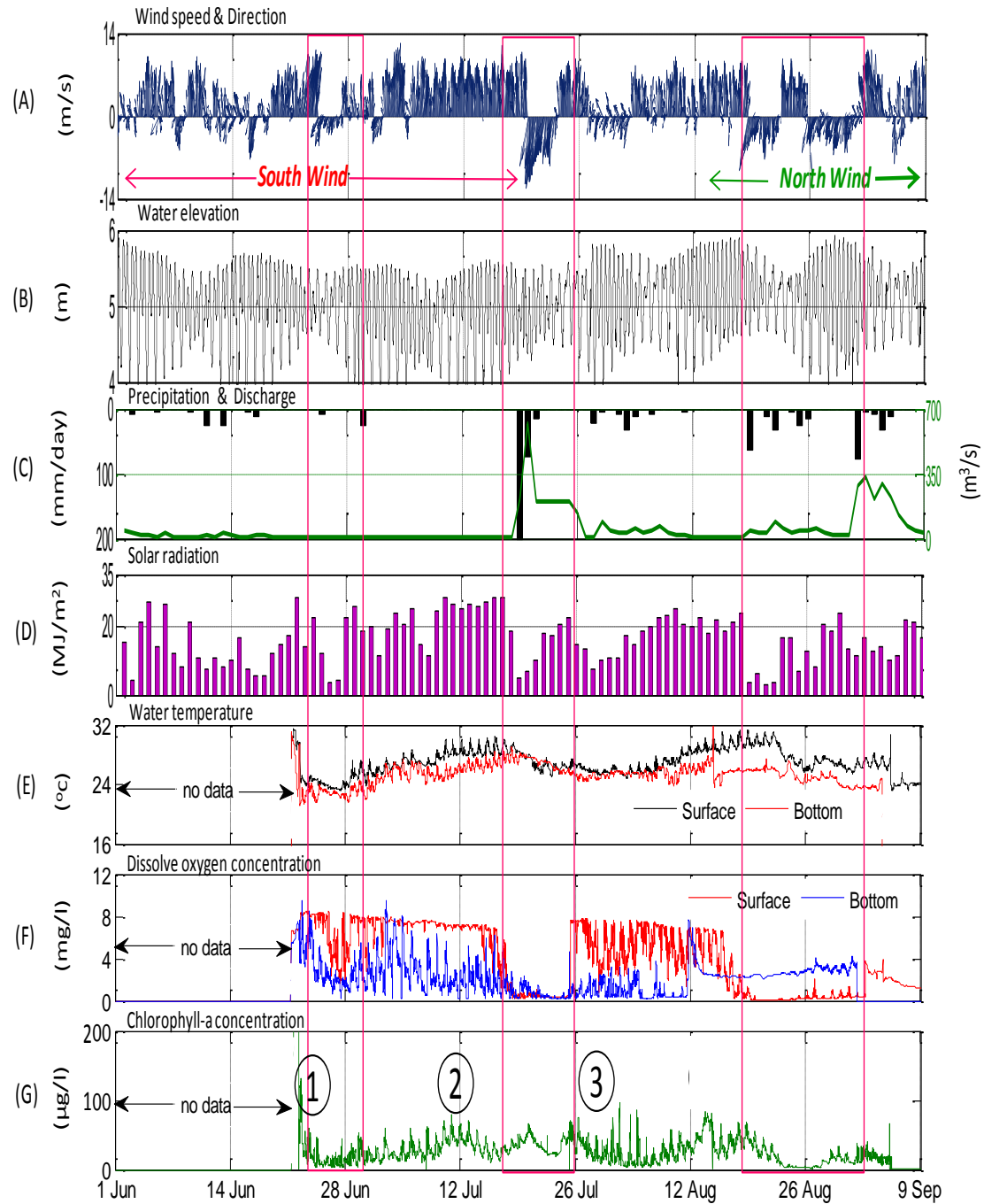


Fig.4.5 Time series of (A) Wind speed and direction (B) Water elevation (C) Daily Precipitation and Discharge (D) Solar radiation (E) water temperature (F) Dissolved Oxygen concentration and (G) Chlorophyll-a concentration at Station 3 during summer 2011. The vertical red colored rectangular indicates three hypoxic events and black circle indicates four phytoplankton blooms. The mechanism on the development and fate of hypoxic events and phytoplankton blooms has been discussed in the section 4.2.1 and 4.2.2 respectively.

4.1.4 Interaction between wind and water quality parameters

The general wind governing water circulation in this area is described as follows. The south wind results in reversed estuarine circulation where the surface currents flow toward the bay- and bottom currents flow toward the estuary region. This causes accumulation of upstream water around the estuary region. In contrast, the north wind enhances the estuarine circulation that the coastal water flow out estuary underneath. This attributes are consistent and correspond with present study results (Figure 4.3, 4.4, 4.5 and 4.36) where phytoplankton bloom and hypoxic events were driven by wind events. It was seen that, in general, south wind cause the accumulation of seawater from the upstream to estuary mouth by the downstream directed currents. The compensation currents flow beneath the surface layer. As a result, the water column becomes less stratify in period of prevailing south wind causes accumulation phytoplankton biomass around the estuary region. In contrast, prevailing north wind can strengthen the stratification in water column. It also enhanced the estuarine circulation, in which coastal bottom waters flow towards upstream causes movement of hypoxic waters from the bay to estuary. This kind of circulation can draw the lower temperature and higher salinity in this region.

4.1.5 Freshwater input and stratification

Data on freshwater input to the river were estimated and collected from two sources (Figure 4.2). First, the daily average discharge was calculated form the water level of 2011 measured at Sugama observation point of Arakawa river using the measured discharge of 2001 by using H-Q function. Secondly the data obtained from HADCP deployed at the outer part of Odaiba that was mounted 1 m above from the river bed was used to calculate river discharge by using along channel current velocity and water level data for comparison to the upstream discharge to the downstream discharge.

Combined river discharge was fairly for the measurement period, showing a few small peaks and slightly few average high peaks flow during the second half of July, August and September. Variation in the degree of stratification over time was recorded by the surface and bottom sensors at each station. Plotted in Figure 4.6, Figure 4.7 and Figure 4.8 are the temperature, salinity and water density for stations 1, station 2 and station 3 respectively. Surface and bottom temperature and salinity at station 1 were extremely dissimilar over the entire deployment (Figure 4.6). Both temperature and salinity displayed tidal trends, but long time average temperature varied more than salinity, altering from 20⁰c to 30⁰c (with tidal peaks 31⁰c), while

average salinity hovered 25 psu. There was one significant fresh water or discharge event on 19th July, 27th August and 1st September, in which salinity dropped to 15 psu, 12 psu and less than 10 psu respectively, which correspond to several peak discharge events as well. Temperature and salinity returned to levels observed prior to the discharge events within a few tidal cycles.

Station 2 showed similar trends to station 1, with the exception of gradual differences in surface and bottom temperature (and hence, density) over the course of deployment (Figure 4.7). It was not uncommon for this to occur due to the position or location of the station that is enclosed by land than that of station 1 which is directly affected by incoming fresh water from upstream and tidal flow from the bay. However, the change in thermal stratification that was much higher at station 2 due to the stagnant water column and surface heating in summer period as well. From June 22 to July 20, the surface and bottom temperature tracked each other well and mixing occurred for both surface and bottom layer of water column. On approximately 8th August, the surface and bottom temperature began to rise steadily and continued to gradual rise until 16th August with both for bottom and surface temperature and surface and bottom temperature remained uniform at this period on a semidiurnal frequency. After that period, the tidal amplitude ceased and consistent salinity as well as temperature increase was observed until August 20 at which point surface and bottom salinity and temperature were quite mixed. However followed by discharge events, the surface and bottom layer with regard to temperature and salinity were separated caused stratification during this period and this trends continued upto the rest of the observation period that are the indication of pronounced halocline stratification with high to moderate discharge events.

Aside from the data discrepancy, the T/S data at station 2 followed very similar trends to station 1, if not nearly identical. One notable difference was a slight disparity between surface and bottom salinity and temperature during the period surrounding the discharge peaks on 19th July, 27th August and 1st September in which surface salinity and temperature fluctuate to much. These were the only some significant periods in which there appeared to be high stratification in the water column.

Temperature and salinity data from station 3, enclosed area apart from the main channel of the discharge show somewhat different trends (Figure 4.8). Long-term tidal trends are similar (such as the periods of warmest temperature occurring in July and August); however tidal variability didn't appear to be as significant, particularly in the bottom layers. In addition, average temperature was higher at this station in contrast to that of station 1 and salinity was almost

same than those of other two stations. There were also more differences between surface and bottom temperature than those of two stations, which was not particularly surprising given its proximity to the fresh water input of the river. In this view, the disparity between surface and bottom water density was more evident, averaging between 1-2 kg/m³. It was also clear that on a few occasions, bottom waters was actually warmer than surface waters, which may corresponds to periods when higher temperature discharge water from the Sumida river intruded upstream in the near bottom layers. Since the salinity of the water is more important in the density, the bottom waters were still denser during these brief events (21-23 July, 18-19 August and 5-9 September at station 1 and 21-25 July, 4 August at station 2 and station 3).

Upon closer examination, the dominant oscillation period of temperature data was actually diurnal, whereas the period of the salinity data was semidiurnal, in both surface and bottom layers. This discrepancy between temperature and salinity was most likely due to the fact that the discharge from the river changed the temperature of water, but not the salinity, as the cooling water originated from the bay.

The general trend noted throughout the observation period that the water column was more stratified at the inner part (station 2 and station 3) of Odaiba and to some extent vertically mixed at the outer part of Odaiba (station 1), with occasionally stratified water noted. Although the water column was vertically mixed at the inner part, a marked difference in surface and bottom water density were noted between 8-27th July and 19th August to 3rd September. On the other hand, during the whole observation period, a marked differences in both for surface and bottom water density were noted at both station 2 and station 3 which indicated pronounced stratification associated with lower and peak discharge events.

The fact that salinity varied on a semidiurnal cycles suggest that either a salinity front propagates up- and down-channel with tide, or mixing of lower salinity river water with higher salinity bay water occurred on a tidal basis. Therefore the tidal variability in salinity is most likely due to tidal mixing of estuarine waters and incoming bay waters.

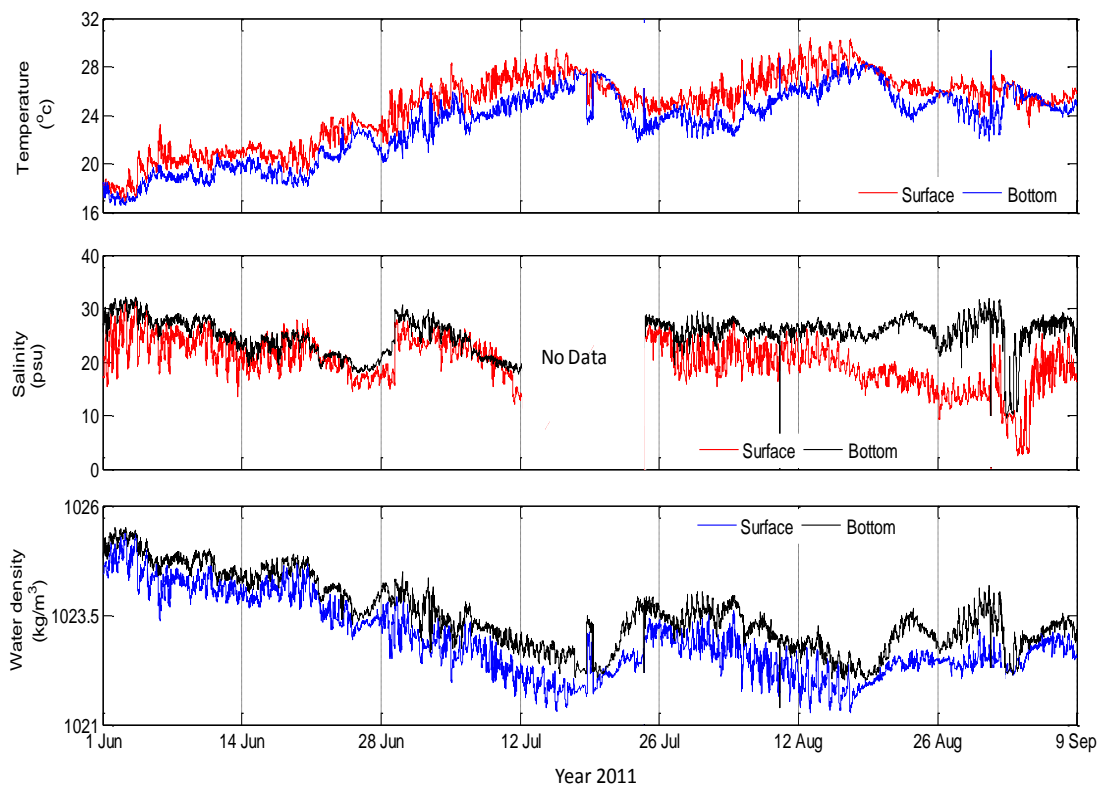


Fig.4.6 Time series of temperature (top panel), salinity (middle panel) and water density (bottom panel) at Station 1 during 1 June to 9 September, 2011 recorded by YSI sensors.

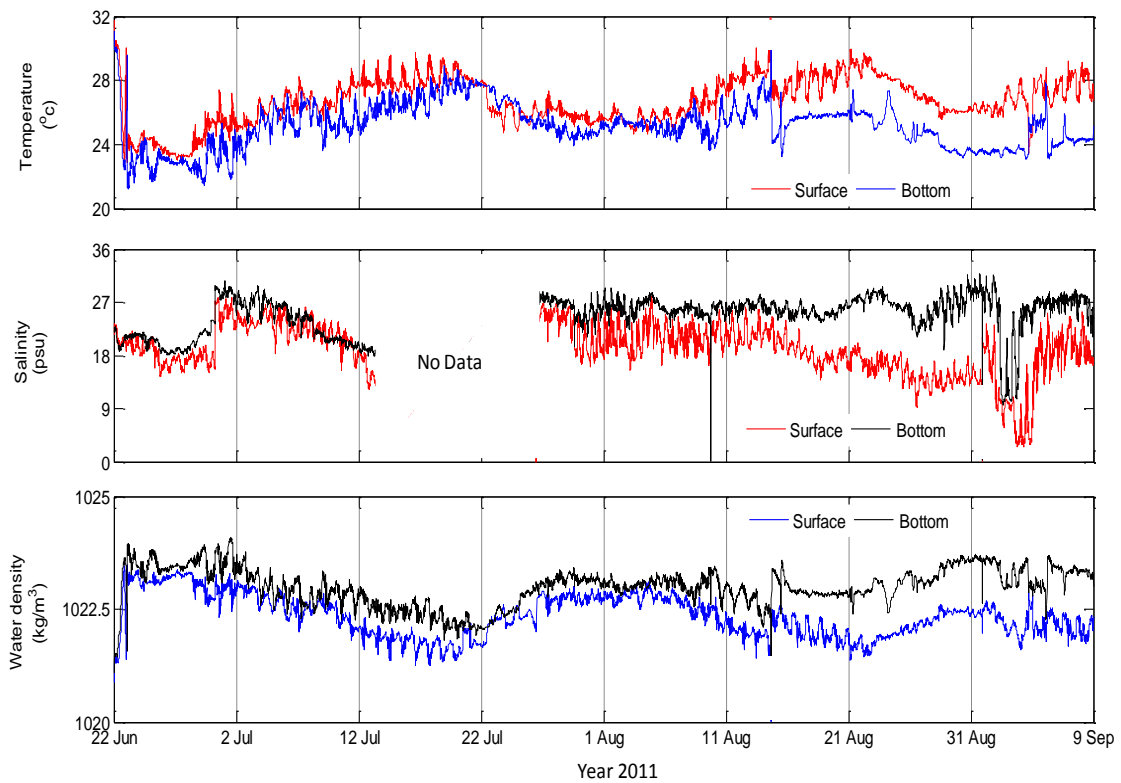


Fig.4.7 Time series of temperature (top panel), salinity (middle panel) and water density (bottom panel) at Station 2 during 22 June to 9 September, 2011 recorded by moored Alec Electronics sensors.

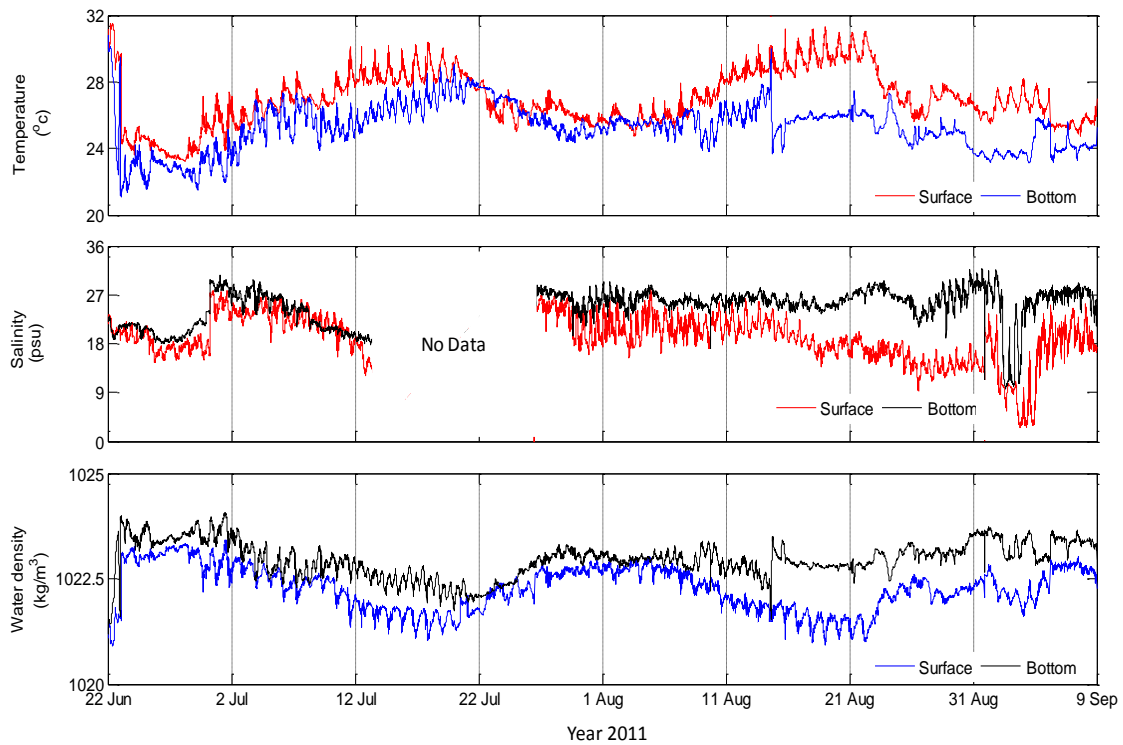


Fig.4.8 Time series of temperature (top panel), salinity (middle panel) and water density (bottom panel) at Station 3 during 22 June to 9 September, 2011 recorded by moored Alec Electronics sensors.

4.1.6 Stratification and DO

Surface to bottom density differences and surface and bottom dissolved oxygen at the three stations (June 1, 2011 to September 9, 2011) are shown in Figure 4.9 and 4.10. The variations in surface to bottom density differences at the three sites reveal episodic stratification events. The density differences are primarily driven by changes in salinity at station 1 and by temperature changes at other two stations. The surfaces to bottom density differences at station 2 and 3 were greater than at the station 1. While the amplitudes of events varied with location, they were nearly always in phase (Table 4.1). The difference between surface and bottom sigma-T, which is also an index of water column stratification, was highest at the inner part of estuary and decreased down estuary characterized as outer part of the estuary. Salinity influenced water column stratification more than temperature (surface and bottom T and S; Table 4.1) indicating that thermal stratification was low at the sea ward end of estuary. In contrast, the surface and bottom temperature were high in the inner part of estuary, indicating pronounced thermal stratification than the halocline stratification. Stratification at the inner part of estuary was strong and persistent; it did not exhibit prompt responses to physical factors such as fresh water runoff/or tidal flows immediately, which regulated stratification down-estuary. Stratification

index (the difference between surface and bottom sigma-T) was low at station 1 in contrast to station 2 and station 3 as seen in Table 4.1, where the influence of environmental factors on stratification was greater. Stratification was eroded due to the influence of tidal action and onset of southerly wind.

Table 4.1: Average Temperature (T), Salinity(S), Water Density (Sigma T) in the surface and bottom layers at the three stations

Stations	Surface T	Bottom T	Surface S	Bottom S	Surface Sigma-T	Bottom Sigma-T	Stratification Index
Stn.1	26.06	24.58	17.31	24.13	1022.53	1023.15	0.62
Stn.2	26.73	25.15	17.31	24.13	1022.34	1022.99	0.64
Stn.3	27.02	25.26	17.31	24.13	1022.26	1022.95	0.69

High stratification prevented ventilation and resulted in low DO in the bottom layer. Higher stratification index indicated bottom layer DO concentrations throughout the inner part of estuary (station 2 and station 3). At these two locations of inner part of estuary, high stratification resulted in high surface water DO, suggesting that oxygen produced by photosynthesis remained in the surface layer rather than the mixing throughout the water column. However, the changes in surface to bottom density shows that higher fluctuations in dissolved oxygen concentration occur during times when the surface to bottom density difference was smallest (i.e., when water column is vertically mixed). This evidence is at station 1 of the outer part of the estuary. In contrast when the density difference was greater the hypoxic events occurred intermittently at the inner part of the estuary.

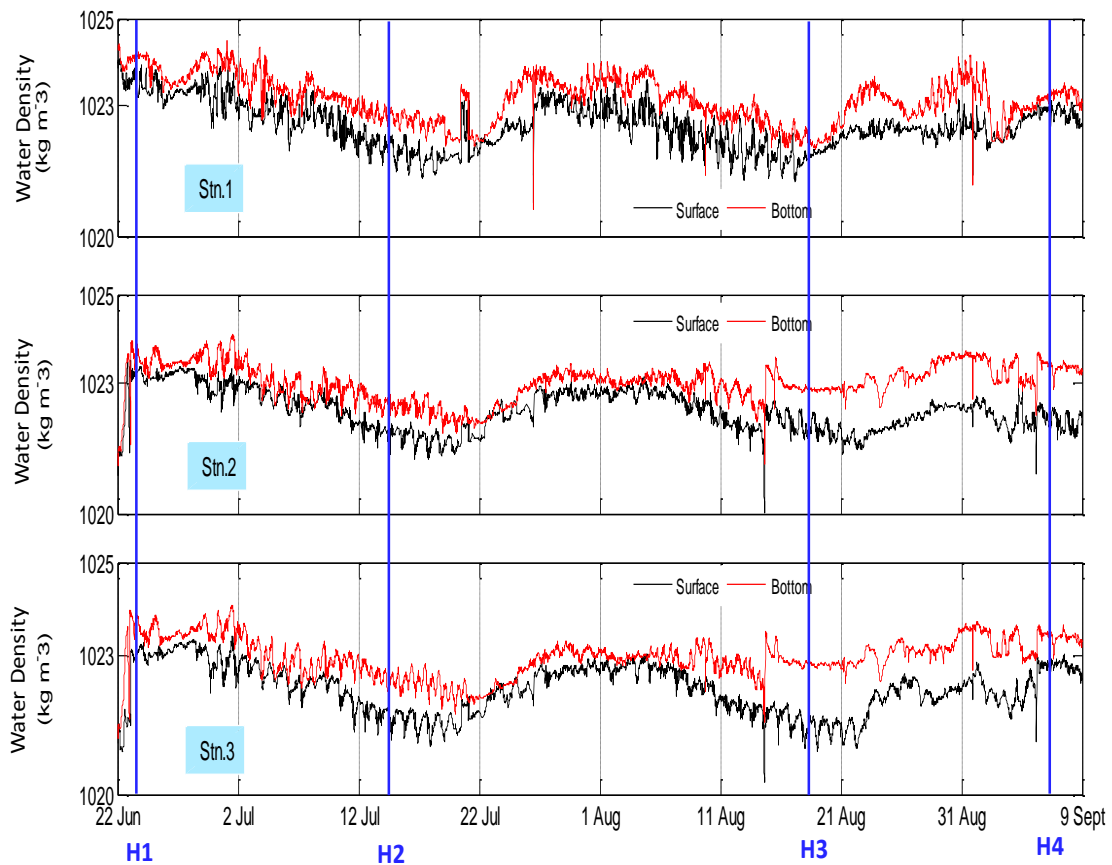


Fig.4.9 The difference between the bottom and surface Sigma-T at the outer part of Odaiba (Station 1), inner part of Odaiba (Station 2 and 3). Blue vertical lines indicate the beginning of four hypoxic events starting on 25th June (H1), 17th July (H2), 19th August (H3) and 5th September (H4).

4.1.7 Spatial heterogeneity of Dissolved oxygen

Figure 4.10 shows the observation results in terms of temporal changes of near surface and near bed dissolved oxygen concentration from station 1, 2 and 3 indicated by H1(25 June-3 July), H2(17-25 July), H3(19 August-1 September) and H4(5-9 September). Dissolved oxygen concentration record indicated that stratification and associated hypoxia around Sumida river estuary were spatially heterogeneous over the study period. High DO in the surface layer were observed at station 1, where chlorophyll-a concentration coverage was high during entire observed period (Figure 4.3H). Inner part of the estuary (station 2 and 3), the difference between surface and bottom layers dissolved oxygen concentrations were more prominent and evident. Photosynthetic oxygen production in well-illuminated surface layers resulted in $DO > 7-12 \text{ mg/l}$ for all the three locations. In contrast, DO in bottom layer for station 2 and 3 was lower which was approximately $<2-3 \text{ mg/l}$. DO in the bottom layer at the station 2 (Figure 4.10) was comparable with DO observed at the station 3 and at the seaward location of the estuary (station

1), excluding several periods of pronounced hypoxia. After recovering every hypoxic events, dissolved oxygen concentration abruptly increased to around 10-15 mg/l and this increasing of dissolved oxygen corresponding to the sudden increasing and decreasing of near bottom salinity and water temperature presented in Figure 4.3EF, 4.4E and 4.5E. Moreover the changes pronounce also with the wind speed and direction as can be seen in Figure 4.3A, 4.4A and 4.5A respectively. The overall dissolved oxygen concentrations at the outer part of Odaiba (station 1) were higher than those of the station 2 and 3 in terms surface level oxygen concentration. Dissolved oxygen concentration in the bottom layer of station 2 and station 3 were always above the anoxic level at about <1 mg/l.

Around this area, spatial heterogeneity of DO production and consumption in combination with tidal mixing resulted in complicated patterns of DO distribution in space and time that were not well predicted by simple analysis. Most, but not all hypoxic events were developed at the inner part (station 2 and 3), where bottom water waters were oxygen poor and surface water were oxygen rich. Neap tidal flow (Figure 4.3B, 4.4B and 4.5B) transported waters from inner part that were sometimes oxygen rich (daytime) and sometimes oxygen poor (nighttime) towards outer part of estuary resulting in subsurface hypoxic condition at the outer part (station 1) where influence of river discharge (Figure 4.2) is high than that of inner part.

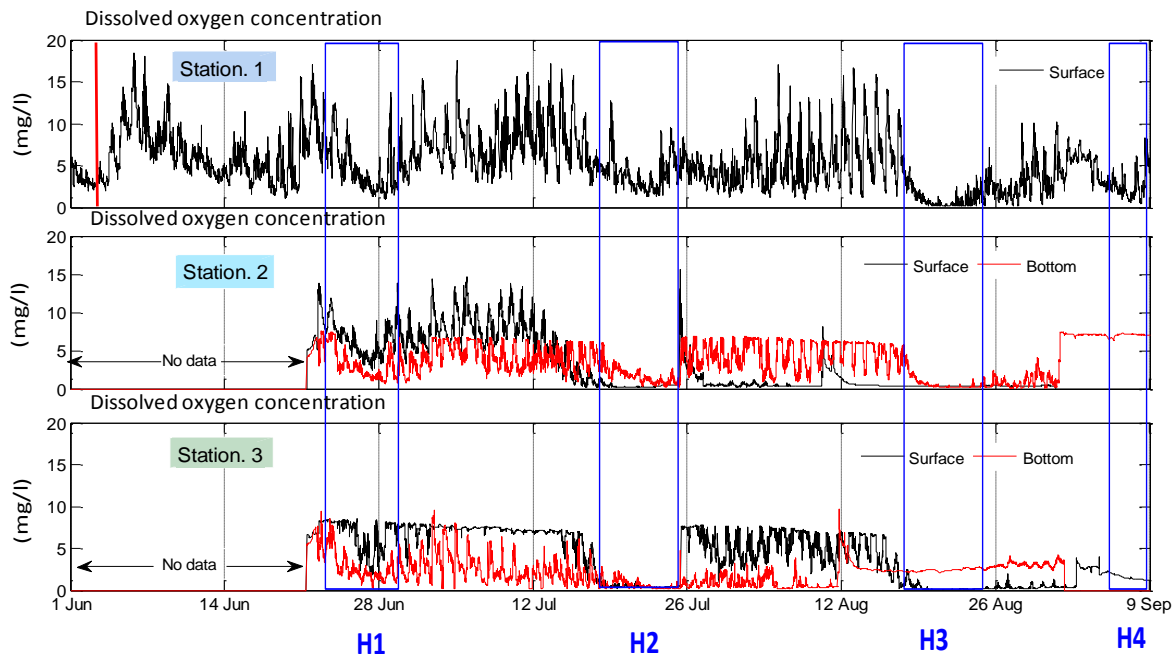


Fig.4.10 Dissolved oxygen concentration in surface layer (black line) and in bottom layer (red line) at station 1, 2 and 3. Blue rectangles indicate four hypoxic events (H1, H2, H3 and H4).

4.1.8 Spatial distribution of chlorophyll-a concentration

Observed spatial distribution of surface layer chlorophyll-a concentration indicated by B1(19-24 June), B2(16-20 July), B3(4-10 August) and B4(15-20 August) as phytoplankton bloom and dissolved oxygen concentration are given in Figure 4.10 and 4.11, respectively around the region. Observed chlorophyll-a concentration showed that the phytoplankton biomass was concentrated more at the station 1 than those of station 2 and 3. Thus the highest concentration of chlorophyll-a was found at the outer part (station 1) and second highest concentration was observed at station 2 and the lowest concentration of chlorophyll-a was found at the station 3. It is mentionable that the station 1 is located at seaward position which is directly influenced by the incoming bay water as well as outgoing river water and as a result concentration of chlorophyll-a was much higher than those of station 2 and 3. In contrast, station 2 and 3 were located at the innermost part of Odaiba which are enclosed by land and less influenced by river water and sea water which are the dominant of source phytoplankton accumulation. Furthermore significant differences in chlorophyll-a concentration between station 2 and 3 was observed although the distance between these two locations is not more than 100 m. This significant differences were due a floating fence which was set in between these two stations as a barrier to limit the horizontal transport of phytoplankton and results of chlorophyll-a concentration between these two stations are well demonstrated and explained. Dissolved oxygen concentration also displayed strong temporal and spatial variations with the variations of phytoplankton biomass. Higher concentration of dissolved oxygen could be found only at the near surface water corresponding well with the distribution of chlorophyll-a distribution (Figure 4.10).

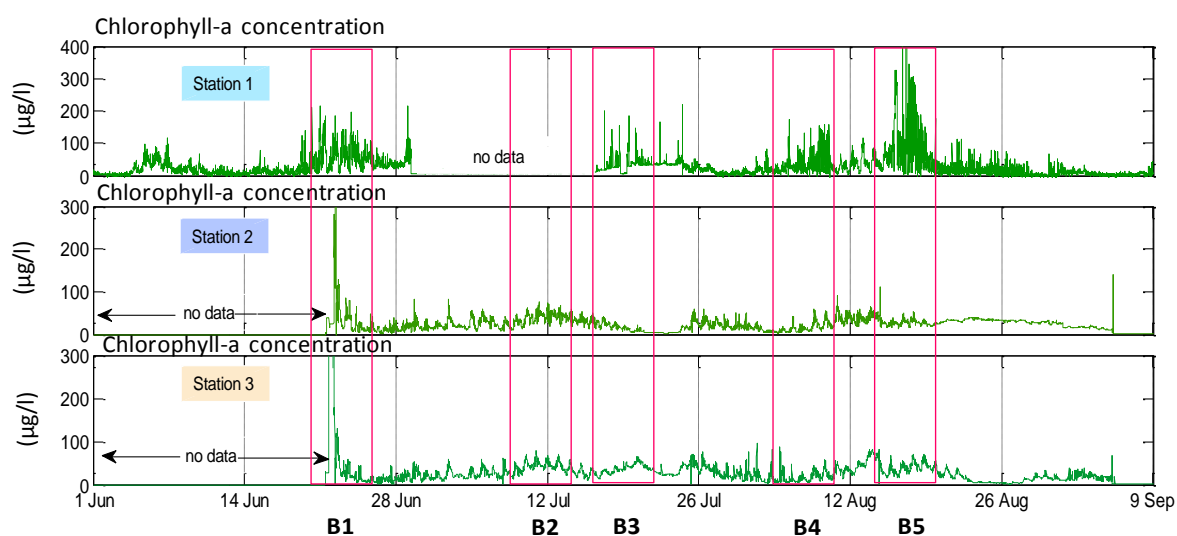


Fig.4.11 Chlorophyll-a concentration in surface layer (green line) at station 1, 2 and 3. Red rectangles indicate five phytoplankton bloom events (B1, B2, B3, B4 and B5).

Spring-neap tidal modulation controlled the surface and bottom layers of water column and influenced the distribution of chlorophyll-a. During spring tides, salinity intrusion occurred by strong horizontal transport of saline water from the bay as a result chlorophyll-a concentration declined from the riverine source. During neap tide, the estuarine water column stratified, with maximum horizontal transport from river and vertical mixing to surface and bottom layer were restricted and as a result in the surface layer chlorophyll-a concentration increased. But this evidence was more prominent at the station 1 rather than station 2 and 3. So the results from the spatial distribution of chlorophyll-a concentrations suggested that the tidally forced spring-neap variation in salinity was strengthened during this summer observation period, with higher temperature and salinity (Figure 4.3, 4.4 and 4.5).

4.1.9 Tidal range, hypoxia and phytoplankton bloom

Figure 4.3, 4.4 and 4.5 show the relationship of tidal range, hypoxia and associated phytoplankton bloom during the study period. During periods of low tidal range (around the neap tides), there is oxygen depletion in surface waters. However, the occurrence of hypoxia in only 4 lower tidal range events indicates that hypoxia does not occur during all neap tides. During periods of high tidal range (around the spring tides), surface oxygen values were restored. However, on early June and late July, the DO values were not consistent with spring tide because of strong stratification at this time, thereby requiring more tidal mixing to restore DO to the surface layer. The major controlling variable of surface DO values is solar irradiation. The periods of high surface oxygen values are indicative of phytoplankton blooms which correspond to water column stratification. It is observed that bloom occurred during spring tide and bloom terminates during neap tide by vertical stratification. This is because of turbulent mixing of water column during spring tide. So, from the figures, it was evidenced that photosynthetic blooms tend to occur during periods of spring tide while conversely blooms were disrupted or could not be sustained during neap tide.

4.2.1 Mechanism of hypoxic water generation and termination

Hypoxic events were defined as periods when either the DO value was <3 mg/l or < 4 mg/l in any observation during the 24 hours period. Five hypoxic events were occurred from June to early September 2011 as shown in Figure 4.3, 4.4 and 4.5. All of these events seemingly resulted from one or more of three environmental factors: low solar radiation (resulting in reduced oxygen production via photosynthesis), increased fresh-water discharge (resulting in enhanced halocline stratification preventing ventilation of waters) and sluggish subsurface water ventilation due to stratification often occurring during neap tidal phase. The most intense hypoxic event occurred in the second half of August and early September following rain events and increases in freshwater flow from the river.

The first hypoxic event occurred between 1-4 June during the start of the observation at the outer part of estuary (station 1). This event coincided with low solar radiation, moderate river discharge during the moderate northward wind (3-4 m/s) with maximum thermal and haline stratification. (Figure 4.12). The tidal cycle of ebb and flood phase are evident and tides are predominantly semidiurnal. The current vectors indicate an overall ebb directed (positive currents) flow towards the south along the estuarine axis. The along river currents indicate much ebbing phase than the flooding phase and from 1-4 June currents was much positive than the negative currents indicate the upstream flow and velocity magnitude was found to be higher resulting in the transport of oxygen depleted water caused thermo and haloclines in this area which initiated subsurface hypoxic events.

Another hypoxic event was occurred during 25 June to 3 July when the average DO concentration was 3.18 mg/l. However, during this period estuary stratification was quite higher than the normal (Figure 4.13, 4.17 and 4.20). This may have led to insufficient ventilation of the surface layer, producing hypoxic waters that were transported down-estuary affected by the north wind and subsequently the hypoxic condition was alleviated when strong south wind started to blow and at the same time solar radiation began to rise associated with thermal stratification. In addition, in the development of this hypoxic event, there were stratifying events with the gradual drops in surface and bottom temperature and salinity due to moderate river discharge structures as well as surface cooling due to low solar radiation affected by northerly wind. During this hypoxic event, the current vectors was directed to downstream and upstream successively which indicates flooding and ebbing phase of along river current velocity which produced sometimes well mixed due to flooding phase and sometimes ebbing phase creating

stratified layers in the water column and as a result oxygen concentration were also fluctuated. The bottom hypoxia at the inner part (station 2 and 3) almost coincided but surface oxygen concentration for all the three locations were found to be different as because stratification was more pronounced at the inner part than that of outer part. However, this hypoxic event was terminated by the breakdown of stratification associated with stable south wind up to July 5.

The third hypoxic event was developed at the three stations between 17-25 July when the average DO concentration was < 3.0 mg/l (Figure 4.14, 4.18 and 4.21). There were gradual decrease in surface and bottom temperature due to rainfall events and sudden increase in river discharge structures as well as surface cooling due to low solar radiation affected by strong northward wind (Wind speed >10 m/s). The tidal elevation and along river currents were stronger between 17-22 July when the river discharge was also high resulting in higher DO values at the three locations. But increase in stratification to the rest of the period implied decrease in DO concentration for all the stations and tidal mixing at this period was low because the flooding and ebbing phase current magnitude was shown to be weak which induced low oxygen period. Bottom hypoxia was severe at inner part as stratification was more persistent. On the contrary, this hypoxic event was eventually alleviated by southward wind and restored oxygen contents in the water layer by vertical mixing.

The most pronounced period of hypoxia started between 19 August to September 1, DO concentrations measured were <1 mg/l during this period (Figure 4.15, 4.19 and 4.22). This hypoxic event likely resulted from lowest solar radiation associated with a rainfall fronts and northerly wind. Subsequent settling and oxidation of organic matter associated with the freshwater discharge may have contributed to the development of this hypoxia, which propagated down the estuary (station 1) as a result of horizontal advection by ebb tide when along river currents directed to downstream was prominent and before ebbing phase the presence of vertical density gradient and input of fresh water from the river results in gravitational circulation where bottom water were directed to upstream by which low DO water were transported and concentrated in the inner part (station 2 and station 3) of the estuary. At the same time, the subsurface layer at the head of estuary was repeatedly affected by hypoxia because the freshwater discharge and salinity gradient (20–25 psu in the subsurface layer) stratified the water column strongly and subsequently hypoxia was terminated followed by reverse mechanism when water column became well mixed.

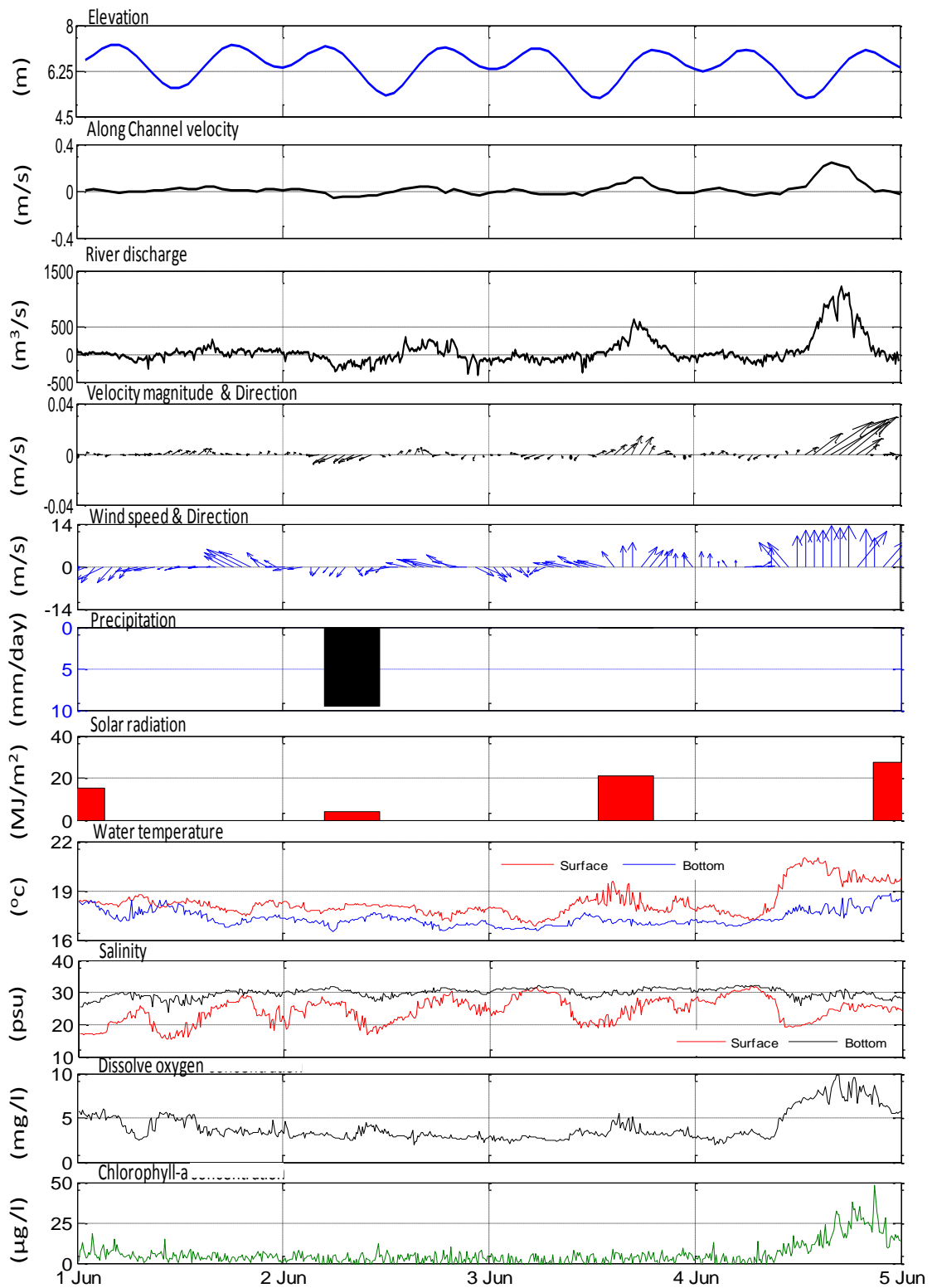


Fig.4.12 Hypoxic event 1 during 1-4 June at the outer part of Odaiba (Station 1)

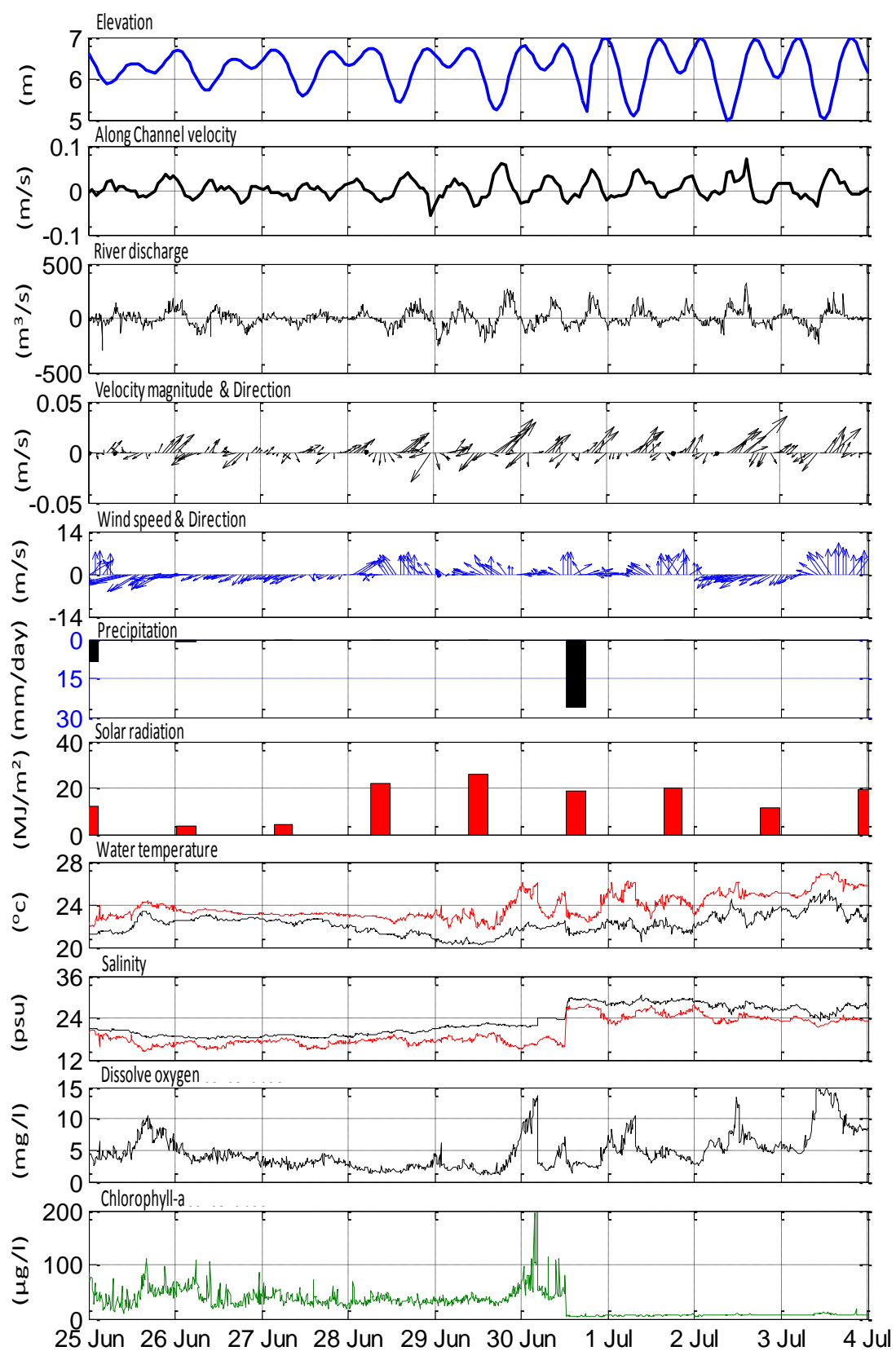


Fig.4.13 Hypoxic event 2 during June 25 to July 3 at the outer part of Odaiba (Station 1)

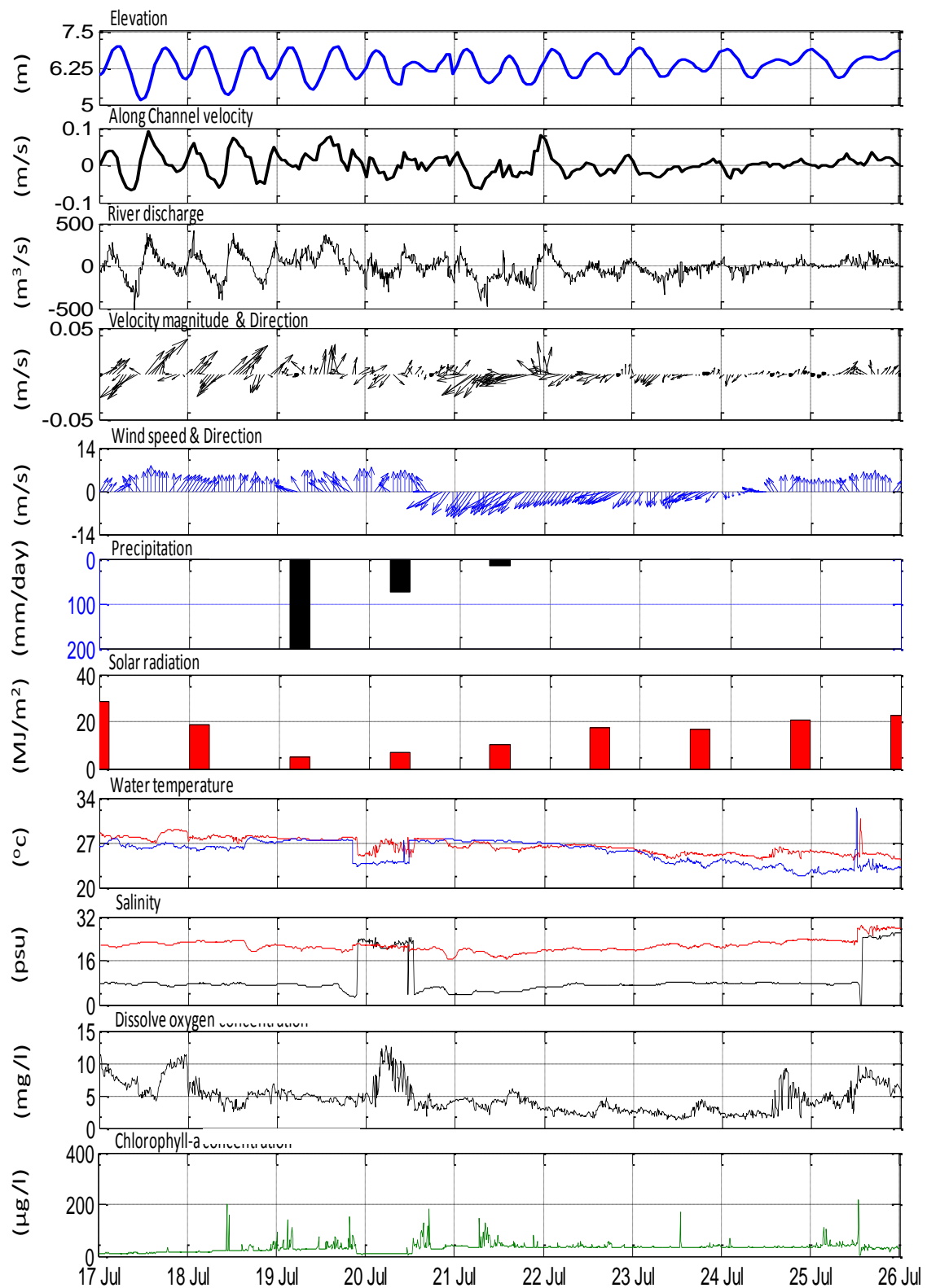


Fig.4.14 Hypoxic event 3 during July 17-25 at the outer part of Odaiba (Station 1)

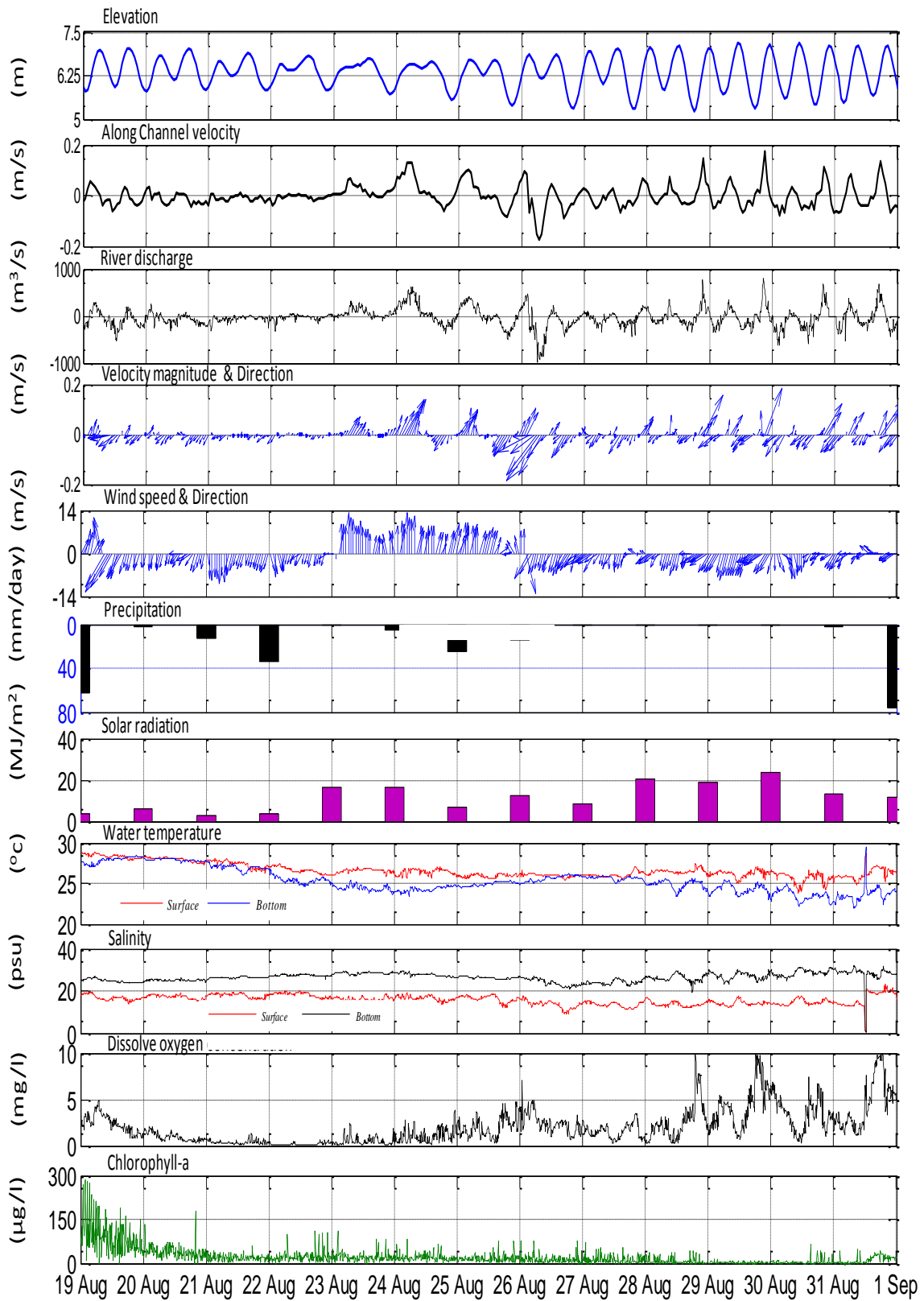


Fig.4.15 Hypoxic event 4 during 19-31 August at the outer part of Odaiba (Station 1)

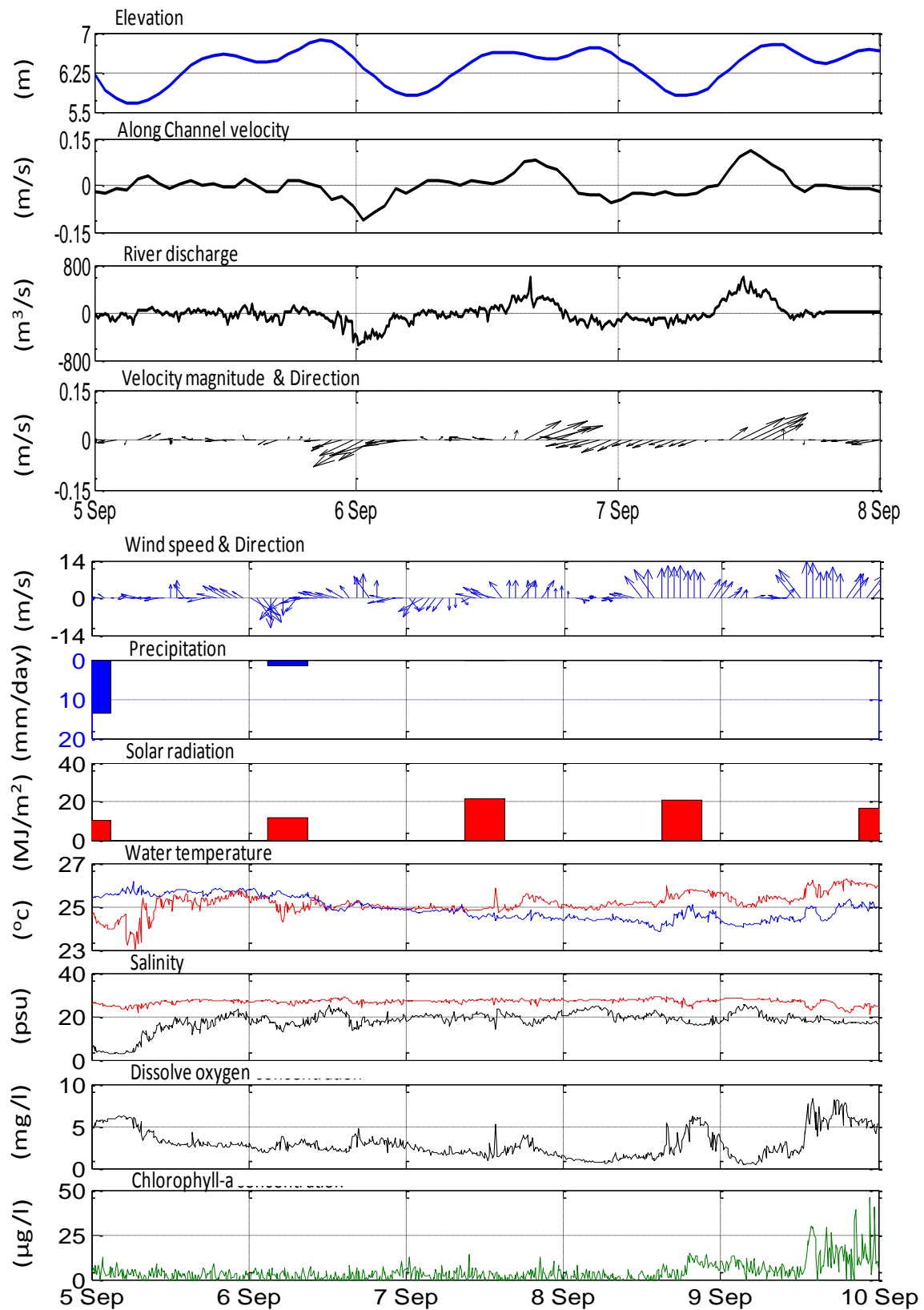


Fig.4.16 Hypoxic event 5 during 5-9 September at the outer part of Odaiba (Station 1)

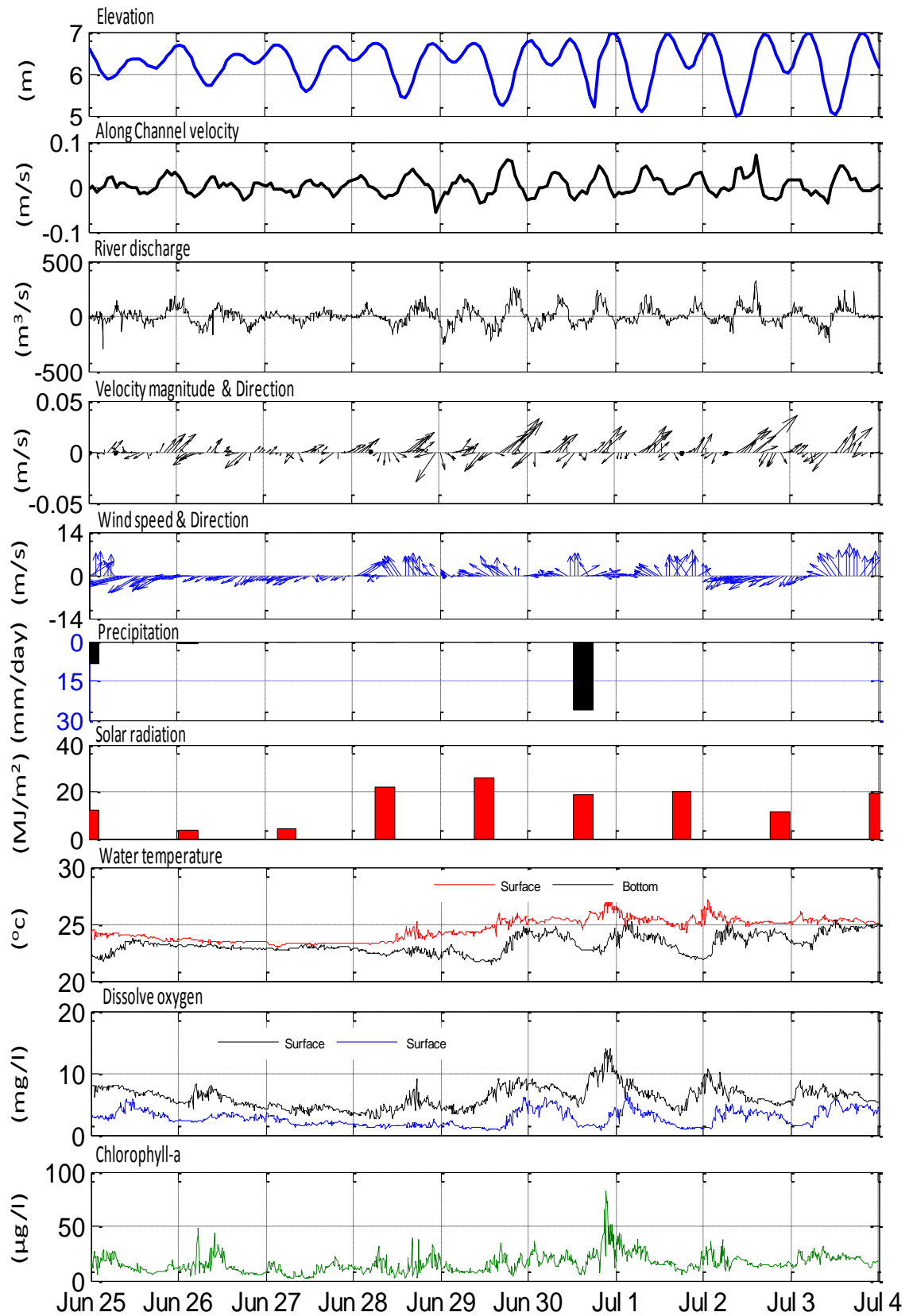


Fig.4.17 Hypoxic event 1 during 25 June -3 July at the inner part of Odaiba (Station 2)

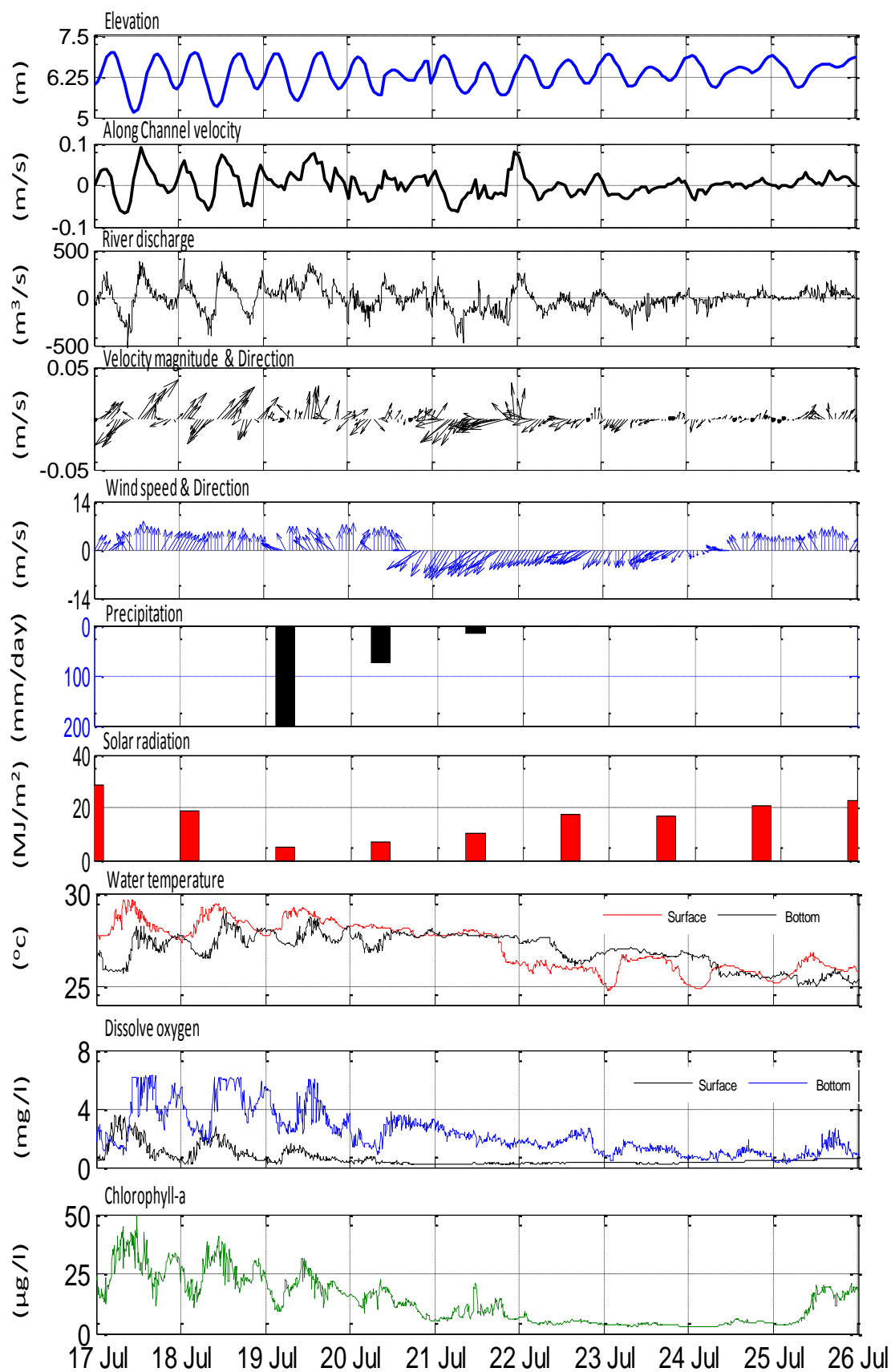


Fig.4.18 Hypoxic event 2 during 17 -25 July at the inner part of Odaiba (Station 2)

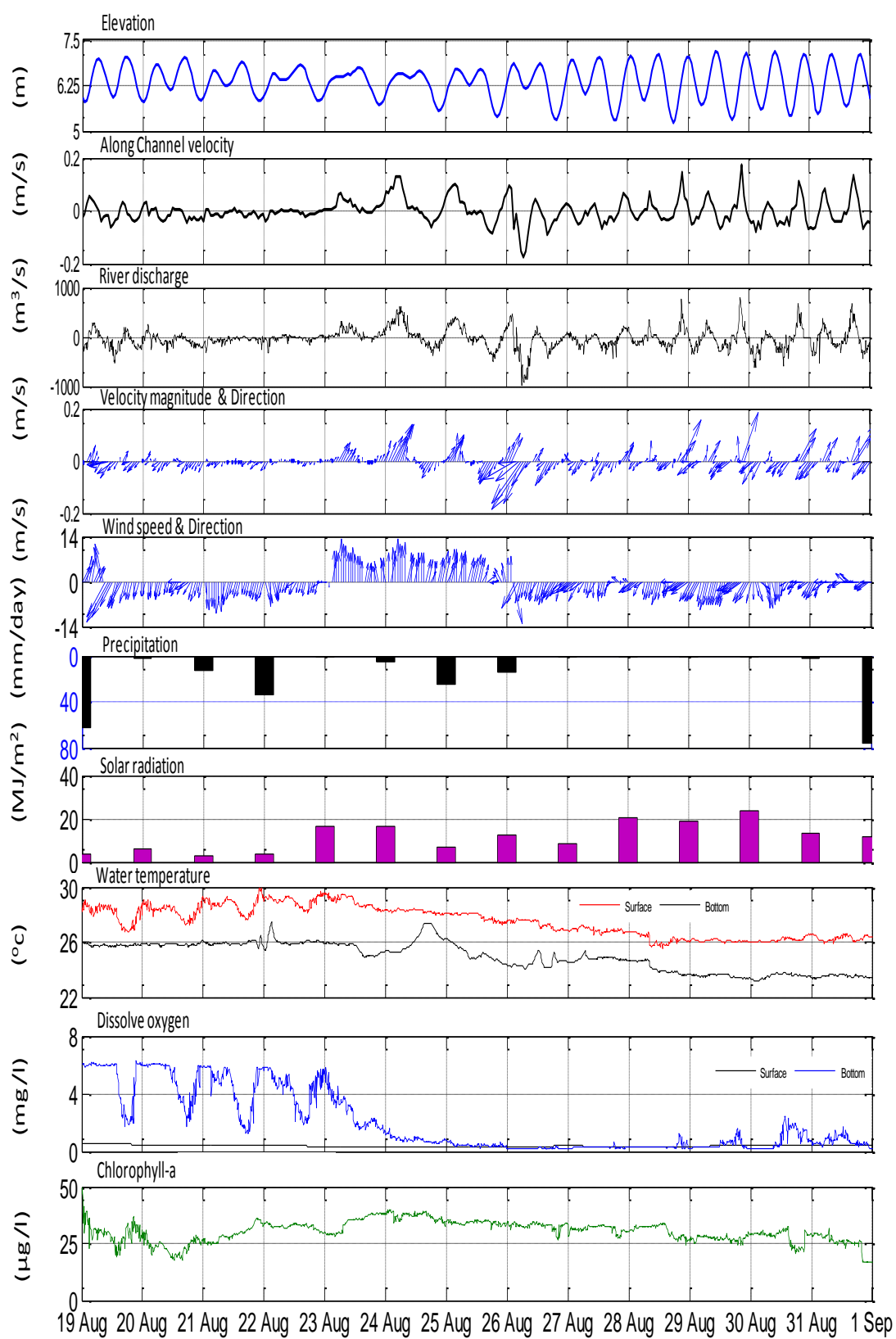


Fig.4.19 Hypoxic event 3 during 17 August -1 September at the inner part of Odaiba (Station 2)

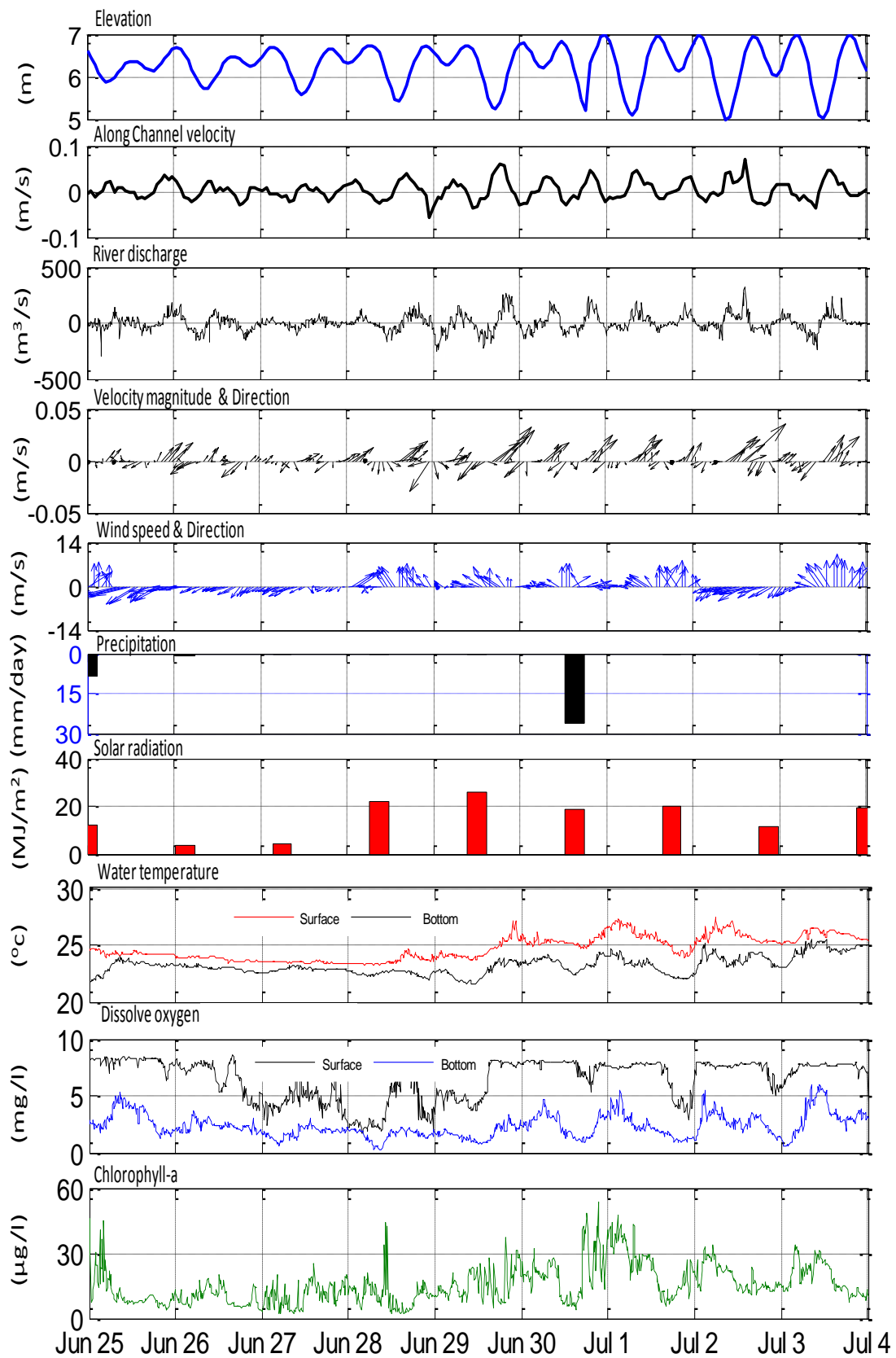


Fig.4.20 Hypoxic event 1 during 25 June -3 July at the inner part of Odaiba (Station 3)

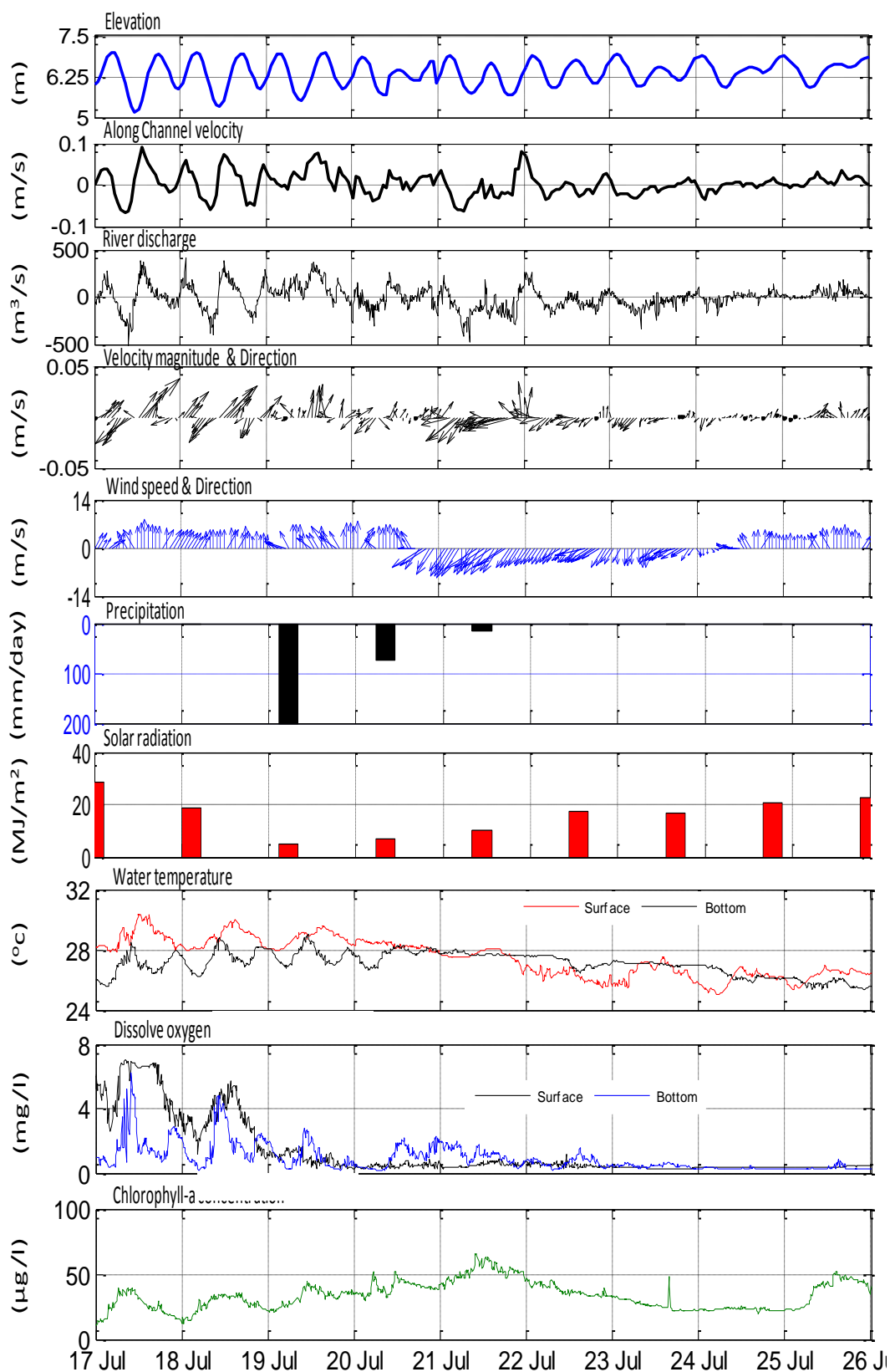


Fig.4.21 Hypoxic event 2 during 17 -25 July at the inner part of Odaiba (Station 3)

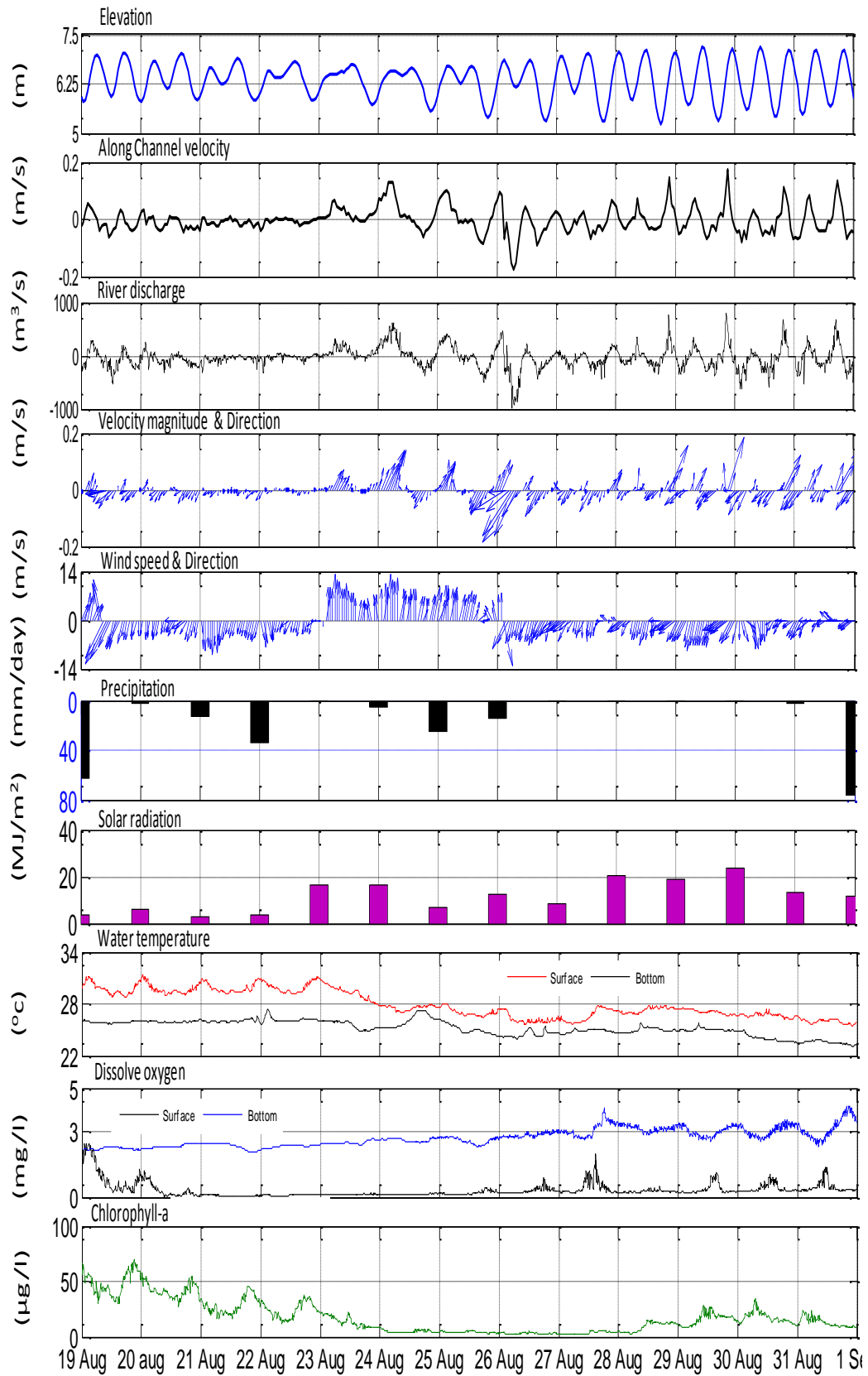


Fig.4.22 Hypoxic event 3 during 17 August -1 September at the inner part of Odaiba (Station 3)

The last hypoxic event occurred at station 1 during 5-9 September followed high haline stratification and an increase in discharge and rainfall events associated with northerly wind and low solar radiation (Figure 4.16) when dissolved oxygen concentration was <3 mg/l throughout the period. This event was preceded by a small rain event. During this hypoxic events, the along river currents were found to weak at the time of flooding phase and vice-versa during ebb phase.

Hypoxic waters were terminated between every successive period by the sudden or abrupt increase in DO concentration as indicated by the five hypoxic events with the combined effect of south wind and experienced by large river discharge structure followed by precipitation. In addition, mixing of water column, due to changing winds and rainfall events caused by passing weather fronts, results in the breakdown of the oxygen depleted water mass. In other words, factors important for oxygen depleted waters include surface salinity decreased due to rainfall events and river flows and surface warming due to solar irradiance. Conversely, hypoxia was alleviated or eliminated by rapid surface cooling and change of wind pattern. All of these hypoxic events were developed and eliminated with direct influence of the horizontal advection or transport by along river currents which were directed to upstream during flooding phase and downstream during ebbing phase.

A summary of dissolved oxygen concentration depletion rate is given in Table 4.2 where at the outer part and inner part the surface dissolved oxygen concentration coincided well. But in case of station 2 and 3, depletion rate of bottom DO was much lower which dropped below the hypoxic level indicating stressful aquatic environment for fish and other marine organisms during these very low oxygen periods.

Table 4.2: Summary of 2011 oxygen depletion rates at the three stations of Sumida river estuary

Start date	End date	Initial DO (mg/l)	Final DO (mg/l)	Oxygen depletion rate (mg/l/day)
<i>Station-1</i>				
6/1/2011	6/4/2011	5.82	2.54	0.82
6/25/2011	7/3/2011	4.81	1.21	0.4
7/17/2011	7/25/2011	6.76	1.32	0.6
8/19/2011	9/1/2011	3.33	0.17	0.24
9/5/2011	9/9/2011	5.08	0.39	0.93
<i>Station-2</i>				
Surface				
6/25/2011	7/3/2011	6.78	2.47	0.47
7/17/2011	7/25/2011	3.58	0.53	0.33
8/19/2011	9/1/2011	0.44	0.3	0.01
Bottom				
6/25/2011	7/3/2011	2.92	0.62	0.25
7/17/2011	7/25/2011	2.57	0.22	0.26
8/19/2011	9/1/2011	4.48	0.09	0.31
<i>Station-3</i>				
Surface				
6/25/2011	7/3/2011	8.21	1.65	0.72
7/17/2011	7/25/2011	5.95	0.42	0.61
8/19/2011	9/1/2011	2.22	0.34	0.13
9/5/2011	9/9/2011	2.83	1.18	0.33
Bottom				
6/25/2011	7/3/2011	2.89	0.25	0.29
7/17/2011	7/25/2011	0.89	0.22	0.07
8/19/2011	9/1/2011	3.05	2.21	0.06

4.2.2 Phytoplankton bloom mechanism

A number of factors including availability of nutrients and sunlight influenced the occurrence of phytoplankton blooms. There were five major phytoplankton blooms (defined as the period with Chlorophyll-a concentrations exceed 60 $\mu\text{g/L}$) during the observation period denoted by period 1, 2, 3, 4 & 5 in Figure 4.3H, Figure 4.4G and Figure 4.5G. The onset of bloom were strongly influenced by the availability of light ($>10 \text{ MJ/m}^2/\text{day}$), continuous south wind $>6 \text{ m/s}$ and discharge events while the ends were influenced by different factors such as north wind, light limitation and water column stratification.

Phytoplankton bloom 1 at the outer part of the estuary (station 1) was developed due to the transport of high chlorophyll-a concentration water from the bay to estuary induced by southerly wind (wind speed $>8 \text{ m/s}$) with light attenuation when water temperature increased and salinity decreased gradually (Figure 4.23). During this period tidal elevation, along river current velocity, current vectors and river discharge were well corresponded at times when ebb tide (during spring tide) occurred, maximum along river velocity was found during ebb tidal phase of spring tide and the velocity time series and vectors diagram were shown to be positive indicating downstream movement in most of the time between 3-7 June. This kind of current movement pattern during ebb tidal phase can force to accumulate high chlorophyll-a water at station 1 and this bloom was terminated by light limitation and onset of north wind.

In contrast, Figure 4.24, 4.28 and 4.31 show that phytoplankton bloom 2 was developed at the outer part (station 1) and inner part (station 2 and 3) of the estuary between 19-24 June with active light attenuation affected by southerly wind during periods of spring tide with flooding and ebb tidal phase where ebb tidal phase was much stronger than the flooding phase indicates along channel currents and currents vectors mostly directed to downstream (positive currents) dominated by river discharge input from the upstream which were the source of phytoplankton source. At the time of bloom 2, water temperature steadily increased and salinity decreased gradually with strong solar radiation and southerly wind. It was also terminated by light limitation, decrease in discharge affected by north wind, breakdown of stratification and change of current pattern.

Phytoplankton bloom 3 was generated at the three stations between 16-20 July (Figure 4.25, Figure 4.29 and Figure 32) by the inflow of highest river discharge followed by a high rainfall events although there was light limitation during this period but due to the transportation of high

chlorophyll-a concentration water from the upstream to downstream by high discharge may contribute to the development of bloom 3 with a minimum differences in surface and bottom water temperature at time ebb tidal phase was much stronger and current pattern followed as that of the current pattern of the period of bloom 2 which correspond to downstream directed current resulting in active transport of upstream water to downstream and then it terminated rapidly affected by north wind and a maximum differences in surface and bottom water temperature and flow rate with uniform salinity followed by limited light availability.

Similarly Figure 4.26, 4.30 and 4.33 show that Phytoplankton bloom 4 was also generated at the three locations (station 1, station 2 and station 3) between 4-10 August by the active attenuation of light combined with continuous south wind and a gradual increase in water temperature. Both the flooding and ebbing tidal phase of along river currents associated with current direction were dominant during this period which could be observed from the fluctuations of the chlorophyll-a concentration time series and at this time bottom dissolved oxygen concentration at the inner part (station 2 and 3) were below the hypoxic level which meant that water column was not fully vertically mixed but high concentration of surface dissolved oxygen concentration could be observed at the outer and inner part at the same time corresponding well with the distribution of chlorophyll-a concentration. The elimination of this period was followed as of the previous periods of each bloom.

Phytoplankton bloom 5 was developed at the outer part of the estuary (station 1) between 15-20 August (Figure 4.27) with the minimal stratification associated with strong south wind and after 17 August of this period, chlorophyll-a concentration at this location exceeded 200 $\mu\text{g/l}$ which indicates high bloom during this period. In addition, it was occurred with the combination of rainfall events and discharge structures associated with mostly ebb tidal phase directed to downstream and it was soon broken down by the effect of northerly wind followed by low solar radiation, gradual decrease in water temperature and persistent stratification.

It is clear that regarding the mechanism of phytoplankton bloom around Sumida river estuary the highest concentration is always at the outer part (station 1) of estuary than that of inner part (station 2 and 3). Higher concentration of dissolved oxygen concentration could be observed at the outer part corresponding well with the distribution of chlorophyll-a concentration as because at the inner part of estuary correspond with low dissolved oxygen concentration with low chlorophyll-a concentration compared to outer part of the estuary. Observed chlorophyll-a

concentration showed that the phytoplankton biomass was concentrated more at the station 1 than those of station 2 and 3 as station 1 was more influenced by river water as well as sea water which are the dominant of source phytoplankton accumulation around the estuary. In another sense, there was a significant difference in chlorophyll-a concentration between station 2 and station 3 as a floating fence was positioned at the surface water which may restrict/hinder the horizontal transport of chlorophyll-a from station 2 towards station 3. Thus the highest concentration of chlorophyll-a was found at the outer part (station 1) and second highest concentration was observed at station 2 and the lowest concentration of chlorophyll-a was found at the station 3. The observed phytoplankton bloom exhibited with several environmental factors such as wind forcing, light availability and river discharge structures. During summer, chlorophyll-a transport to the Sumida river estuary was dominated by river discharge input from the upstream. High chlorophyll-a concentration of <15 psu salinity in water indicates a fresh water origin. During ebb tides, high-flow periods with minimal salinity intrusion within the estuary, fresh water phytoplankton can be transported directly to the Sumida river estuary.

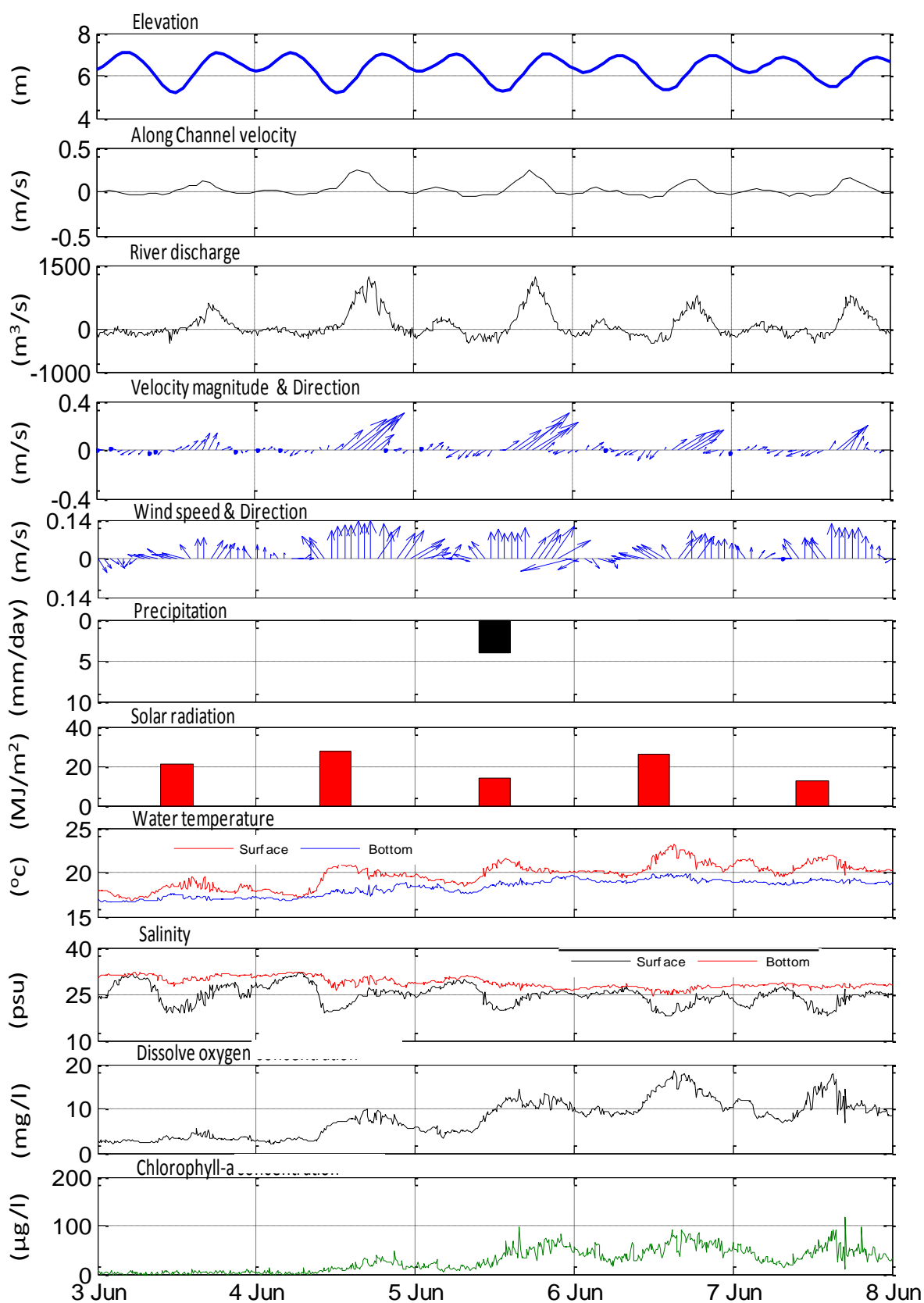


Fig.4.23 Phytoplankton bloom 1 during 3-7 June at the outer part of Odaiba (Station 1)

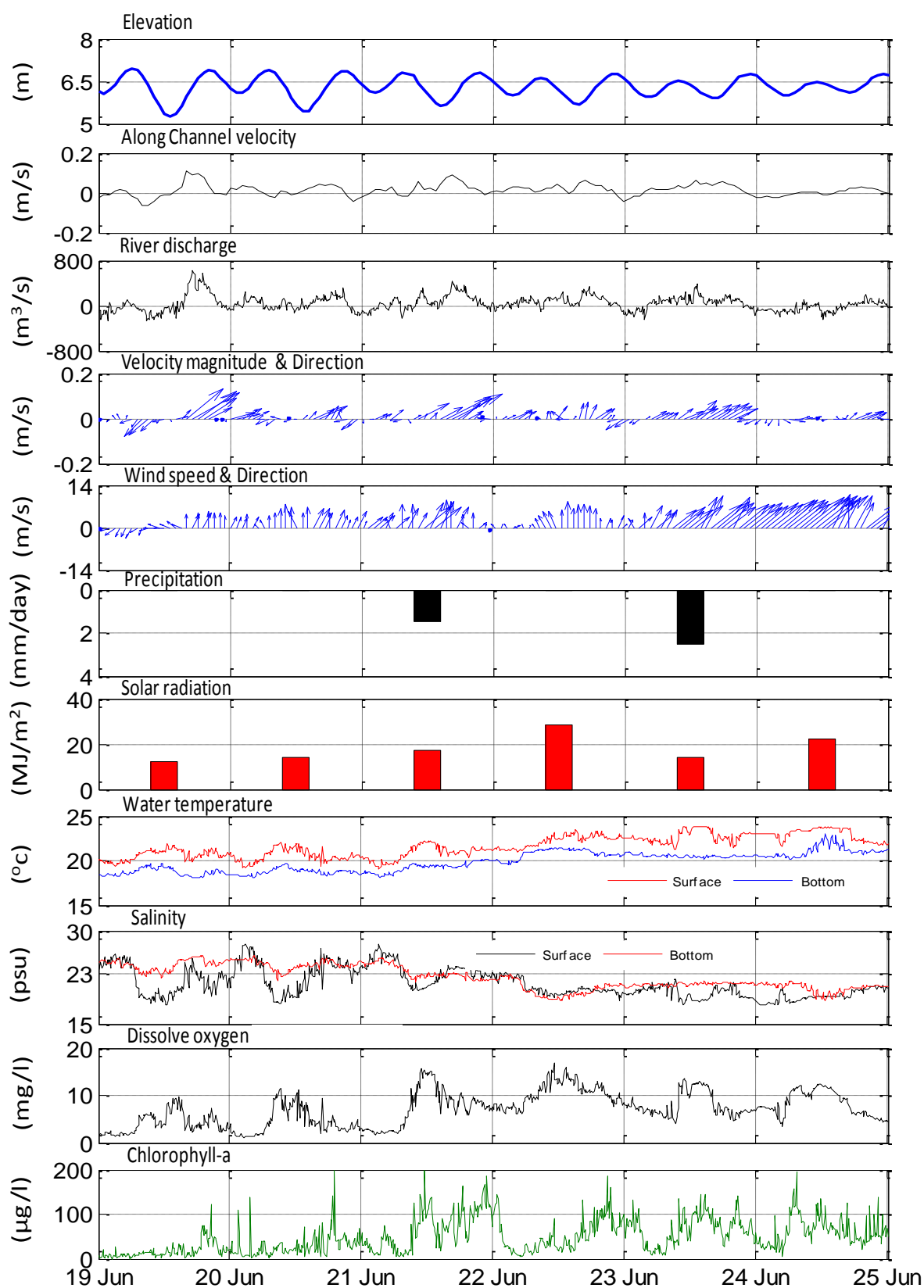


Fig.4.24 Phytoplankton bloom 2 during 19-24 June at the outer part of Odaiba (Station 1)

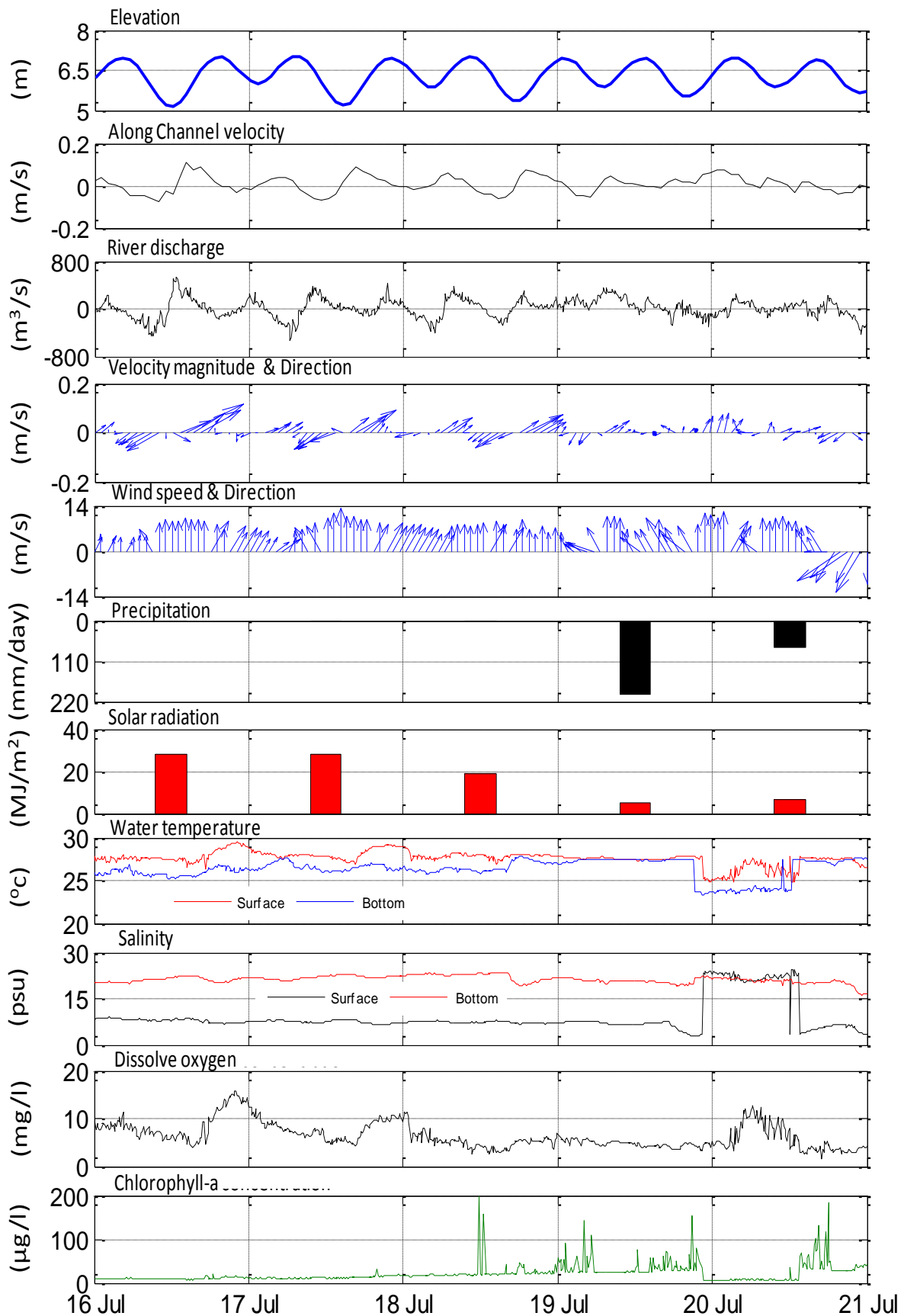


Fig.4.25 Phytoplankton bloom 3 during 16-20 July at the outer part of Odaiba (Station 1)

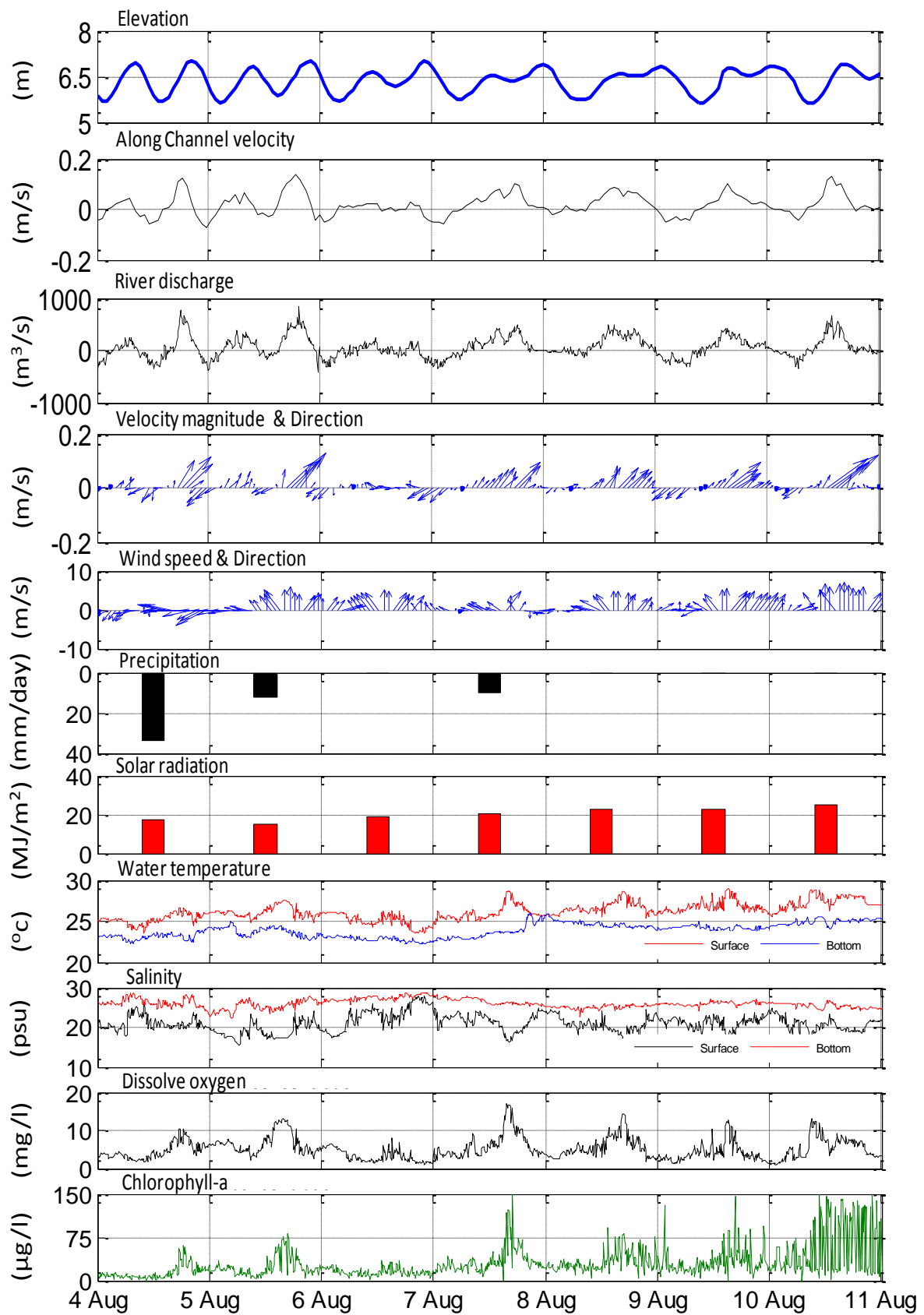


Fig.4.26 Phytoplankton bloom 4 during 4-10 August at the outer part of Odaiba (Station 1)

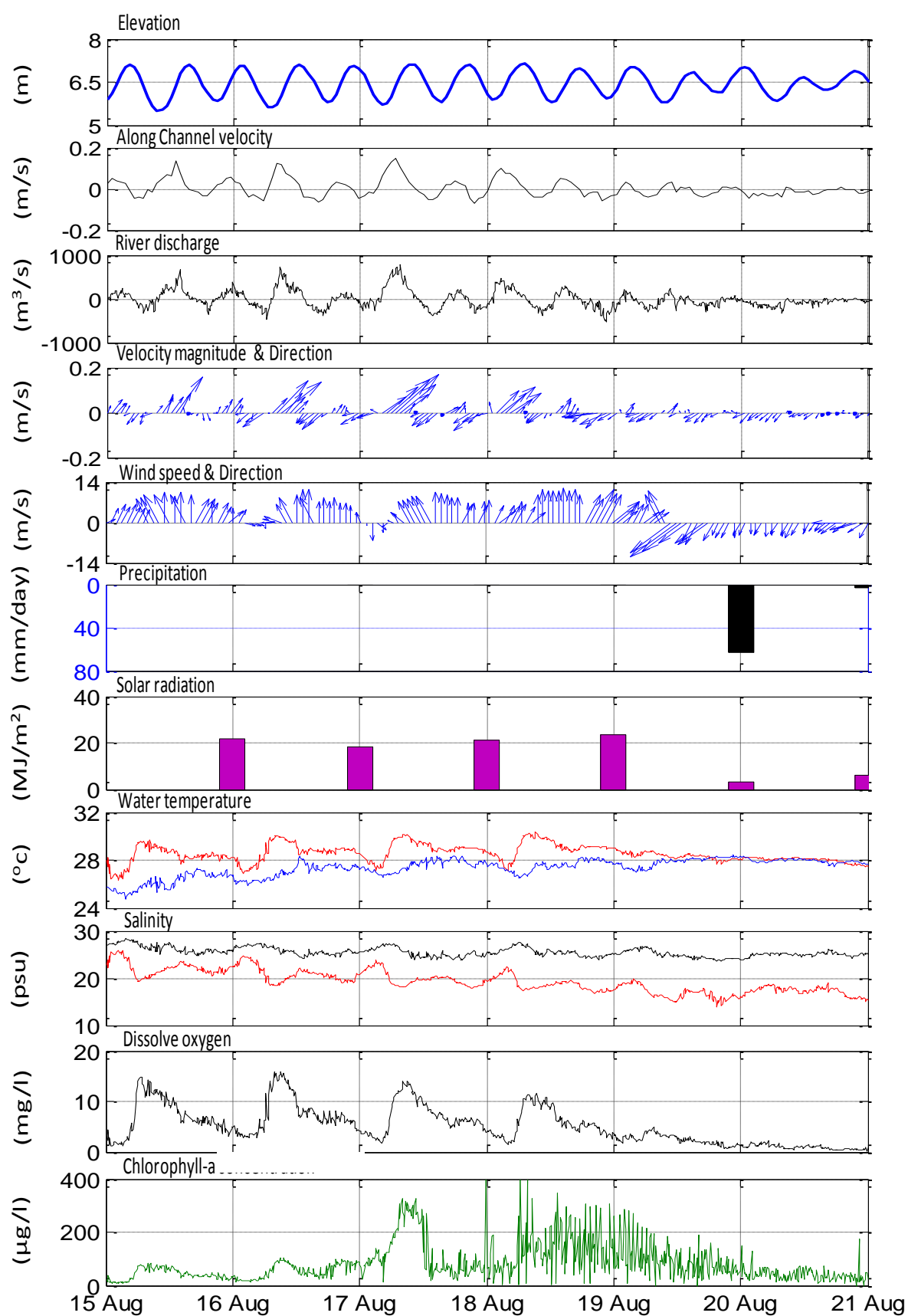


Fig.4.27. Phytoplankton bloom 5 during 15-21 August at the outer part of Odaiba (Station 1)

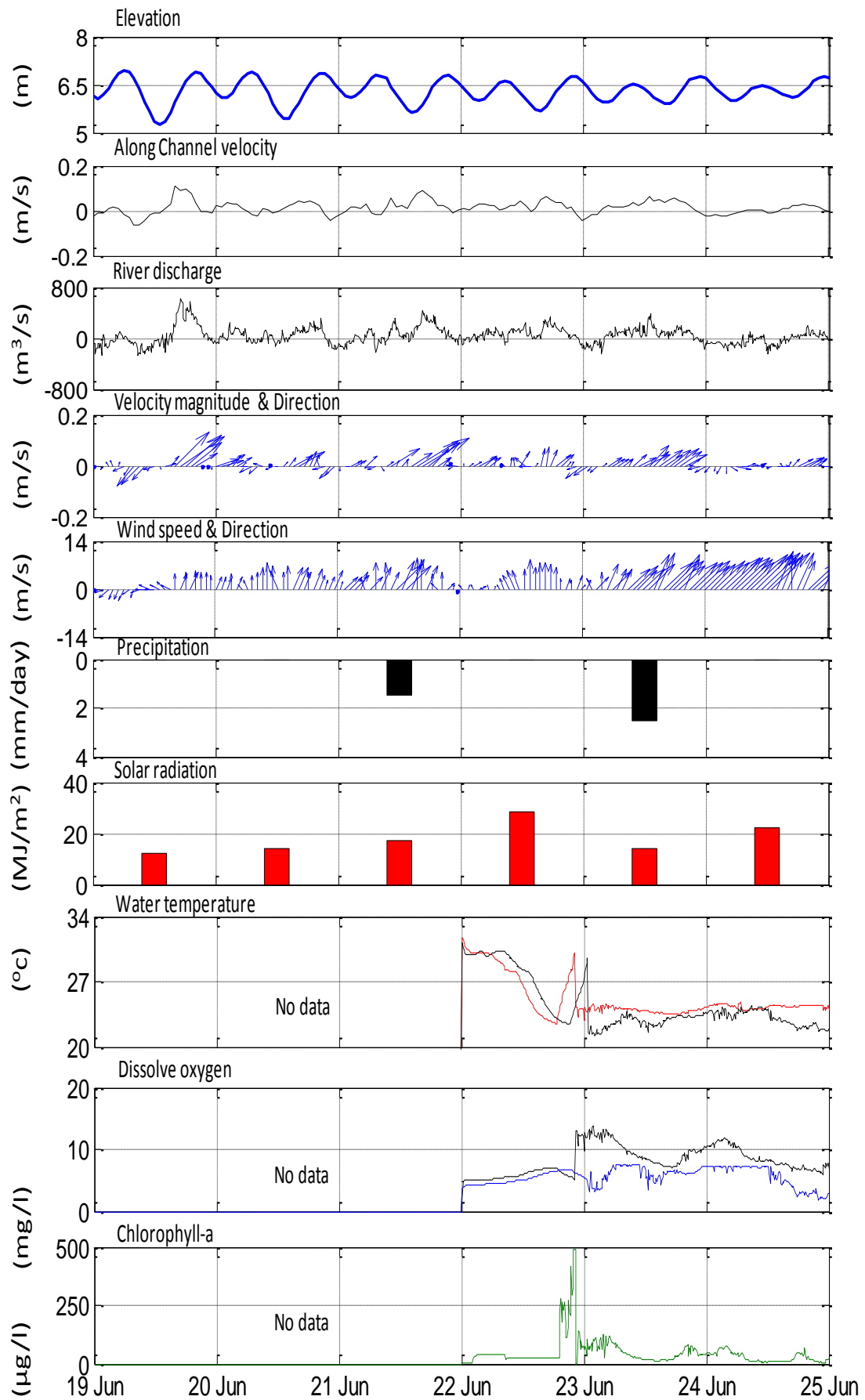


Fig.4.28 Phytoplankton bloom 1 during 19-24 June at the inner part of Odaiba (Station 2)

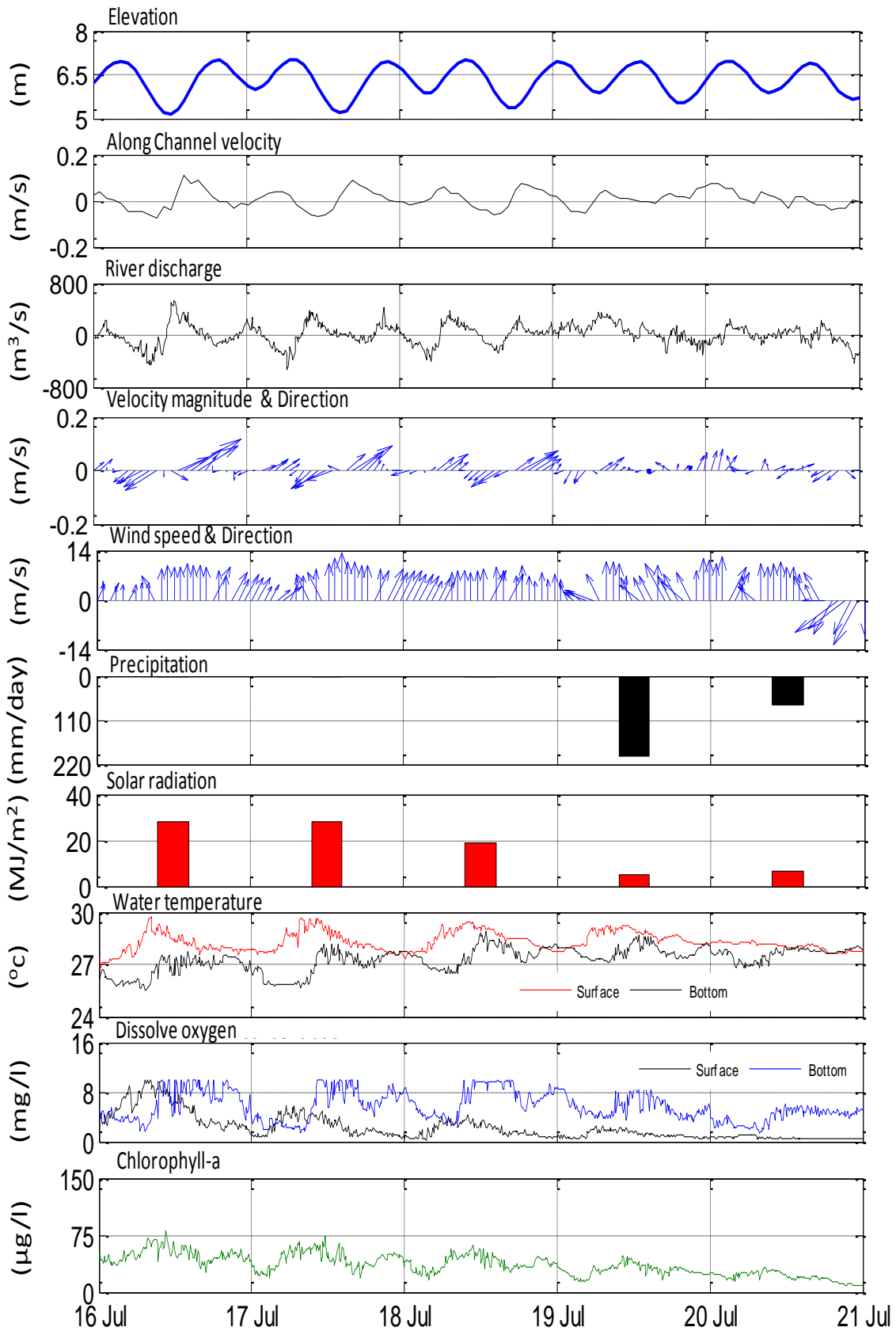


Fig.4.29 Phytoplankton bloom 2 during 16-20 July at the inner part of Odaiba (Station 2)

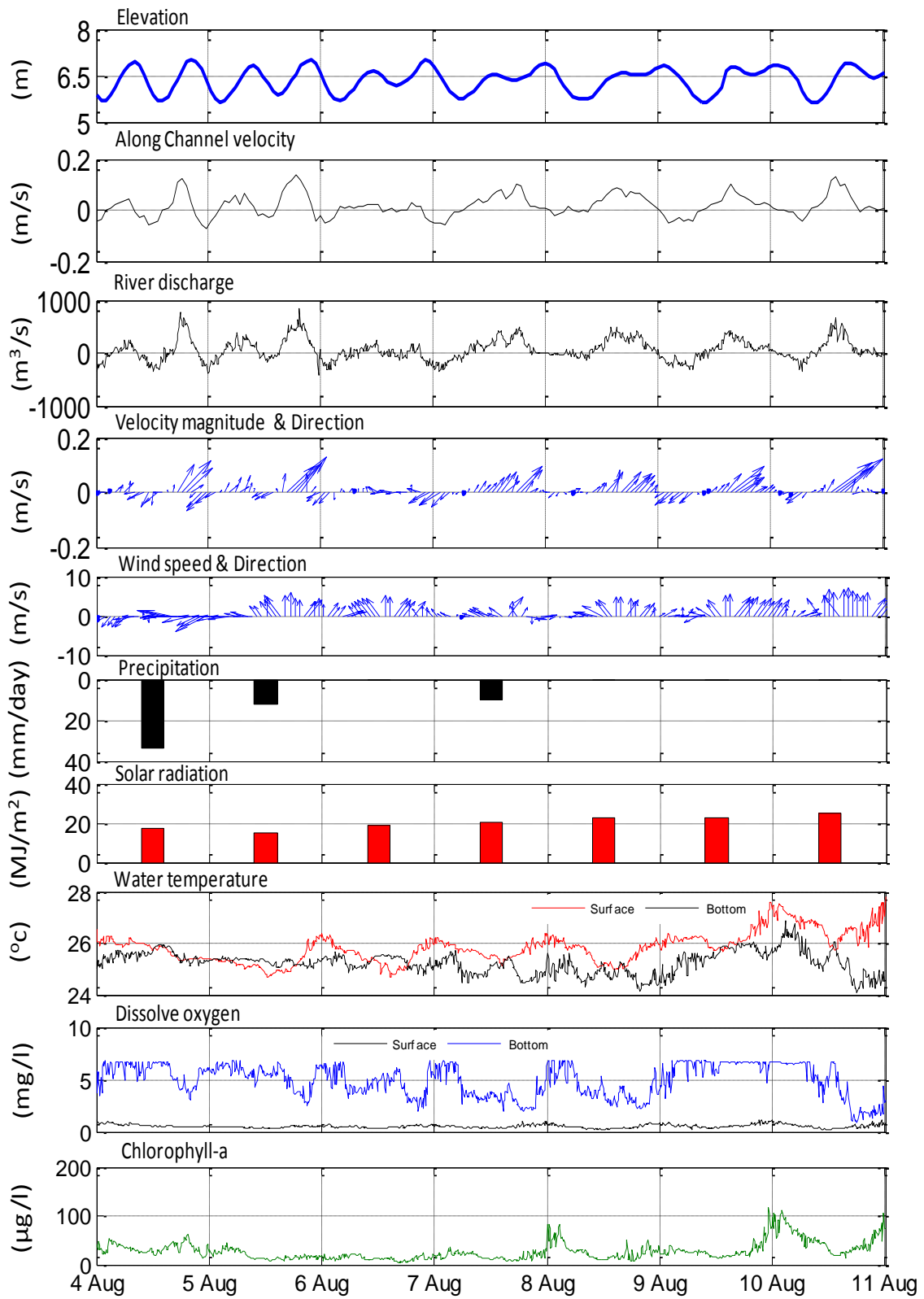


Fig.4.30 Phytoplankton bloom 3 during 4-10 August at the inner part of Odaiba (Station 2)

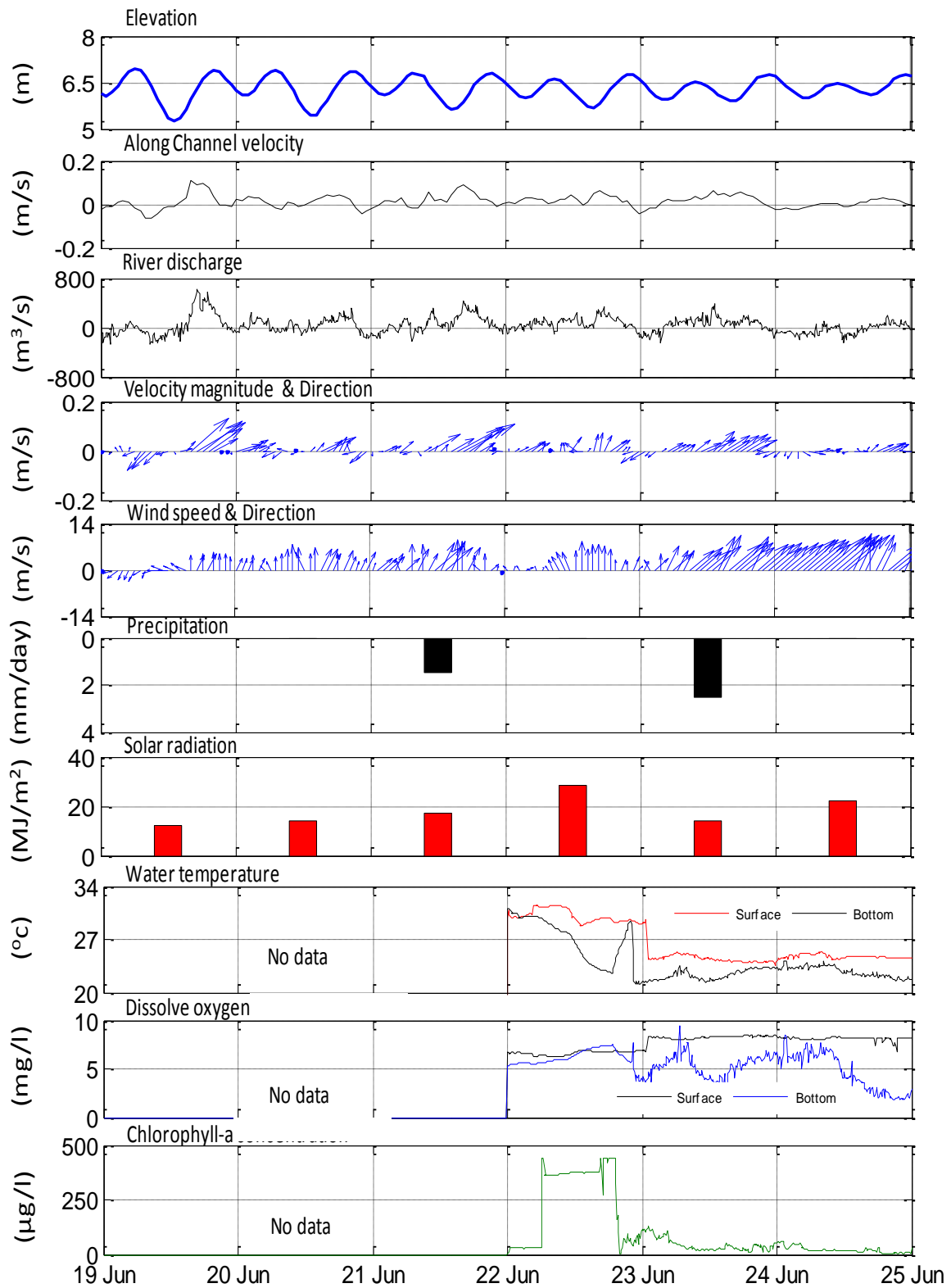


Fig.4.31 Phytoplankton bloom 1 during 19-24 June at the inner part of Odaiba (Station 3)

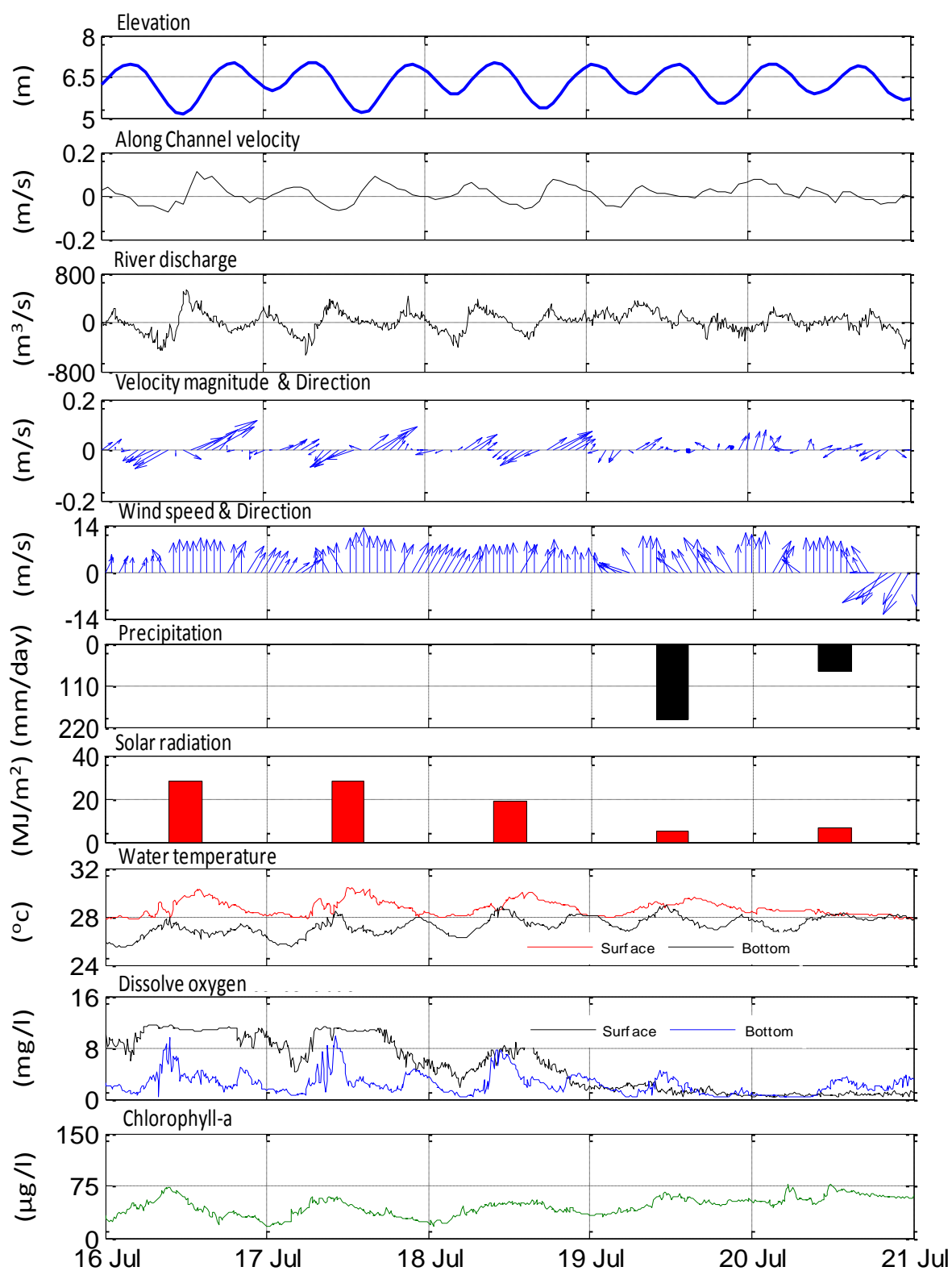


Fig.4.32 Phytoplankton bloom 2 during 16-20 July at the inner part of Odaiba (Station 3)

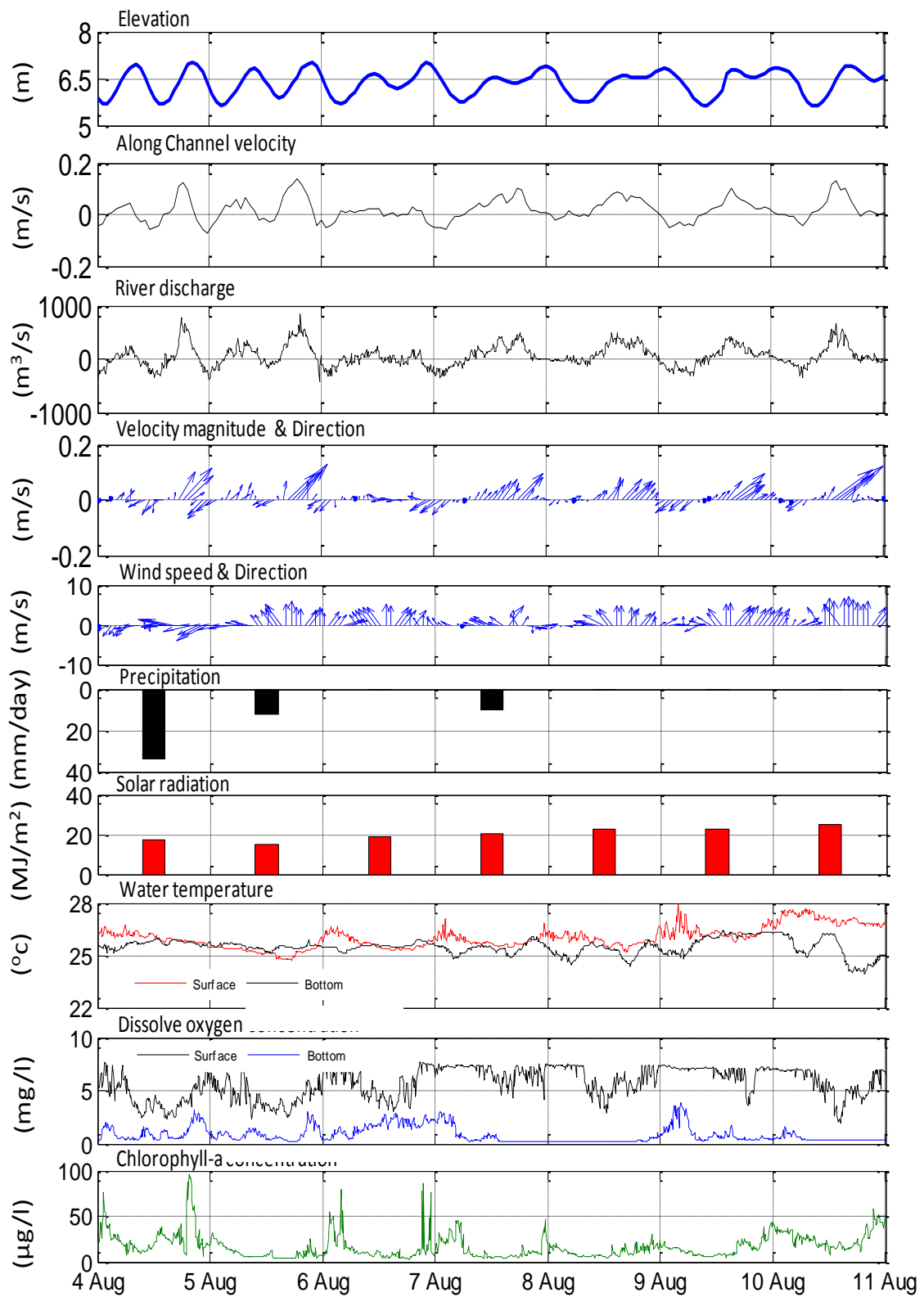


Fig.4.33 Phytoplankton bloom 3 during 4-10 August at the inner part of Odaiba (Station 3)

4.3.1 Tidal currents and across river distance

The tidal currents in the estuary are evident in the cycle of currents measured by the H-ADCP. Figure 4.34 shows the current cycles for the observation period throughout the cross section by along channel velocity components. The tidal cycle of ebb and flood phases is evident from the measured north-south components of velocities and water elevation as these velocity components are closer to the riverbed approximately 6-7 m below from the surface water level. The velocities near the bottom demonstrate that tides are predominantly semi-diurnal, with a tidal period close to 12 hours. The strength and clarity of the tidal cycle near the riverbed indicates the large effect of tidal action initiated bottom circulation.

At the beginning of observation period, the currents indicate much stronger during ebb tidal (positive) phase than the flood tidal phase (negative). This continues throughout the observation period until approximately 12 June. After this period an increase in fresh water flow causes extended period of positive currents. In connection with this, another positive current was dominated during the period of 26 June to 10 July and then again preceded by positive and negative currents from 12 July to 20 August. During this extended period, tidal cycle of ebb phases is more prominent than the tidal phases. During 26 August to rest of the observation period shows some stronger currents, in both the positive and negative currents and during this period tidal elevation was stronger as well with some significant discharge events.

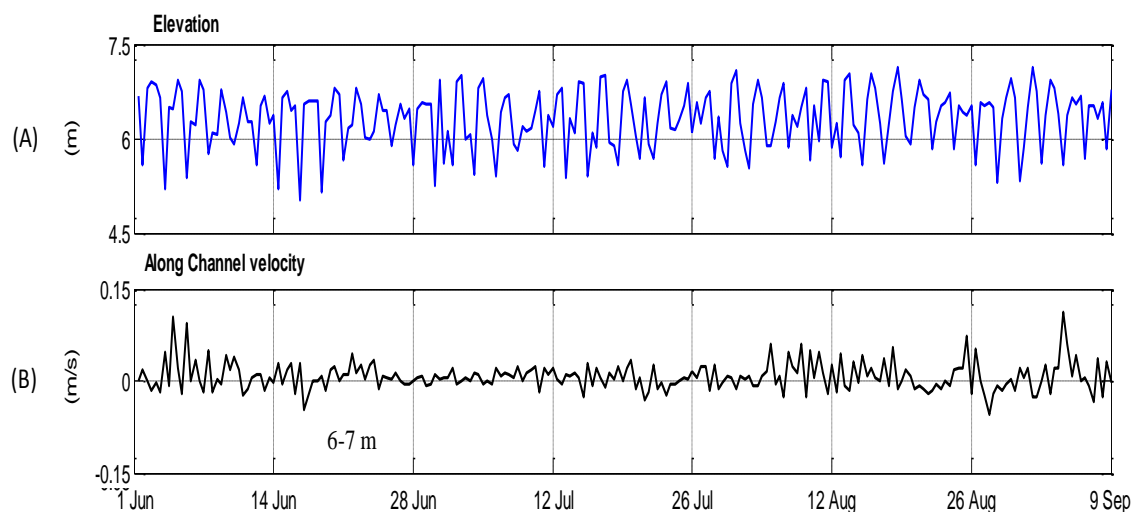


Fig.4.34 Current velocities parallel to the river channel, (A) Water elevation (B) Along channel velocity, Height above river bed are inset. Positive currents indicate downstream currents and negative upstream flow.

The measured along channel velocity component (north-south components) as seen in Figure 4.37 were plotted against the distance perpendicular to the river or distance along the cross section of the river to show the cycle of rise and fall of along channel velocity (north- south components) compared to across channel distance or range in the estuary. The total width of the channel is assumed to be 500 m but the acoustic beams from the H-ADCP was covered to 204 m distance along the cross section of the river. A 42 hours period of comparison is shown in Figure 4.35. The figure shows a clear correlation between the across channel distance starting from the left bank towards the right bank of the river but the beam range didn't reach to the right bank and as result along channel velocity could not be measured for the right bank of the river and north-south velocity components. It demonstrates that at the near bank of the river the along channel velocity was much positive except for the period between 18 hour to 24 hour that predominantly indicates the downstream flow (positive currents) and velocity magnitude was found to be higher at this distance (0-50 m) after 36 hours. At distance 50-100 m currents was found to be following towards upstream and positive currents that flows to downstream were dominant between 6 hours to 12 hours, 18 hour to 24 hours and 30 hour to 36 hours respectively. Similarly in between range 100-150 m, the positive currents followed the same pattern as those of range 50-100 m. At this distance, positive currents/downstream currents were much higher around 150 mm/s between hours of 12 to 18 and 36 to 42 respectively indicating a flood phase. A similar phenomenon was found at distance of 150 to 200 m at times flooding phase (upstream flow) was more evident than that of ebbing phase. As expected, more flooding and ebbing phase were observed from distance 50 to 150 m and the current velocities are shown to be stronger and much more clearly represented at the middle of the river, possibly due to strong tidal cycle, indicating movement upstream and downstream at the same time.

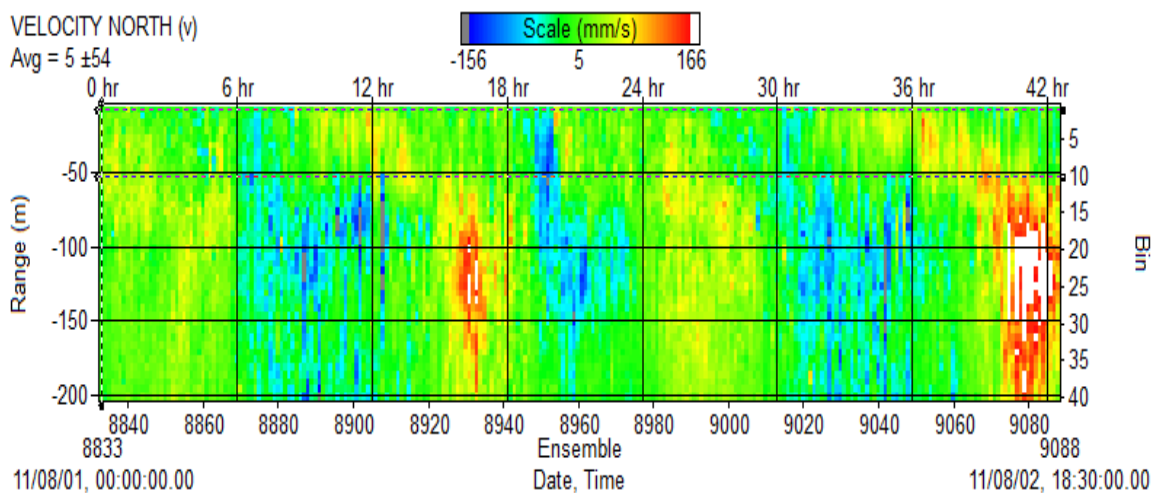


Fig.4.35 Comparison between measured currents with across channel distance.

4.3.2 Tidal circulation

Figure 4.36 shows the along river current velocity amplitude and vector diagram as a function of time and across river distance. For comparison purposes, the time series of semidiurnal tidal elevation together with winds and river flow have also been plotted. Along channel peak velocities occurred at the end of the ebb, when the combined discharge and tidal water exit in the estuary. Minimum velocities occurred at slash high tide, when incoming tidal water balances outgoing river discharges. During spring tide, along channel current speed were <0.05 m/s, but in neap tides they were upto three times higher. Regardless of tidal phase, the maximum currents over the lunar months coincided with the occurrence of tidal oscillations. Maximum current speeds were upto 0.1 m/s and occurred just prior to the water level maximum on day 4 June. A similar feature of elevated current speed with smaller magnitude (0.01 m/s), occurred from days September 5-6 and preceded a water level decrease of 0.35 m. 10 hours averaged stick vectors of a current velocity (Figure 4.36D) indicates the variability of current speed and direction.

In Sumida river estuary area (Odaiba), the maximum currents flew northward and seaward with a peak velocity of 0.12 m/s. A large along channel flow was observed at the Odaiba peer with a north-south velocity of less than 0.1 m/s. Current oscillations with a period of 2-3 days were prominent features in the current along channel time series (Figure 4.36C). Meteorological variability such as wind speed and direction explained overall variance for the north-south velocity component. In addition, the vector diagram of current velocity indicates an overall ebb-directed flow towards the southwest along the estuarine axis and at times the net flow was flood-directed towards the northeast along the

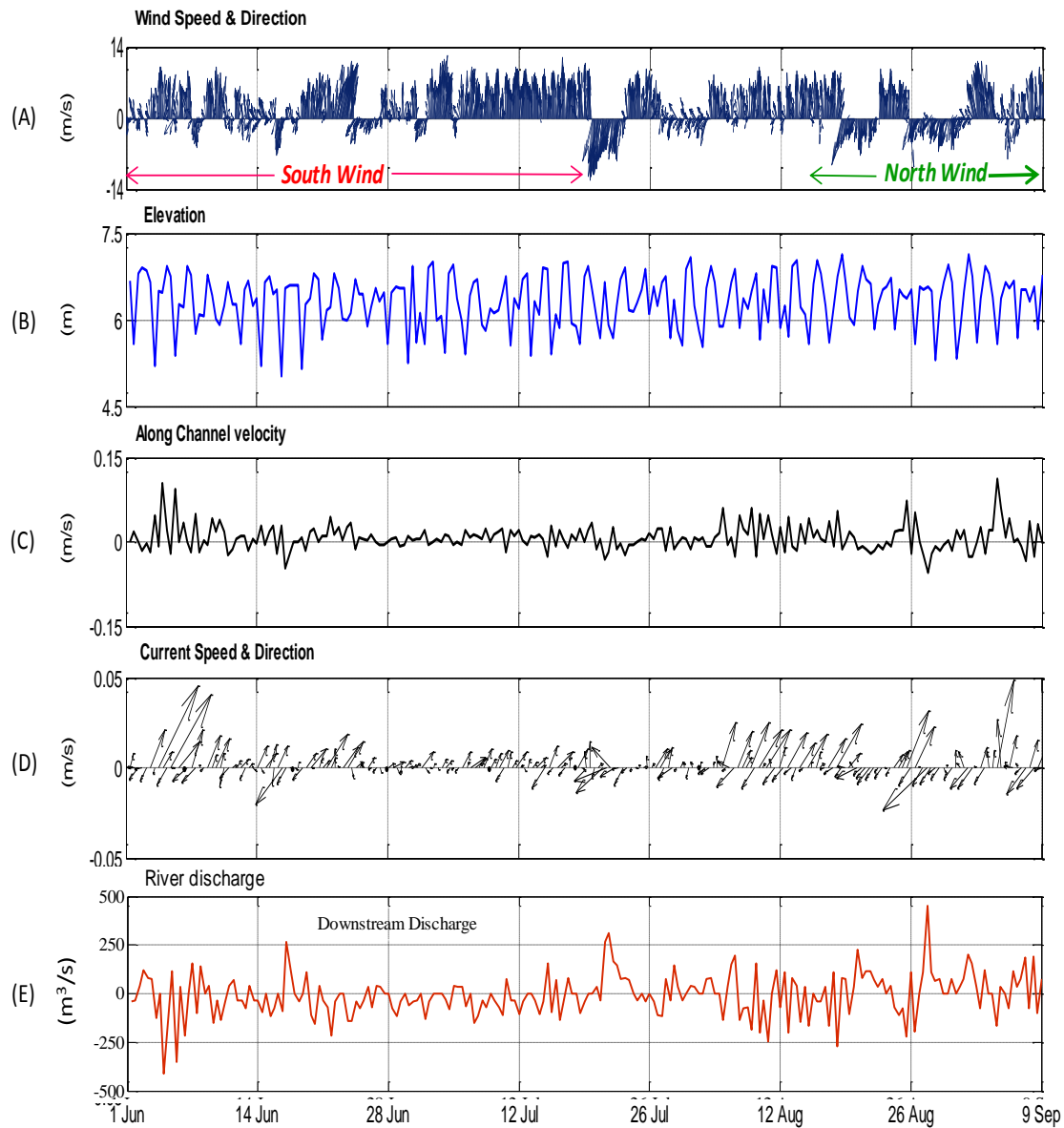


Fig.4.36 Relationship between (A) Wind velocity and direction (B) Water elevation (C) 12 hrs averaged along channel flow velocity and (D) Stick diagram for flow velocity and direction along the channel (E) River discharge during June to September 2011 showing the relationship of wind and flow pattern at Station 1. The location of Station 1 (Odaiba pier) is given in Figure 1. Positive values represent flow downstream and vice versa for negative values. Currents and wind speed are shown in m/s in this figure.

estuarine axis. Semidiurnal tidal amplitude at this point decreases with increasing river flow due downstream movement of water and interaction between tides and river flow. So, some decrease in tidal along river velocity amplitude (Figure 36C and Figure 36 E) with increasing river flow may be expected.

Around Sumida river estuary, circulation modes varied from seaward and streamward flow at all distances during intermediate runoff conditions to weak gravitational circulation during rising and high discharge periods. In addition the overall intensity of net flow and circulation appeared to be controlled by the morphological features of the estuary. In Odaiba, the character of the inlet (deep ebb channel flanked by the marginal flood channels) resulted in an ebb response. Additionally, high along river flows around this area indicated a transverse circulation mode influenced by topographic features. Thus Odaiba area appears to be an active tributary, maintained by river discharge and tidal flows, with characteristics features of tide dominated areas. Winds do not seem to have any major discernible role on the bottom velocity amplitude of the tidal flows. The overall hydrographic and environmental interrelationship with water quality parameters are depicted in Figure 4.37 according to the mechanism on the development and fate of phytoplankton bloom and hypoxic events as can be seen in Figure 4.12 to 4.22 and Figure 4.23 to 4.33.

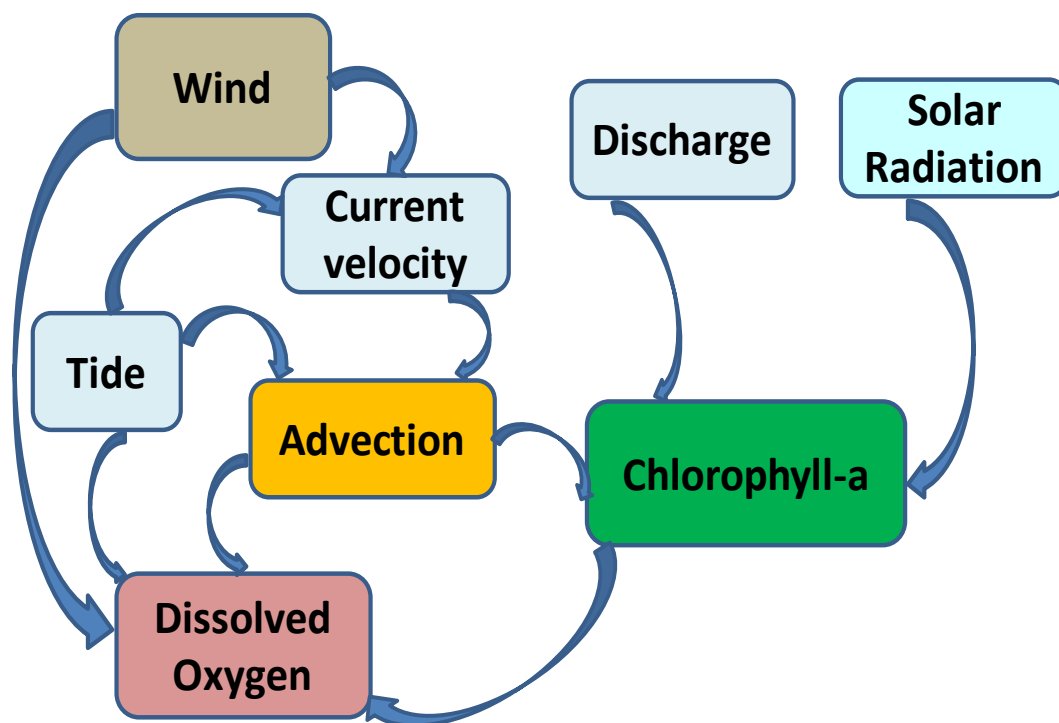


Fig.4.37 Conceptual diagram for environmental & hydrographic factors most influence hypoxia and phytoplankton bloom as well as water circulation in the estuary.

CHAPTER 5: DISCUSSION

5.1 Solar radiation

Solar radiation was an important factor on the occurrence of phytoplankton bloom because light availability directly impacts photosynthesis rates and the balance between oxygen production and consumption via respiration. Most hypoxic events in the Sumida river estuary followed cloudy days when photosynthesis was lower than normal and similarly most phytoplankton bloom developed during high solar radiation (Figure 4.3, 4.4 and 4.5), similar to the findings of D'Avanzo and Kremer (1994), Pokavanich et al., 2009 and Koibuchi and Isobe (2007). In these cases, it is likely that photosynthetic oxygen production could not keep pace with cellular respiration and hypoxia resulted and high solar radiation induced high photosynthetic rate resulting in phytoplankton bloom.

5.2 Freshwater discharge

In addition to setting up halocline vertical stratification, freshwater discharge was crucial in stimulating heterotrophic conditions and hypoxia in the Sumida river estuary (Figure.4.3CG, 4.4CF and 4.5CF). Similar relationships have been documented in other estuaries, especially in the upper reaches most influenced by freshwater discharge (Stanley and Nixon, 1992), which contributes terrigenous organic matter for oxygen consumption (Russell et al., 2006). In the Sumida river estuary, the most severe hypoxic event that began on August 19, 2011, the same day there was a high rainfall event of 70 mm with discharge of $200 \text{ m}^3/\text{s}$ resulting in pronounced hypoxia. Another hypoxic event occurred at the onset of high river discharge of $>600 \text{ m}^3/\text{s}$ during the study period.

5.3 Tidal forcing

Tides were a principal source of ventilation of near-bottom water in the Sumida river estuary. Spring tides eroded vertical stratification; during neap tides, the residence time of near-bottom waters increased, hindering oxygen transport to bottom layer and increasing the chance of hypoxia. This pattern is typical of small estuaries with intensive tidal mixing (e.g., Melrose et al., 2007; Park et al., 2007). However, the influence of tides on stratification was not consistent: tidal range was different with stratification, where stratification was consistently high and independent of tides due to sustained freshwater discharge (Figure.4.3, Figure 4.4 and Figure 4.5). Also, stratification in the estuary increased during periods of elevated tidal level when

horizontal tidal flows transported sea water to the bottom layer enhancing haline stratification around this area.

The effect of the tides becomes clearer close to the riverbed (Figure 4.34A). At a height of 1 m above the river bed, the tidal cycle of spring and neap tides has become clear, and is similar at the bed. In these plots the maximum velocities are not as large as would be near the surface, and there appears to be a greater symmetry between flood and ebb phases.

The plots of currents in the along-river direction show, to some extent, a similar cycle (Figure 4.34B). The velocity range at all range or distance is not similar, and again the cycle is much clearer near the river bank. At the river bank there is less of a cycle than in the distance across increased, which is to be expected. Local winds and the effect of low tidal range may influence the along-river currents (Figure 4.35 and 4.36)

Figure 4.35 shows the current cycles for the observation period throughout the cross section by along channel velocity components. At the beginning of observation period, the currents indicate much stronger ebb (positive) phase than the flood (negative). Negative and positive currents were preceded due to the discharge and tidal effect.

The measured along channel velocity component (north-south components) were plotted against the distance perpendicular to the river or distance along the cross section of the river to show the cycle of rise and fall of along channel velocity (north- south components) compared to across channel distance or range in the estuary. As expected, more flooding and ebbing phase were observed from distance 50 to 150 m and the current velocities are shown to be stronger and much more clearly represented at the middle of the channel, possibly due to strong tidal cycle, indicating movement upstream and downstream at the same time.

The time series of along river velocity (Figure 4.36) shows that at the time of high discharge the current velocity shows the stronger velocity and weak during low discharge. Along channel peak velocities occurred at the end of the ebb, when the combined discharge and tidal water exit in the estuary. Minimum velocities occurred high tide, when incoming tidal water balances outgoing water discharges. The vector diagram of current velocity indicates an overall ebb-directed flow towards the southwest along the estuarine axis (Figure 4.36) and at times the net flow was flood-directed towards the northeast along the estuarine axis.

However, in connection with the present study results, previous studies has pointed out on along channel velocity patterns in many estuaries and bays and they mostly focused on the vertical

velocity profile to show relationship with water quality pattern as well as estuarine circulation pattern (Hunt, T., 2003, Yanagi et al., 2003 and Pokavanich et al., 2008). But the relationship between along river current velocity with the water quality in an estuary like Odaiba in Tokyo Bay has not been studied in the previous time. In that sense, this study results regarding aforementioned is a new observation results.

5.4 Wind forcing

The influence of wind on stratification and DO dynamics in the Sumida river estuary was quite significant. There are three possible explanations for this. First, wind speed and direction play an important role in the estuaries where tidal range is small (Geyer, 1997; Borsuk et al., 2001); in the Sumida river estuary, the tidal range was important and tidal mixing significantly correspond with the influence of wind. Second, the estuary is long, narrow, and wind by surrounding topography. Third, the influence of wind on subsurface oxygen balance was significant. Strong winds can induce sediment resuspension and turbidity in the water column, resulting in low DO (Reyes and Merino, 1991; Lawson et al., 2007). The continuous south wind in this area induced to accumulate phytoplankton resulting in phytoplankton bloom and at the same time north wind initiated hypoxic events around this area.

The prevailing wind play a key role to govern the water circulation in Tokyo Bay has been pointed out extensively in the previous studies (Yagi et al., 2008; Pokavanich et al., 2009). The general wind governing water circulation in this area is described as follows. The south wind results in reversed estuarine circulation where the surface currents flow toward the bay-head and subsurface currents flow toward the bay-mouth. This causes accumulation of coastal water around the bay-head region. In contrast, the north wind enhances the estuarine circulation that the coastal water flow out of the bay in the surface and the sea water flow into the bay underneath. This attributes are consistent and correspond with present study results where phytoplankton bloom and hypoxic events were driven by wind events. Figure 4.15 and Figure 4.25 show as example from the present study similar patterns in case of hypoxia and phytoplankton blooms. It was seen that, in general, south wind cause the accumulation of freshwater from the upstream to estuary mouth by the downstream directed currents. The compensation currents flow in the surface layer. As a result, the water column becomes less stratified in period of prevailing south wind which induced to accumulation of phytoplankton biomass around the estuary region. In contrast, prevailing north wind can strengthen the stratification in water column induced hypoxic events. It also enhanced the estuarine circulation, in which surface flows towards upstream. This kind of circulation can draw the lower

temperature and higher salinity. Although, this kind of pattern on estuarine circulation by prevailing wind has been studied by previous studies in Tokyo Bay, the present studies focused not only on estuarine circulation but also on bloom and hypoxic events are taken into consideration to explain the whole phenomena in relation to current velocity and other water quality properties.

5.5 Salinity and Temperature

Figure 4.3EF, 4.4E and 4.5E show the time series of observed water temperature and salinity at the depth close to the water surface and close to bottom from station 1, 2 and 3 respectively. It was seen that the water column was stratified since the beginning of June when the water temperature and salinity were most deviated. This kind of water quality pattern was also found in the previous studies conducted in the Tokyo bay and Tama river estuary (Pokavanich et al., 2009). Salinity in the Sumida River estuary is seen to decrease with the input of river discharge. This is consistent with previous knowledge of estuarine circulation, and that to be expected. Downstream, bay water increases salinity, and upstream salinity is lowered by freshwater discharge. There appears to be little transfer of momentum to cause mixing between isohalines, shown by the time series in figure. Low salinity water was shown to occupy the surface waters of the estuary. This salinity increases in the bottom layer, demonstrating a vertical salinity gradient. As shown in figure, the river discharge increased before the day of observation, producing a lower salinity level at the surface. The effect of the increase indicates that larger river discharges may greatly alter the salinity of the estuary.

Salinity below the surface layer appears relatively constant at the outer part of estuary (station 1), with a range of approximately 18-30 psu. The salinity below 2 m is almost entirely above 25 psu. The high salinity indicates the extent of tidal influence in the estuary, with bay water increasing salinity through the entire estuary over summer.

The water body receives large inputs of solar radiation during the day, heating the surface layer, with a small amount of this heat reaching the intermediate or bottom depth. During the night, via evaporative cooling, the surface of the water body cools, resulting in instability in the surface layer. The layer overturns, causing mixing above the thermocline. The intermediate or bottom layers remain unmixed, and continue to increase in temperature throughout the summer period. Figure 4.6, 4.7 and 4.8 show the temperature fluctuation during the study period where surface temperature exhibits the higher value at all the stations except some periods on 19-20

July, 1-3 September at station 1, 19-20 July, 16 August to 3 September at station 2 and 3 when bottom temperature exceeds the surface temperature due to surface cooling and the longer period corresponds with the intrusion of cool bay water. This kind of temperature fluctuation was also observed in the Blackwood river estuary, Australia and Tokyo Bay (Hunt, T., 2003 and Asad, 2006).

In case of water temperature, the outer part (station 1) of the estuary shows a moderate temperature fluctuation in both water columns. In the summer period high temperature water was transported to the estuary resulting in the increase of temperature throughout the area. The time series of water temperature (Figure 4.3) at outer part (station 1) revealed that during times of high discharge and ebb tide, water temperature in the upper and lower layer were separated resulting in the thermal stratification and conversely at time of spring tide, cool water were transported from the bay area to the estuary with high saline water resulting in vertical mixing in the surface and bottom layer of the water column. On the other hand, the inner part (station 2 and 3), the thermal stratification (Figure 4.4 and 4.5) was more pronounced and persistent in comparison to the outer part where the river discharge influence was less than that of outer part resulting in stronger stratification in the inner part of the estuary.

Masaya et al. (1999) found that during the summer condition of 1991 all water in Odaiba (Sumida River estuary) salinity was 29-30 throughout the year with lower salinities (<26 psu) in the stratified seasons. Surface temperature was also found $>25^{\circ}\text{C}$ from late August to early September and the difference between surface and bottom temperature was $2.1-6^{\circ}\text{C}$ in the stratified season (June to September). The Sumida River exhibited a similar temperature-salinity gradient and salinity below the halocline approximately 30 ppt. The salinity conditions of the estuary during the summer period are therefore found to be very similar from the time series during this present study. The temperature/salinity time series for the Sumida River shows the presence of the different water bodies influencing the estuary. From the temperature time series, it appears that temperature of the water body is the cause of stratification during summer.

5.6 Chlorophyll-a concentration

Observed spatial distribution of chlorophyll-a is given in Figure 4.11. Chlorophyll-a distribution showed that the phytoplankton biomass were concentrated only to the depth near water surface. The highest concentration is always at the water surface and at the outer part of estuary than that of inner part. Higher concentration of dissolved oxygen concentration could be observed at the outer part corresponding well with the distribution of chlorophyll-a concentration as because at the inner part of estuary correspond with low dissolved oxygen concentration with low

chlorophyll-a concentration in comparison to outer part of the estuary (Figure 4.10 and 4.11). Observed chlorophyll-a concentration showed that the phytoplankton biomass was concentrated more at the station 1 than those of station 2 and 3 as station 1 was more influenced by river water and sea water which are the dominant of source phytoplankton accumulation. In the other sense, there was a significant difference in chlorophyll-a concentration between station 2 and station 3 as a floating fence was positioned at the surface water which may restrict the horizontal transport of chlorophyll-a from station 2 towards station 3. This result due to floating fence in the surface water does not correspond with other previous studies with the phytoplankton biomass control in a particular water area. Thus the highest concentration of chlorophyll-a was found at the outer part (station 1) and second highest concentration was observed at station 2 and the lowest concentration of chlorophyll-a was found at the station 3. The observed phytoplankton bloom exhibited with several environmental factors such as wind forcing, light availability and river discharge structures. During summer, chlorophyll-a transport to the Sumida river estuary was dominated by river discharge input from the upstream. High chlorophyll-a concentration of <15 psu in water indicates a fresh water origin. The phytoplankton assemblage was not ascertained in this study. During ebb tides, high-flow periods with minimal salinity intrusion within the estuary, and neap periods of high stratification, fresh water phytoplankton could be transported directly to the Sumida river estuary. In Sumida river estuary, each and every phytoplankton bloom was developed in combination of south wind, discharge structure and high solar radiation and conversely each bloom was eliminated by the reverse mechanism. However, previous work has shown that fresh water diatoms dominate riverine phytoplankton dynamics based on salinity and velocity characteristics (Roegner et al., 2009) and this pattern is well reproduced in case of Sumida river estuary. In the other previous studies, chlorophyll-a concentration and nutrient concentration dynamic have strong diurnal variation and indicate several phytoplankton blooms (Chl.a conc. > 60 µg/L) those influenced by the dynamic of surface mixed-layer, light availability and transports by and wind-driven circulation in Tokyo Bay and Tama river estuary (Koibuchi and Isobe, 2007; Pokavanich et al., 2009).

5.7 Dissolve oxygen concentration

Low DO occurs naturally in subsurface or bottom waters of the Sumida river estuary system, but the origin of this source water can be from either the north or south of the estuary depending on the influence of large-scale climate factors on this area. Waters from the bay head appear to come primarily from the upstream directed currents. In case of dissolved oxygen concentration, the highest concentration in the subsurface layer was found at the outer part (station 1) of the

estuary than those of inner part (station 2 and 3) of the estuary during period of high bloom (Figure 4.10). In contrast, low concentration of dissolved oxygen was found at the inner part of estuary (station 2 and 3) than that of outer part (station 1) during periods of each and every hypoxic event (Figure 4.3G, 4.4 F and 4.5 F). During period of hypoxic events, the water column was found to be highly stratified followed by rainfall events and river discharge and water column ventilation was restricted to well mixed condition. Salinity and temperature stratification advected by tides was strongly related with bottom water dissolved oxygen in the summer season at the three stations simultaneously. This behavior is also prevalent in systems like the main stem of the Chesapeake Bay (Officer et al., 1984) and Mobile Bay (Turner et al., Schroeder and Wiseman, 1987).

Around this area, spatial heterogeneity of DO production and consumption in combination with tidal mixing resulted in complicated patterns of DO distribution in space and time that were not well predicted by simple analysis. Most, but not all hypoxic events were developed at the inner part (station 2 and 3), where bottom water waters were oxygen poor and surface water were oxygen rich. Ebb tidal flow (Figure 4.3B, 4.4B and 4.5B) transported waters from inner part that were sometimes oxygen rich (daytime) and sometimes oxygen poor (nighttime) towards outer part of estuary resulting in subsurface hypoxic condition at the outer part (station 1) where influence of river discharge (Figure 4.2) was high than that of inner part. Similar process have been observed in other estuarine systems where high photosynthetic and respiratory activity during high tide left a signal that was funneled back to the estuary during ebb tide (e.g., Cai et al., 1999; Sanderson and Taylor, 2003), but the present study found many factors other than previous studies in estuary in the development of hypoxia and phytoplankton bloom which have been attributed in the result section.

Most hypoxic events were developed at the three stations with the increase of discharge followed by precipitation, north wind, ebb tide directed to downstream, light limitation coincided with low solar radiation and breakdown of each hypoxic event followed the opposite hydrographic and environmental phenomena (Figure 4.3, 4.4 and 4.5). This characteristics are well related and with the light availability, nutrients and physical transport, tidal transport, wind related tidal circulation which correspond with the present study (Koibuchi and Isobe, 2007; Pokavanich et al., 2009; N.P. Nikolay et al., 2009)

CHAPTER 6: CONCLUSIONS

Understanding physical process of water properties is essential for successful management of water quality in estuaries. Conceptually, circulation in partially mixed estuaries is considered to be a balance between freshwater discharge, tidal forcing at the estuary mouth and forcing due to density stratification within the estuary. Results from this present study clearly indicated that Sumida river estuary owns complicated interaction between hydrodynamics and water quality process. The study demonstrates that the hydrographic and water quality characteristics around this area were likely affected by wind and the combined effect of wind and tidal circulation associated with river discharge. This particular process can transport warm, high chlorophyll-a concentration water from the upstream and lower concentration of dissolved oxygen water from the bay head to estuary region by tidal circulation particularly in the hypoxic and phytoplankton bloom events during the study period.

Moreover, in contrast with the previous conclusion of different studies in estuary, the present study found that changes in water temperature and salinity around this area could yield substantial changes in the physical system of the innermost part of Tokyo bay, Sumida river estuary. The stratification during summer months is temperature as well as salinity driven and similar to other estuaries in Tokyo bay. The salinity structure in the estuary was found to show sea influence as river discharge was low almost all the periods except some peak discharge events. As the discharge increases, it is thought that salinity and temperature structures would be drastically altered. It is found that the presence of vertical density gradient resulting for the salinity and temperature differences in the water column and input of freshwater at the river associated with local atmospheric conditions and results in gravitational circulation where bottom waters are directed upstream and surface water are directed towards the bay. Salinity stratification was strongly related with dissolved oxygen concentration during the observation period as an increase in stratification implied decrease in bottom DO toward hypoxic conditions. Salinities were found to be fall at the time of each hypoxic event. Hypoxic pattern were found to be also sensitive to wind speed and direction and was advected by tidal currents although river discharge followed by rainfall events induced hypoxia.

This observation found that during times of flooding phase, the along river current magnitude was found to be weak and lowest and during times of ebbing phase current magnitude was found to strong and highest. This response to the tidal circulation can occur either with or

without freshwater discharge. In general, peak velocities were noted at the end of ebb, when the river discharge and tidal discharge combine into one flow. A calculation of total discharge in the downstream of the river from H-ADCP measurements shows that the downstream discharge was approximately 2 times than that of river input from upstream at this time of year and the fresh water event in the early June was indistinguishable from the upstream discharge levels. Since the data from this study focus on the summer season, these conclusions do not necessarily apply to winter conditions, when river discharge is considerably lower. Higher input of freshwater would most likely induce an estuarine style of circulation with strong outflow on the surface and a subsequent return flow up estuary in the bottom, increasing vertical mixing in the water column.

Downstream directed along river currents could force to accumulate high chlorophyll-a concentration water around the estuary that caused several phytoplankton blooms during the summer observation period. Conversely, intrusion of salt water from the bay by tidal circulation of upstream directed currents can force to transport hypoxic water mass around this area rapidly with significant implications for water quality. The effects were intensified by the prevailing south wind that accumulated high concentration of chlorophyll-a water around the estuary and low dissolved oxygen water mass were developed at the onset of north wind associated with spring-neap tidal modulation that can enhance the estuarine circulation.

This study suggests that under the summer condition, the tidal circulation and river discharge were the dominant factors influencing circulation in the estuary. The study also showcases the importance of estuarine and coastal observations in understanding the physical processes in a highly dynamic system such as Sumida river estuary. A permanent network of observation stations allow to explore long term variability and at the same time identify interesting events (such as the prediction by numerical simulation by observed data) that can then be explored in greater scale. In addition comparative analysis of these hydrographic and water quality parameters considering the local environmental factors in several estuarine systems in Tokyo Bay and other regions nationwide and worldwide should help environmental scientists and decision makers in organizing estuarine monitoring, research and management.

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