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Influence of River Plume on Variability of Chlorophyll a Concentration using Satellite Images

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Abstract: Freshwater discharge from rivers into the ocean is an important element of the dynamics in coastal areas. River discharge from land that includes chlorophyll a, nutrients, sediments and pollutants have been identified as one of the major causes of deterioration of the coastal water. The objective of this study was to examine the relationship between river discharge and variability of chlorophyll a concentration in plume area using satellite imagery. Satellite ocean color and Sea Surface Temperature (SST) imagery were used to present the synoptic quantification of chlorophyll a variability on seasonal and interannual timescales for the plume area of Tokachi River, Japan. Five years (1998 to 2002) of SeaWiFS local area coverage, AVHRR imagery and surface wind were analyzed using default NASA coefficients and community-standard algorithms as implemented by SeaDAS. The chlorophyll a climatology seasonal pattern showed seasonal cycles, first peak in spring and second peak in late summer to early autumn. Elevated chlorophyll a concentration demonstrates seasonal cycles and interannual variability are present around plume area associated with variation of river discharge. Elevated chlorophyll a concentration in offshore area was seen to be influenced by low sea surface temperature and wind stress.

Key words: Interannual variability, offshore area, plume area, seasonal variation, SeaWiFS

INTRODUCTION

Coastal zone adjacent to river systems plays an important role in trade, agricultural, fisheries and tourism. At the same time, coastal zone are of extraordinary ecological value it is a transformer and sink for terrestrial nutrients and pollutants. River discharge from rivers into the coastal water is an important element of the dynamics of the continental shelves. River discharge includes not only freshwater, but includes nutrients, sediments, pollutants and other constituents (Higgins *et al*., 2006; Signoret *et al*., 2006; Wysocki *et al*., 2006; Kouame *et al*., 2009). These loading from the river discharge have been identified as one of the major causes of deterioration of the coastal water quality (Schernewski *et al*., 2001; Bay *et al*., 2003). Suspended material directly affects the water column and benthic processes such as phytoplankton productivity (Miller and McKee, 2004).

The plume region off the river mouth plays important role in shelf physical, biogeochemical and ecological functioning. Nutrient concentrations and nutrient ratios in the surface layers are influenced by the plume, thus impacting the lowest trophic levels. Freshwater input changes the stratification, and influences vertical nutrient flux and the light regime in the upper mixed layer controlling the phytoplankton growth (Smith and Demaster, 1996; Shipe *et al*., 2006). Vertical and horizontal transports of nutrient are also influenced by local circulation patterns associated with plumes (Thomas and Weatherbee, 2006).

The behavior of nutrients in plume area is usually considered as a process dominated by biological and degradational function. The ecological aspects of these water bodies are influence by the exchange between the continental shelf and the inner water (Sierra *et al*., 2002). These exchange dynamics are mainly controlled by three different forcing agents; atmospheric factors (wind and atmospheric pressure), marine factor (waves and mean-water level), and riverine factors (river discharge).

The extent of the influence of the discharge depends mainly on the river flow regime (Cravo *et al*., 2006). In areas where rivers are characterized by low discharge, episodic storms accompanied by periods of heavy rainfall, supplies large pulses of fresh water, suspended material

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and nutrient to the coastal zone (Cruzado *et al*., 2002; Perez *et al*., 2003). The impact of river discharge upon the coastal zone depends on the volume of discharge at seasonal and annual scales (Signoret *et al*., 2006). High flow of river discharge leads to an increase nutrient input and enhanced phytoplankton growth (Shah *et al*., 2008). The changing levels of freshwater discharge have marked implications on phytoplankton productivity and composition, as nutrients play a key role in controlling primary production (Cruzado and Velasquez, 1990; Cravo *et al*., 2006).

Understanding variations in the extent and dispersal of plume from the Tokachi River is important because the presence of plume will affect the marine ecosystem especially in limiting productivity due to the reduction in the photic depth, with important implications for coastal fisheries activities (Lihan *et al*., 2008). The objective of this study was to examine the relationship between river discharge and variability of chlorophyll a concentration in plume area using satellite imagery.

MATERIALS AND METHODS

Study area: The Tokachi region is bounded between latitude 42°09′ and 43°38′ N and longitude between 142°40′ and 144°02′ E is a representative agriculture production area in Japan. There is one main river system, the Tokachi River system (comprising 12 major rivers), that irrigates the agriculture area and flow into the western North Pacific Ocean at Otsu, the southeastern coast of Hokkaido Island, northern Japan (Fig. 1). The total catchment's area of this river system is 9010 km. Tokachi River with 156 km in length is the second largest river after Ishikari River (Le *et al*., 2006), originates at Mt. Tokachi-dake (2077 m) of the Taisetsu Mountain Range located in the middle of Hokkaido (Nagao *et al*., 2005). The Tokachi River flows through the broad Tokachi plain which includes old and new alluvial fans and stream terraces. Discharge of freshwater from the river flow to the coastal zone with flow volume of 7 billion tons per year, with average discharge of 233 $m^3 sec^{-1}$ from 1998 to 2002 measured at the Moiwa sampling station. River flow increases in spring and early fall due to snowmelt and an increase of precipitation, respectively (http://www.river.go.jp).

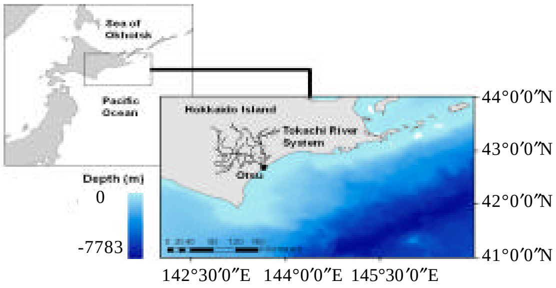

Fig. 1: The study area in the Eastern coast of Hokkaido Island, northern Japan, showing the Tokachi River System and bottom bathymetry (m)

Data: Combination of satellite remote sensing and ancillary data were used to determine the effects of Tokachi River plume. In this study two types of sensor were used to determine the effects of river plume. The satellite data used in this study are Sea-viewing Wide Field-of-View (SeaWiFS) and Advanced Very High Resolution Radiometer (AVHRR). A uniform spatial reference is required to accurately compare the spatial features in the data due to multi-sensor nature of this study. The coastline of the study region was used as a base map to which all other data were projected. In order to map the other data onto the coastline, the satellite data were projected with a cylindrical system identical using ArcGIS.

SeaWiFS data: Daily Level 1A SeaWiFS data intersecting the region 40°-45°N, 140°-150°E for the period of 1 January 1998 to 31 December 2002 were downloaded from the Goddard Distributed Active Archive Center (http://oceancolor.gsfc.nasa.gov/). A total of 488 cloud free images (82 images in 1998; 79 in 1999; 100 in 2000; 108 in 2001; 109 in 2002) were processed to Level 2 geophysical products using default NASA coefficients and community-standard algorithms as implemented by SeaDAS (version 5.0) and remapped to a cylindrical projection at 1.1 km resolution. Daily data were further composite into monthly means for chlorophyll a to study the variability of chlorophyll a concentration. The study area was subset from the images to geographic extents of 42°-43°N, 143°-145°E.

Sea surface temperature data: Sea Surface Temperature (SST) measurements from the NOAA satellites (AVHRR instruments) were collected by the satellite receiving station at the Hokkaido University. A total of 1734 AVHRR images with 1.1 km spatial resolution at nadir were collected from January 1998 to December 2002 (excluding October to December 2001). All daily SST images were navigated (i.e., corrected for distortion and registered to a map) and were nudged (i.e., the entire image shifting to fit map overlap) to correct for receiving system timing errors or satellite altitude errors. All AVHRR images were mapped to the cylindrical equidistant projection. Monthly composite images were formed by arithmetically averaging all available scenes in each month on a pixel by pixel basis (excluding missing data and clouds). The images were subset to geographic extents of study area.

***In situ* chlorophyll a data:** Chlorophyll α concentration off Tokachi region from 1998 to 2002 were downloaded from The Japan Oceanographic Data Center at their home page (http://www.jodc.go.jp) corresponding to the available date of satellite data. This data were used to match-up of concurrent in situ and satellite observations using daily satellite data.

River discharge data: A time series of daily Tokachi River discharge data from 1 January 1998 to 31 December 2002 was obtained from the River Environment Engineering Division, River Bureau, Ministry of Land, Infrastructure and Transport, Government of Japan.

Surface wind data: Wind data were downloaded from the Southeast Fisheries Science Center, NOAA Fisheries Service Environmental Research from their web site (www.las.pfeg.noaa.gov). These files contain regular grids of zonal and meridional wind speeds with 1° spatial resolution at 10 m above the earth surface. The zonal and meridional wind speeds were used to plot the vector winds. These components were transformed to wind stress, τ (kg m^{-1} sec^{-2}) using the equation of Nezlin and DiGiacomo (2005).

RESULTS

Episodic events: Validation of satellite data is important for interpreting satellite measurements. In this study,

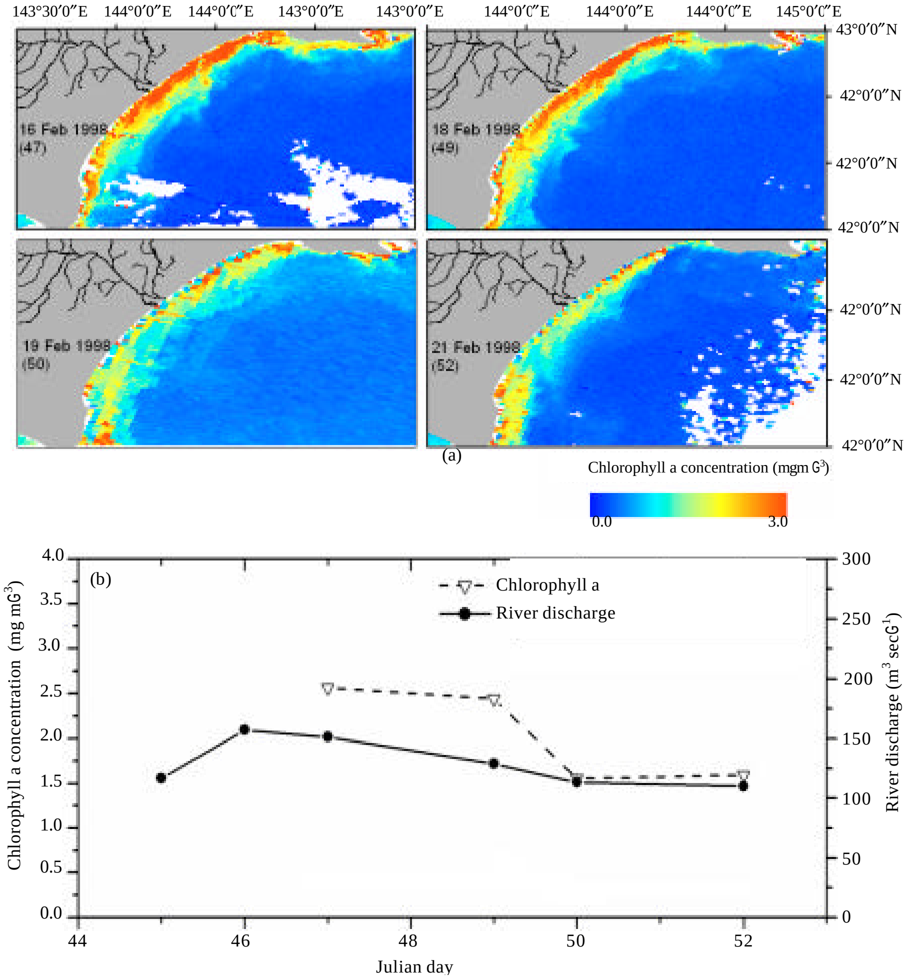

Fig. 2: (a) SeaWiFS daily images showing chlorophyll α distribution after large volume of river discharge event starting from 16 February 1998 (Julian date) to 21 February 1998. (b) High chlorophyll α concentration (dash line) was observed 1-day lag of large volume of river discharge (solid line) event. Chlorophyll α concentration decreased the following day parallel to decreasing of discharge

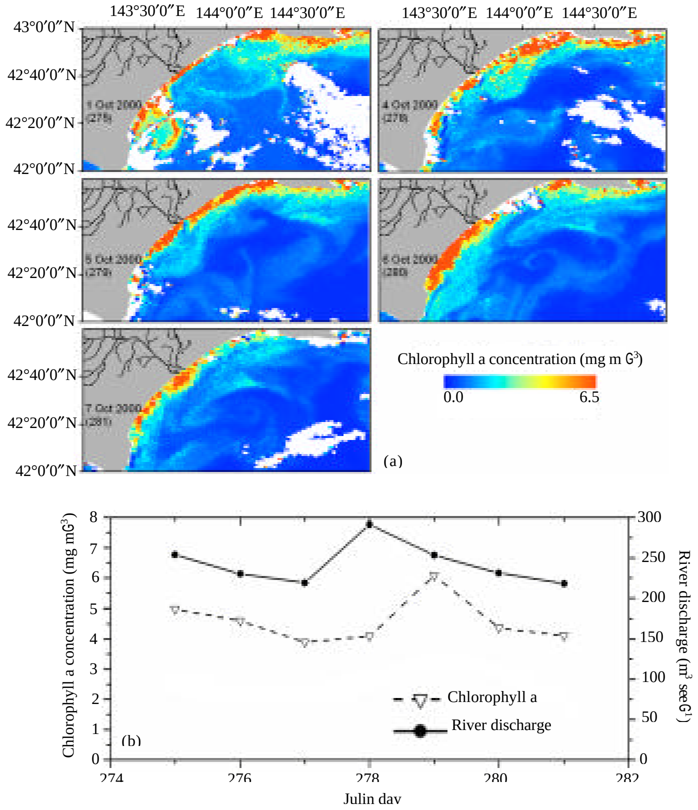

Fig. 3: (a) SeaWiFS daily images showing chlorophyll a distribution before (October 1st) and after (October 5th, 6th and 7th) large volume of river discharge event. (b) Chlorophyll a concentration (dash line) increased dramatically after 1-day lag of large volume of river discharge (solid line) event

cross-reference data set between in situ and SeaWiFS chlorophyll a observation was analyzed to validate the satellite data. A total of 23 matched pairs were obtained between in situ and SeaWiFS daily data. Correlation of the match-ups produced an r = 0.99 (N = 23, slope m = 1.06 and intercept c =- 0.13).

SeaWiFS-derived chlorophyll a showed high variability in concentration in the study area. Analysis of individual scenes typifying runoff events shows high variability. The extent of riverine discharges during high river discharge event also can be assessed using ocean color imageries. High chlorophyll a concentration in plume area occurs during increase in river discharge. This was also observed in several runoff events throughout the study period. In winter volume of river discharge from the Tokachi River relatively low. During increase in volume of river discharge, increase in chlorophyll a concentration in plume area was observed. This event was evident during February 1998, high chlorophyll a concentration (2.4 to 2.5 mg m^{-3}) was observed from SeaWiFS daily data on February 16 to 18th during large river discharge (more than 150 m^3 sec^{-1} on February 15 to 17th). Decrease in volume of river discharge was observed on February 18th (120 m^3 sec^{-1}). Lower chlorophyll a concentration in the plume area the day after (February 19th) with value of 1.5 mg m^{-3} was observed. River discharge remains low in the following days and chlorophyll a concentration also observed to be low (Fig. 2).

Larger discharge events were also observed in late summer to early autumn due to high precipitation. Largest discharge event (exceeding 6000 m^3 sec^{-1}) occurred on September 12, 2001. However chlorophyll a concentration on those dates could not be derived due to cloud cover. Chlorophyll a concentration for other large events also could not be derived due to cloud cover. Similar smaller event were analyze to determine the effects of river discharge on chlorophyll a concentration in plume area. River discharge was observed relatively high (291 $m^3$$sec^{-1}$) on October 4, 2000 and discharge decreased gradually the day after. Chlorophyll a concentration elevated gradually and peak on October 5 (the day after high discharge) with value of 6 mg m^{-3}. After event,

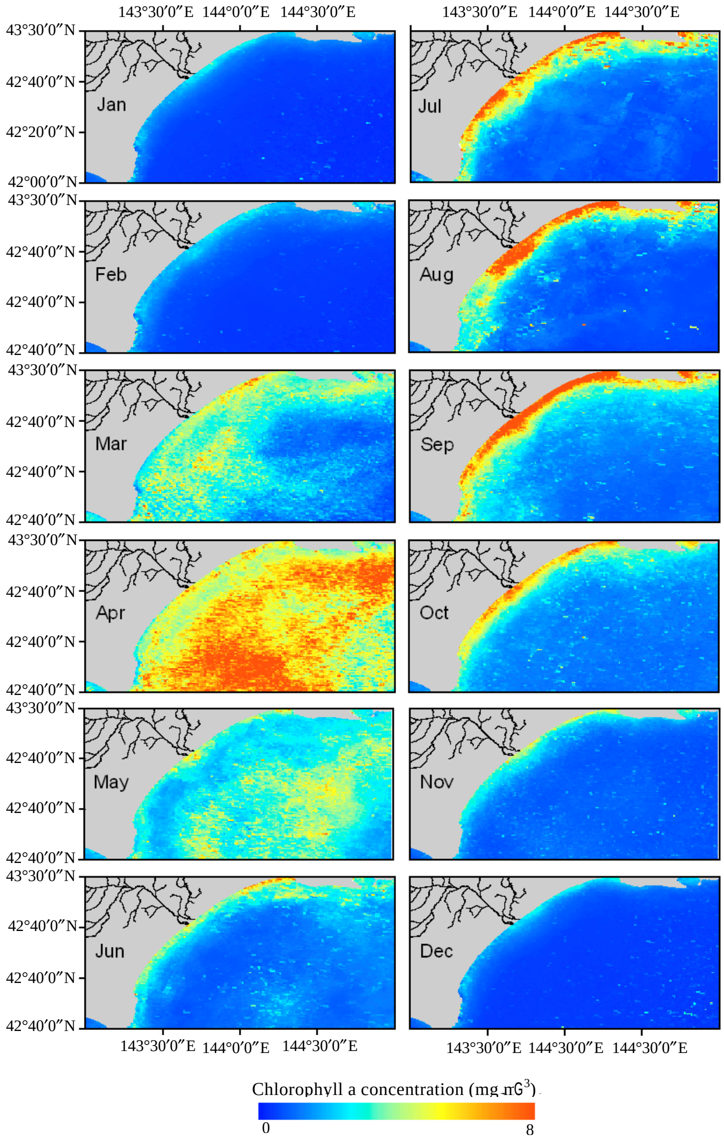

Fig. 4: Climatological (1998-2002) monthly mean of SeaWiFS chlorophyll a (mg m^{-3}) showing the annual cycle over the period of January to December

Chlorophyll a concentration decreased gradually to the normal concentration (4.4 mg m^{-3}). Chlorophyll a concentration remains at 4 mg m^{-3} for the following days and river discharge was also constant (~230 m^3 sec^{-1}) (Fig. 3).

Seasonal and interannual cycles of chlorophyll a: Variability of chlorophyll a concentration was observed using the climatology monthly mean for 5 years. The chlorophyll a concentrations shows bimodal, first peak in spring and second peak in late summer to early autumn (Fig. 4). High peak of chlorophyll a concentration (8.4 mg m^{-3}) was observed during late summer to early autumn compared to spring peak (4.9 mg m^{-3}) in plume area (Fig. 5).

Meanwhile high peak of climatology chlorophyll a concentration in spring (6.5 mg m^{-3}) was observed in offshore water (Fig. 6). In April, chlorophyll bloom covered the whole study region (Fig. 4). However in May, chlorophyll bloom was observed offshore and low chlorophyll a in coastal water. Second lower peak (1.2 mg m^{-3}) was observed in late summer to early autumn

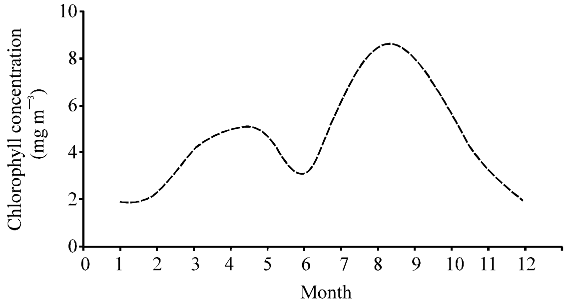

Fig. 5: The climatology mean of chlorophyll a concentration from 1998 to 2002, averaged from monthly images in plume area

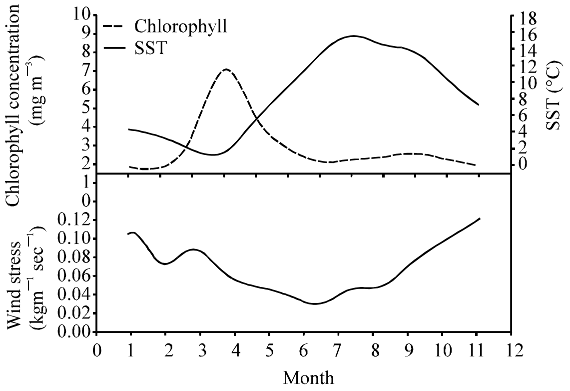

Fig. 6: The climatology means of chlorophyll a concentration, SST (upper panel) and wind stress (lower panel), calculated from monthly mean data spanning 1998 to 2003 in offshore water

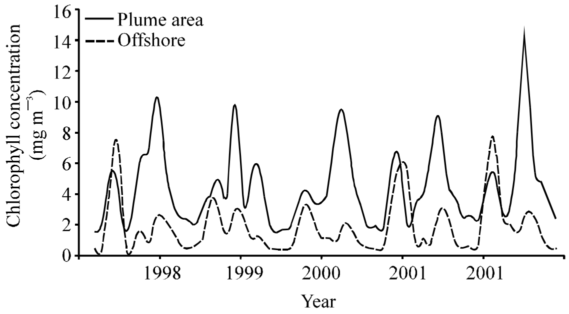

Fig. 7: The SeaWiFS derived chlorophyll a concentration shows interannual variability in plume area (solid line) and offshore water (dash line)

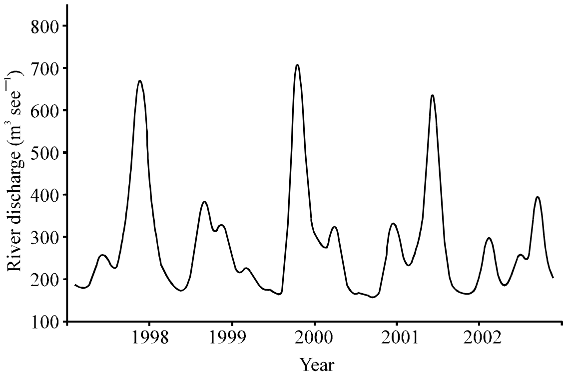

Fig. 8: Time series of Tokachi River discharge for 1998- 2002

in offshore water. Chlorophyll α patterns generally show an inverse relationship with SST especially in offshore water (Fig. 6) where the highest chlorophyll α levels occur in spring (offshore water) and are associated with lowest SST values. Climatology monthly mean chlorophyll a values peak at 7 mg m^{-3} during April while SST values at 1.9°C. Meanwhile winter period shows lowest chlorophyll a value over the 5 years study period with chlorophyll a value of <0.4 mg m^{-3} in offshore water. Wind stress was also observed to be high (>0.06 kg m^{-1} sec^{-2}) in winter and low (<0.05 kg m^{-1} sec^{-2}) in spring to early autumn (Fig. 6).

Chlorophyll a concentrations calculated from monthly mean are high in spring and late summer to early autumn and shows considerable interannual variations in magnitude and duration of these peak events. Chlorophyll α concentrations are also highest in late summer to early autumn compared to spring. Chlorophyll a concentration in plume area was higher than offshore water (Fig. 7). This is also in parallel with river discharge (Fig. 8). The highest mean chlorophyll a values in plume area are 14.4 mg m^{-3} (August 2002), followed by 10.3 mg m^{-3} (September 1998), 9.8 mg m^{-3} (July 1999), 9.1 mg m^{-3} (September 2001) and lowest at 8.8 mg m^{-3} (September 2000). However, high chlorophyll a concentration in spring was observed in April 2001 (6.2 mg m^{-3}), April 2002 (5.4 mg m^{-3}), May 1999 (4.9 mg m^{-3}), March 1998 (4.6 mg m^{-3}) and April 2000 (4.3 mg m^{-3}). For other month, mean of chlorophyll a values are less than 4.0 mg m^{-3}. Chlorophyll a value was observed to be low in winter with value at<2.7 mg m^{-3} (Fig. 7).

Meanwhile, interannual variability of chlorophyll a concentration was also observed in offshore water. High level of chlorophyll a concentration was identified in spring 2002 (7.7 mg m^{-3}), followed by 1998 (7.5 mg m^{-3}), 2001 (5.9 mg m^{-3}), 1999 (3.7 mg m^{-3}) and lowest in 2000 (3.3 mg m^{-3}) (Fig. 9). Spring bloom occurred during low SST and weak wind stress. The collapse of the spring chlorophyll peak begins coastal area, proceeding onto the offshore area by June. Low peak of chlorophyll

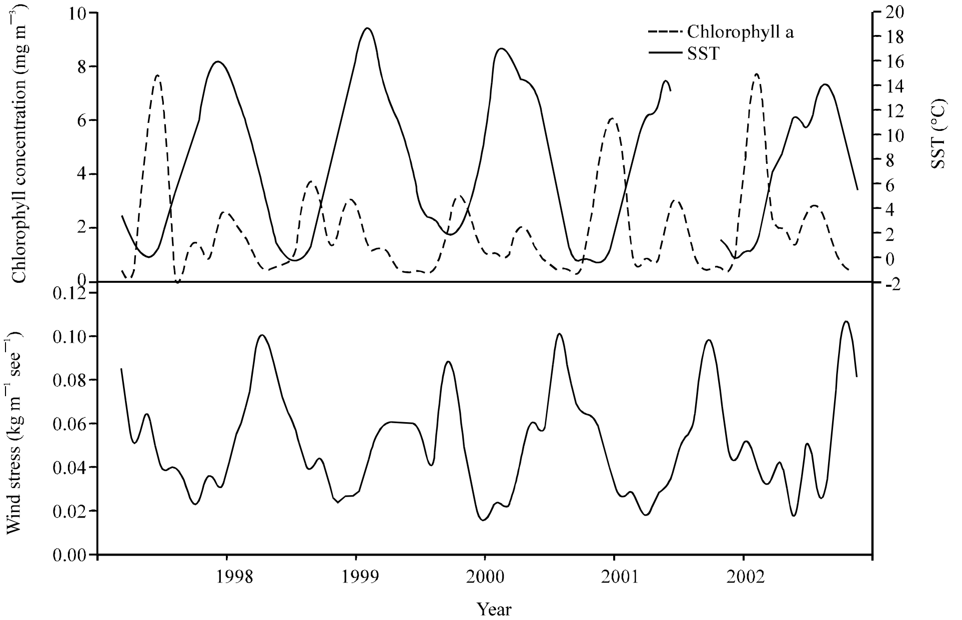

Fig. 9: The time series monthly means of chlorophyll α concentration, SST (upper panel) and wind stress (lower panel) from 1998 to 2003 in offshore water

a concentration was observed in early autumn and also shows interannual variations in values. Highest chlorophyll a concentration occurred in 1999 (3.0 m^3 sec^{-1}) and lowest was in 2000 (2.1 m^{3}sec^{-1}). Low chlorophyll a values (<0.75 mg m^{-3}) are present offshore in summer. However lowest chlorophyll a value was observed during winter (<0.6 mg m^{-3}).

DISCUSSION

The SeaWiFS imagery provides spatial context and synoptic quantification of seasonal and interannual variability of chlorophyll a concentration. The overall seasonal increase in chlorophyll a concentration from spring and late summer to early autumn is consistent. Phytoplankton populations in most temperate and subartic ocean regions undergo strong seasonal cycles, with prominent blooms occurring particularly in the spring and lesser extent in the autumn (Findlay *et al.*, 2006). The spring bloom of phytoplankton is a well-established, regular, seasonal event in the western subartic Pasific (Kasai *et al.*, 1997). The increase in chlorophyll a concentration in autumn has been described as a result of vertical mixing and the breakdown of stratification that causes an influx of nutrients into the upper layers of the ocean (Findlay *et al.*, 2006).

Seasonal and interannual variability in timing, magnitude and duration of chlorophyll a in the study region is dominated by the plume area. In plume area, the timing and magnitude of the spring and autumn blooms is highly variable. Variability in river discharge is parallel with variability in chlorophyll a concentration. Variability of chlorophyll a concentrations is clearly observed during episodic event of river discharge. Chlorophyll a concentration elevated dramatically after a 1-day lag of large discharge event, suggesting that blooms is related to the influence of the runoff event. Wysocki *et al.* (2006), Chen and Chen (2006) also demonstrated that chlorophyll a concentrations in the surface water were higher during the large discharge period. Area of very high chlorophyll a concentration over the continental shelf was also found in plume area effect from river discharge (Davies, 2004; Wang *et al.*, 2004). The amount of the flow of discharge results in variability of nutrient supply, and affects the temporal and spatial changes in the primary productivity in plume area (Hama *et al.*, 1997). In winter, increase in river discharge also affects the chlorophyll α concentration which is evident in episodic event February 1998. This is caused by river flow-induced haline stratification which allows phytoplankton to develop (Gohin *et al.*, 2003).

Large river discharge in spring and late summer to early autumn influences the chlorophyll α concentration in plume area. Chlorophyll a concentration in plume area during spring and late summer to early autumn shows variability. High primary production reflects in high chlorophyll a concentration in plume area observed in early summer 1999, late summer to early autumn 1998, 2000, 2001 and 2002. Lower peak of chlorophyll a in plume area also evident during April of 1998, 2000, 2001 and 2002 and May 1999. In this study, the Tokachi River discharge increases in spring and from August to September due to snow melting and rainfall causes by atmospheric depression or typhoons respectively (http://www.river.go.jp). Similar pattern were reported in Mississippi River where chlorophyll *a* data showed elevated concentration in spring and autumn due to increasing of river discharge (Wysocki *et al*., 2006). According to Usui *et al.* (2006), chlorophyll a concentrations in the water column were highest in spring and autumn while lower in summer in Tokachi River water. Wang (2006) reported that chlorophyll a concentration in Changjiang plume was highly correlated with Changjiang freshwater discharge and phosphate concentration.

Phytoplankton blooms are commonly reported in river-influenced marine water (e.g., in Amazon estuary by Shipe *et al.* (2006); Bay of Biscay by Gohin *et al.* (2003); Guadiana River plume, Gulf of Mexico by Signoret *et al.* (2006); Iberian Peninsula by Cravo *et al.* (2006); Mississippi River plume by Wysocki *et al.* (2006); Sepik River by Davies (2004) and Higgins *et al.* (2006)) during high river discharge. High amounts of nutrient (Si, N, P etc.) enter the coastal water from terrestrial freshwater input that enhances phytoplankton growth rates (Sierra *et al*., 2002; Perez *et al*., 2003). Huret *et al.* (2005) also indicated that increasing primary production in plume area due to high nutrient supply during high river discharge in Rio de la Plata plume.

The chlorophyll a concentration in Tokachi River plume was approximately two times higher during high river discharge than during low discharge. Higgins *et al.* (2006) also indicate that higher chlorophyll a concentration occurred in the Bismarch Sea during high river discharge compared to low river discharge. During low river discharge, a decrease in nutrient input occurs, leading to a reduction in primary productivity (Signoret *et al*., 2006).

However, higher chlorophyll a was observed in offshore water over the 5-year study period during spring. High chlorophyll a concentration in offshore area was observed in 1998, 2001 and 2002. This was also indicated by low SST and increased in wind stress. Elevated chlorophyll α in spring with increment of wind stress was also shown in Gulf of California (Douglas *et al*., 2007). Lower chlorophyll a concentration occurred in 1999 and 2000. According to Kasai *et al.* (1997) and Usui *et al.* (2006) offshore water of this study region was characterized as Oyashio water. In the Oyashio water, intensive phytoplankton blooms occurred in April and May and relatively small blooms are observed in October.

A small secondary bloom of chlorophyll a (offshore water) in September/October due to increased of primary productivity. This increase can be attributed to renewal of wind mixing and injection of nutrient into a nutrient-depleted upper layer and adequate mean irradiance in the mixed layer (Limsakul *et al*., 2002).

Coastal areas receive significant amounts of nutrient mostly from land-based source, which contribute to increased chlorophyll a concentration in coastal and marine environment. The effects of freshwater discharge to the coastal water can be minimized by controlling the flow using civil infrastructure (e.g., dam). This will minimize eutrophication rates processes in coastal water. Coastal areas are important nursery ground for various marine fish species and are directly affected by freshwater inputs. Freshwater inputs also contribute to increasing coastal fisheries production due to land-based run-off. This has been recognized in many places, i.e., nursery grounds for the common sole in Vilaine Bay, France (Le Pape *et al*., 2003), major feeding ground of the Japan Pacific population of walleye Pollock in the southeastern coast of Hokkaido Island (Yamamura *et al*., 2002).

CONCLUSIONS

This study revealed variability of chlorophyll a concentration at the Tokachi River plume using satellite images and GIS. The variability of chlorophyll a concentration in plume area was strongly influenced by river discharge. The variability in chlorophyll a concentration in the Tokachi River plume was linked to variability in discharge of the Tokachi River, especially during late summer to early autumn. Offshore chlorophyll *a* bloom was influenced by low sea surface temperature and also low wind stress.

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