Distribution of Si Compounds in Surface Water of Brunei Bay, Borneo Island

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Abstract**—** A study has been carried out to investigate the spatial and seasonal changes of Si compounds in Brunei Bay during dry (SW monsoon) and wet (NE monsoon) seasons. Water samples were collected for the measurement of dissolved and particulate (both organic and inorganic) Si and chlorophyll *a* (chl-a) concentrations. The concentrations of Si compounds in Brunei Bay primarily resulted from riverine inputs due to forest clearing activity which released soils consisting predominantly of siliceous minerals into local rivers. Comparison with other study areas revealed that in general, slightly higher concentration of dissolved inorganic Si was recorded in Brunei Bay. The distribution of Si compounds showed clear seasonal changes with higher concentrations recorded during wet season due to high runoff from the terrestrial area to the marine system. Phytoplankton may have played a role in high salinity areas but the changes in dissolved inorganic Si were dominated by dilution processes during transport along salinity gradient from coastal to offshore regions.

Keywords**—**Surface water, Si compounds, Monsoon, Brunei Bay

I. Introduction

Silicon (Si) compounds, especially silicate, are important macronutrients in marine environment especially for diatom growth [1], [2]. Riverine transport of Si to the coastal area occurs in both dissolved and particulate forms, where the main source is from chemical weathering of mineral silicates, while the particulate Si is transported in suspended particulate matter load [3], [4]. Brunei Bay is situated in the Borneo Island and opens to the southern region of the South China Sea. This bay is shallow along the coastal area (<5 m) becoming deeper towards its outer part (20-40 m). The bay is influenced by dry Southwest (SW) and wet Northeast (NE) monsoons. To date, no study has been carried out to investigate the spatial and seasonal changes of Si compounds in Brunei Bay. Thus, this study was initiated to generate a baseline data of Si compounds and determine its seasonal cycling.

II. Materials And Methods

Two sampling trips were performed for the whole area in June 2013 (SW monsoon) and January 2014 (NE monsoon) (Fig. 1). Water samples were collected and stored in high density polyethylene bottles for the measurement of dissolved and particulate (both organic and inorganic) Si and chlorophyll *a* (chl-a) concentrations. Chl-a was used to estimate the phytoplankton biomass. After sampling, the bottles were stored in an ice cooler at <4 °C, then brought back to the laboratory and immediately filtered. After filtration through pre-combusted (450-500 °C) 0.7 µm pore size glass fiber filters (Whatman GF/F), samples for chl-a were extracted with 90% acetone and analyzed spectrophotometrically according to Parsons et al. [5].

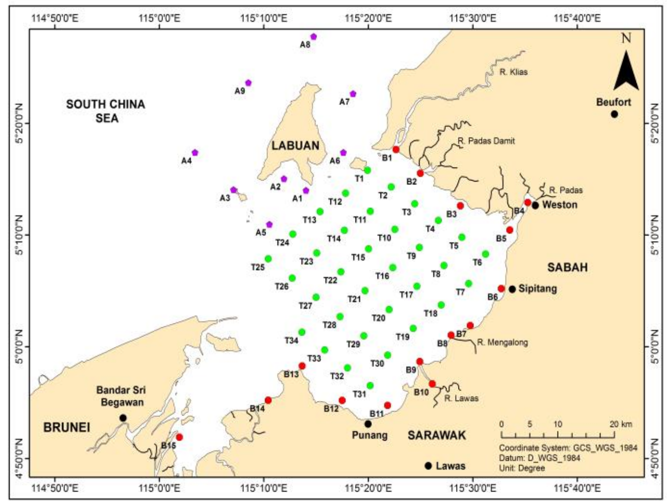

Fig. 1: Sampling stations in the Brunei Bay

In the laboratory, the filtered samples were used for dissolved Si analysis, while unfiltered samples were used for particulate Si analysis. Dissolved inorganic Si (DISi) concentration was determined colorimetrically with a Smartchem 200 Discrete Chemistry Analyzer (AMS-Alliance). The total dissolved Si (TDSi) concentration was determined after the persulphate oxidation on the dissolved samples according to Grasshoff et al. [6]. The concentration of DOSi was obtained from TDSi concentration after subtracting the DISi concentration in the sample. Meanwhile, the unfiltered sample was digested similarly to TDSi to determine the total Si and total particulate Si (TPSi) was then determined by subtracting TDSi.

III. Results And Discussion

The surface water concentrations of Si compounds during both dry (June 2013) and wet (January 2014) seasons ranged

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from 11.20 to 40.50 (mean 18.68 $\pm$ 6.25) µM, 0.02 to 25.68 (mean 4.93 $\pm$ 5.29) µM and 0.07 to 16.58 (mean 3.68 $\pm$ 3.05) µM for DISi, DOSi and TPSi, respectively (Fig. 2). The Si compounds were generally higher at stations nearest to the coastal region for both seasons and then decreased towards the middle of the bay. These results support the input of Si compounds being from the riverine sources. This distribution was more pronounced during the wet season, probably due to the high runoff from the terrestrial area which transports more topsoil runoff into the river systems and ultimately to the bay. Higher input of Si compounds was from Padas and Lawas Rivers probably due to the clear-cutting of forests at upstream of these areas. This activity is expected to result in input of soils into neighbouring rivers since soil consists predominantly of siliceous minerals (SiO_4^{4-}) i.e. a compound containing Si. It is worth noting that Sabah is one of the states in Malaysia facing major deforestation, losing approximately half of its forest cover (more than 1.85 million ha) between 1990 and 2008. In addition, the deforestation rate at Sabah increased from 0.9% per year between 1990-2000 to 2.7% per year between 2000 and 2008 [7]. Therefore, it is not unexpected that high Si compounds concentrations occurred in the river systems of the current study area, especially with the increased in clear-cutting of forests in the past few years resulting in soil run off into rivers.

Concentrations of Si compounds, especially DISi, may be reduced by diatom uptake. For example, study by Letolle et al. [8] has shown surface concentrations of DISi along the Siberian coast and Laptev Sea can be reduced from 25-30 µM to 0.1-1.0 µM during the diatom blooms. The Si compounds are essential nutrient required for the growth of diatoms which consists about 60% of all species of phytoplankton [9]. The influence of phytoplankton distribution on the Si compounds in this study was investigated by plotting DISi, DOSi and TPSi concentrations against chl-a concentration. A weak correlation was obtained between these parameters (R^2=0.15; R^2=0.01; R^2=0.14, respectively) suggesting that phytoplankton is not the main factor for decreasing Si concentration in Brunei Bay. The dilution of the riverine input as it mixes with seawater can be expected to be the main driver for Si compounds concentrations declining from the coastal region to the open sea. In order to examine whether other factors were important in DISi uptake or production, property-salinity plots for DISi for June 2013 (SW monsoon) and January 2014 (NE monsoon) for selected stations are shown in Fig. 3. In both plots, higher concentrations of DISi were recorded at the low salinity region and it gradually decreased towards the high salinity region showing the simple dilution of riverine DISi by the seawater. However, slightly decreased of DISi concentrations were found at high salinity regions in January 2014 suggesting phytoplankton may have played a role during this season.

Fig. 2 also shows that Si compounds generally exhibited higher concentrations during wet NE monsoon (January 2014) as compared to SW monsoon (June 2013), related to higher rainfall, and hence riverine input, during the NE monsoon period. The pattern of higher concentrations of Si compounds recorded during highest rainfall suggests an important influence of wet NE monsoon on Si compound concentrations in Brunei Bay. This finding supports the expected association of increasing river flow bringing more Si compounds from terrestrial areas into the coastal area via rivers. A positive relationship of Si compounds concentration in seawater with the wet monsoon has been reported extensively in other studies [10], [11]. In addition, the Si compounds in river bottom sediment may be re-suspended into the water column during the strong NE monsoon season due to strong currents and heavy rains leading to the increased of Si compounds concentrations [12]. Therefore, it is not unexpected that high Si compounds concentrations were observed during wet monsoon season compared to the dry monsoon season.

The Si concentrations obtained were compared with some selected studies reported in the region (Table 1). Most of the Si compounds measurements in previous studies were for DISi only, thus comparisons are made only for this type of Si. With the exception of Uttara Kannada coast in India, the concentration of DISi in the present study generally covered a higher range than most of the selected areas with the higher concentrations recorded at Uttara Kannada coast due to sampling stations location being close to the main rivers [11]. Their riverine input contained high DISi concentrations with the highest nutrient discharge into the coastal water during the monsoon period. In Brunei Bay, higher concentrations of DISi were recorded mainly at the coastal stations especially stations situated at Padas and Lawas Rivers. However, it should be noted that the magnitude of riverine input will influence the concentration of Si compounds in the marine system and this is not considered in this comparison. Low concentrations recorded in other studies were attributed to uptake due to diatoms which play important role in regulating the DISi concentration as previously noted. They suggested the low concentration of DISi in the water column was due to DISi uptake by diatoms during the bloom and the concentration increased due to remineralisation of their siliceous shells into the water column [13]-[16]. As mentioned earlier, this factor did not show a significant role in Brunei Bay and is shown by weak correlation between DISi and phytoplankton and

TABLE I
COMPARISON OF DISI WITH THOSE OF SELECTED MARINE AREAS

Location	DISi (µM)	References
Brunei Bay, Malaysia	7.73-181.87	Present study
Uttara Kannada coast, India	0.36-575	[11]
Strait of Malacca, Malaysia	2.12-10.8	[13]
Palk Bay, India	5.15-12.52	[14]
Sishili Bay, China	0.28-6.40	[15]
Northern South China Sea near China	1.0-9.3	[16]

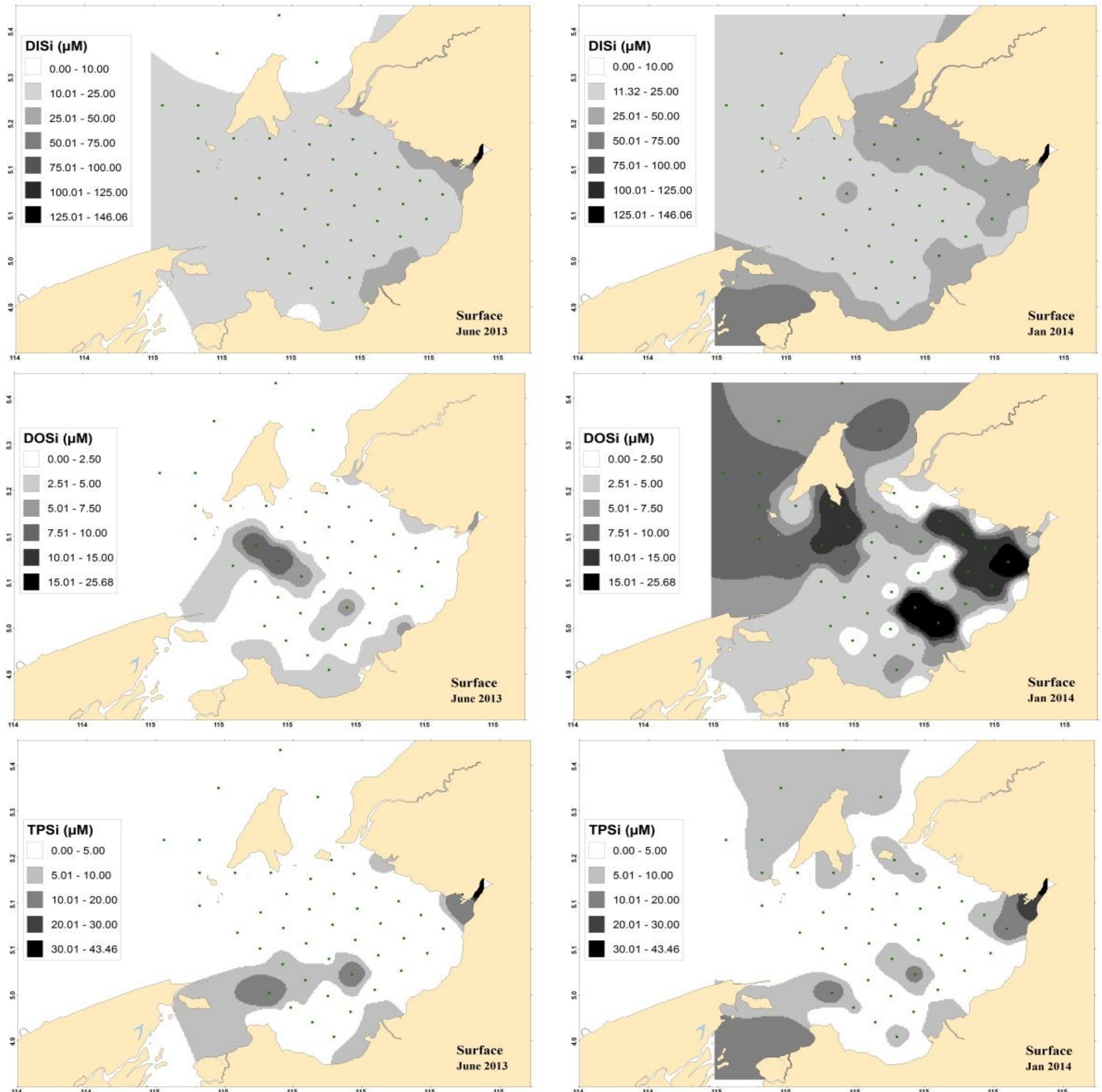

Fig. 2: Surface distribution of Si compounds in Brunei Bay

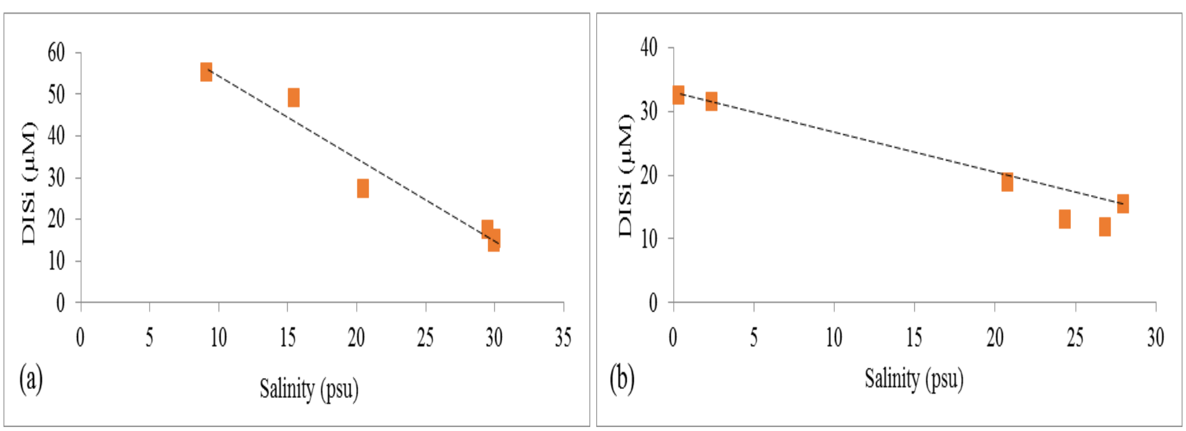

Fig. 3: DISi-salinity plot for (a) June 2013 and (b) January 2014

property-salinity plots. Removal of DISi is clearly less influenced by phytoplankton uptake than dilution along the salinity gradient as it enters the coastal zone.

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