

# Spatial-temporal dynamics of biogenic silica in the southern Yellow Sea

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## Abstract

Concentrations of biogenic silica (BSi) in the southern Yellow Sea were determined during four cruises (spring: April–May 2014; autumn: November 2014; summer: August–September 2015; winter: January 2016). Samples of BSi were measured using the double extraction method. Seasonal and spatial variations of BSi and the potential correlation between chlorophyll *a* (Chl *a*) content and BSi in four seasons were measured in this study. Significant spatial variability was observed in seawater BSi concentrations. The average concentration of BSi was highest in winter and lowest in spring. Furthermore, the relationships between concentrations of BSi and hydrological parameters were also discussed. There was a significant positive correlation between Chl *a* and BSi. The concentrations of BSi showed significant relationships with temperature and the concentrations of silicates, total inorganic nitrogen and total inorganic phosphorus, indicating that distribution of BSi was affected by temperature and nutrient level.

**Key words:** biogenic silica, nutrients, chlorophyll *a*, phytoplankton, diatom, Yellow Sea

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## 1 Introduction

Biogenic silica (BSi) is not only an important component of biogenic substances but also an important biogenic factor regulating the silicon biogeochemical cycle in marine ecosystems (Coradin and Lopez, 2003). BSi is a mainly amorphous silicon formed by marine organisms such as siliceous diatoms, flagellates, radiolarians and sponge spicules (Coradin and Lopez, 2003). The silicon in the ocean is mainly derived from river input and hydrothermal eruption (Ehrlich et al., 2010). The distribution of BSi in the global oceans presents obvious temporal and spatial variations (Ehrlich et al., 2010).

The biogeochemical cycle of silicon begins with the migration of silicates from the ocean to the biosphere (Leynaert et al., 1993). This process is a main way to link the silicon cycle and the carbon cycle (Ehrlich et al., 2010). Siliceous organisms synthesize their own siliceous bones by absorbing dissolved silicates in the sea water (Brzezinski, 1985). The BSi can be released into the seawater during senescence and grazing, and the dissolved BSi will continue to be used by organisms in seawater (Brzezinski, 1985). The undissolved part is settled down in the form of marine aggregates or clasts and eventually buried in sediments (Takeda, 1998). The BSi in the sediments can be transformed by diagenesis and return to the geological circle (Varela et al., 2016). Some of them are dissolved into silicate on the seabed and enter into the overlying water through diffusion, while the other part is in-

involved in the formation of aluminosilicate minerals (Soetaert et al., 2000).

Hydrodynamic processes will affect the distribution of chemical components related to BSi and the distribution of biological particles, such as silicate and diatoms. Therefore, the hydrological conditions will seriously affect the distribution of BSi in seawater.

The Yellow Sea is semi-closed inland seas as well as marginal seas of the continental shelf. With the development of the economy, all kinds of human activities have a great effect on the biogeochemical processes of rivers, increasing the frequency of algal bloom (Arrigo et al., 2008). The change of silicon in the ocean is related to human activities of the earth, and may also have a bearing on the changes in the marine environment, which makes the study of BSi more significant (Ragueneau et al., 2005a; Exley, 2003; Ye et al., 2002).

Over the last decades, there have been a lot of studies on BSi in marginal seas of China (Ye et al., 2002; Liu et al., 2008, 2016a, b). Most of studies have focused on the indication function of biogenic silicon to paleoclimate change in sediments. Ye et al. (2002) discussed the determination and existing problems of biogenic silicon in sediments of the Yellow Sea and Bohai Sea. Liu et al. (2008) used <sup>29</sup>Si isotope tracer culture method to measure the formation rate and dissolution rate of silicon by means of quadrupole mass spectrometry isotope dilution technique in the Jiaozhou Bay. Liu et al. (2016a) analyzed the parameters of dis-

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solved silicon and BSi in water and sediment combined with historical data, and studied the regional characteristics, influencing factors and sources and sinks according to the comprehensive survey of the Yellow Sea in 2012. Cao et al. (2011) conducted area survey and *in situ* incubation experiment to determine suspended particulate biogenic silica (PBSi) and lithogenic biogenic silica (LSi) in the Changjiang Estuary and adjacent waters during spring, and discussed the distribution of PBSi in the suspended particles and its impact factors. It was found that both of these two kinds of BSi were high in nearshore waters due to the effect of terrestrial input. The concentrations of BSi in surface seawater of the Changjiang River Estuary decreased from the river mouth to the southeast open sea, with the highest values occurring at the river mouth. In the vertical distribution, the content of PBSi and LSi were higher than those in the surface layer due to high content of resuspended particles in the bottom water. PBSi was closely related to the content of dissolved silicate and suspended particulate matter (SPM).

Since the 1970s, many researchers have made a great deal of explorations for the determination of BSi, which the method of determination has been developed rapidly. The determination method of BSi came from the extraction method of NaOH proposed by Paasche (1973). Subsequently, Brzezinski and Nelson (1989) described in detail and added HF extraction to determine total silicon content. Tréguer et al. (1991) applied this method to the southern ocean and found that more than 90% of BSi could be extracted. Ragueneau and Tréguer (1994) extended the NaOH/HF extraction method to the determination of BSi in offshore and estuary waters. Ragueneau et al. (2005b) proposed the double extraction method, which was not only simple, but also determined the Si:Al ratio of samples from different sources, which improved the accuracy of the method and had wide applicability. Therefore, the double extraction method had been widely used to determine the BSi concentration.

To date, only very few data are available on the spatial and temporal variation of BSi in the southern Yellow Sea. Environmental factors affecting BSi and their internal links remain unclear. To improve the knowledge of BSi distribution and its related biogeochemical processes in the southern Yellow Sea, spatiotemporal distributions of BSi were investigated in surface water and water column in the southern Yellow Sea during four seasons. The effects of temperature, salinity, and nutrient level on BSi distribution were examined to gain insight into the main impact factors of BSi.

## 2 Materials and methods

### 2.1 Study area and sampling methods

In this study, samples were collected aboard the R/V *Dongfanghong II* in the southern Yellow Sea (31.9°–37.5°N, 119.0°–124.5°E) in spring (27 April–21 May) 2014, summer (17 August–6 September) 2015, autumn (7–26 November) 2014 and winter (21 January–1 February) 2016, respectively. During the cruise in spring and autumn 2014, seawater samples were collected at 21 and 28 stations, respectively (Figs 1a and c). The summer 2015 and winter 2016 cruises included 24 and 20 stations, respectively (Figs 1b and d).

Water samples of different layers with specific hydrological conditions were collected by the Sea-Brid 911plus CTD. For the BSi analysis, the water samples for BSi were collected by the Niskin bottles. For each sample, 250 mL seawater was filtered onto polycarbonate filters (47 mm diameter, 0.7 μm pore size) under less than 30 mm Hg filtration pressure. The filters were then transferred into the 2 mL EP tube. And then, they were

placed in a –20°C refrigerator in dark for storage.

### 2.2 Determination method of BSi

The samples were measured using a double extraction method described by Ragueneau et al. (2005b). It consists of a double wet-alkaline digestion where the filter sample is submitted to a first digestion (0.2 mol/L NaOH) at 100°C for 40 min. At the end of this first leach, all the BSi and part of the LSi have been converted into Si(OH)<sub>4</sub>. Si and Al concentrations ([Si]<sub>1</sub> and [Al]<sub>1</sub>) in the supernatant are analyzed. After rinsing and drying, the filter is submitted to a second digestion, exactly identical to the first one, leading to the determination of the (Si:Al)<sub>2</sub> ratio that is characteristic of the silicate minerals present in the sample. The corrected BSi concentration is thus given by Ragueneau et al. (2005b):

$$[\text{BSi}] = [\text{Si}]_1 - [\text{Al}]_1 (\text{Si} : \text{Al})_2.$$

The filter sample was folded into a 15 mL plastic centrifuge tube, and then added 4.0 mL 0.2 mol/L NaOH solution. It was extracted consecutively for 40 min at 100°C. A total of 1.0 mL 1.0 mol/L HCl solution was added to neutralize the digesting solution to stop digestion after cooling to room temperature. Then, it was centrifuged for 10 min at 3 000 r/min. The supernatant of 2 mL was used for the determination of Si and Al respectively. Milli-Q water was added the remaining solution to 13 mL and centrifuged. After repeated washing 3 times, 2.5 mL of liquid was finally left in the centrifuge tube. The above steps were repeated and the second extraction was completed after drying. Si was determined by an automatic nutrient analyzer (SEAL German). The method of silico molybdenum blue was used for the determination of dissolved silicate. This automated procedure for the determination of soluble silicates was based on the reduction of molybdate in molybdate blue acid solution. Oxalic acid was introduced to the sample stream before the addition of ascorbic acid to minimize interference from phosphates. Al was determined by molecular fluorescence spectrophotometer (SHIMADZU RF-5301PC spectrophotometer). Finally, the concentration of BSi was calculated according to the following formula: [BSi]=[Si]<sub>1</sub>–[Al]<sub>1</sub>(Si:Al)<sub>2</sub>.

### 2.3 Determination method of nutrients and chlorophyll a

The collection of nutrients samples was conducted in strict accordance with the national marine code: chemical elements of sea water. The determination was conducted using the automatic nutrient analyzer (SEAL German) in accordance with the J-GOFS standard.

The samples of Chl *a* were measured by Turner fluorometer. The filter sample was put in an extraction flask, then added 5.0 mL 90% acetone. Then, the extraction flask was tightened and shocked. And it was put in the low temperature refrigerator (–20°C) for more than 18 h. After extraction, Turner fluorometer was used to determine the fluorescence value.

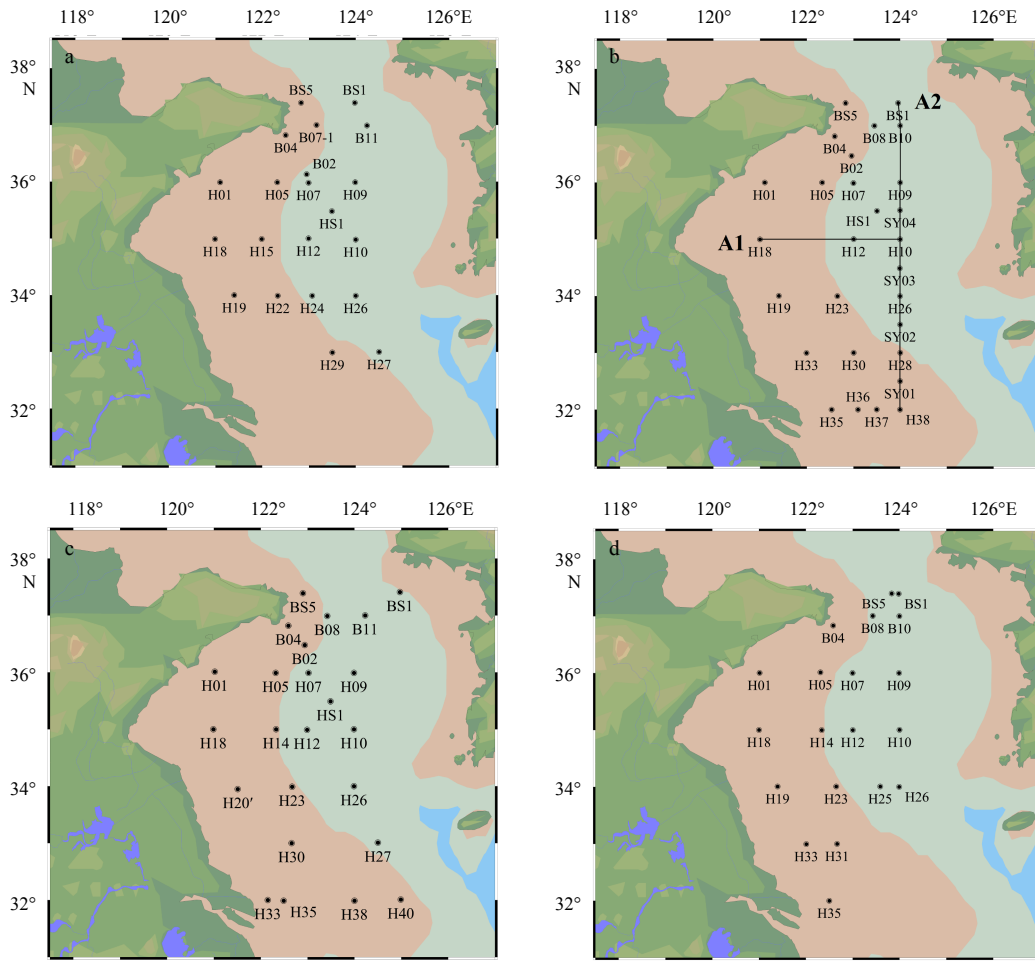
### 2.4 Data analysis method

Data analysis was performed using software SPSS (IBM statistical packet) and Origin 8.5. Analysis of significant differences between samples was assessed using single factor analysis method (one-way ANOVA) or *t*-test. A probability value of *p*=0.05 was used as significance threshold.

## 3 Results

### 3.1 Environmental conditions

The Yellow Sea Cold Water Mass (YSCWM) is a water body



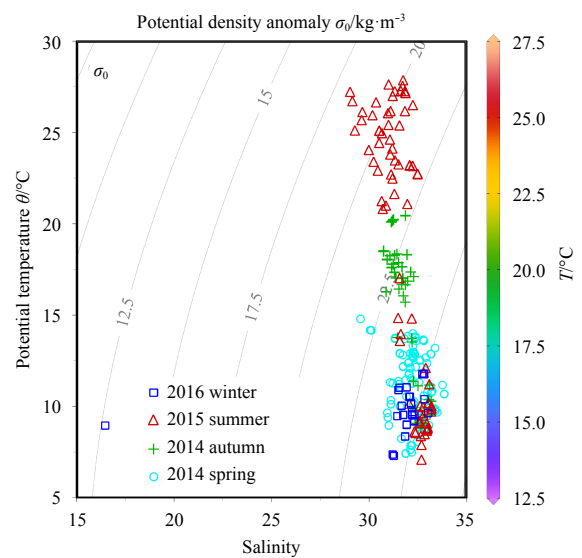
**Fig. 1.** Sampling stations of BSi in the southern Yellow Sea during spring 2014 (a), summer 2015 (b), autumn 2014 (c) and winter 2016 (d) cruises.

with a large temperature difference and a small difference in salinity, and low temperature as its major characteristic. This cold water is actually the central water mass of the Yellow Sea that remains in the bottomland during the winter. Compared with the upper water body with larger temperature increasing in warming season, the lower water body appears to be cold water mass.

The temperature-salinity (*T-S*) diagram based on the data of the temperature and salinity in study area was analyzed using the ODV (Ocean Data View) software (Fig. 2). It contained the hydrological data of four seasons of the 2014–2016 year. It can be seen that the data of some stations in summer showed the characteristics of low temperature and high salinity (Fig. 2). In summer, the YSCWM was characterized by temperature less than 10°C and salinity more than 32, which was located in the water layer of 30–50 m. The horizontal distributions of temperature and salinity also confirmed that the YSCWM appeared in the middle of the southern Yellow Sea in summer, located in 34°–36.5°N and 122.5°–125°E.

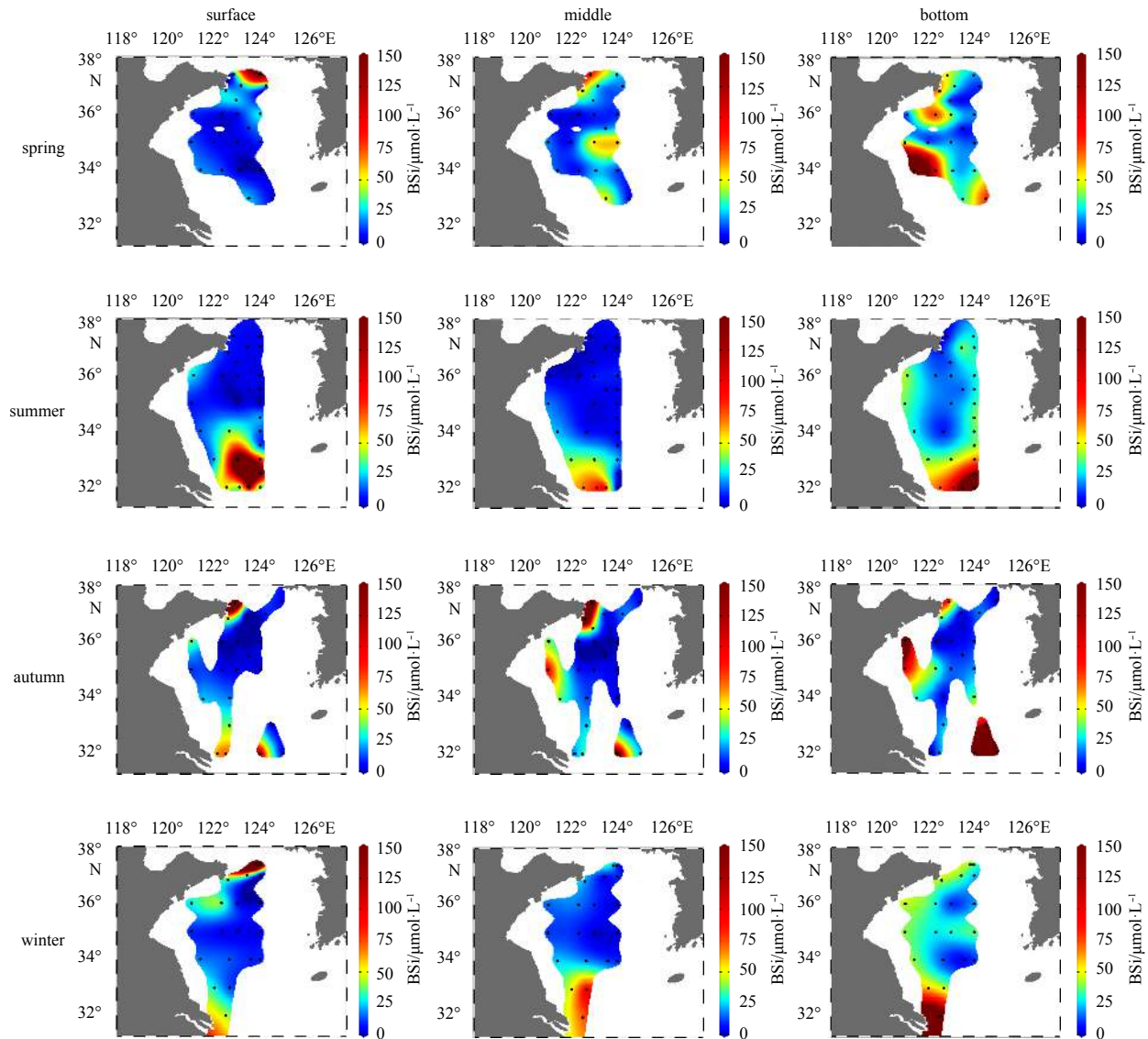
**3.2 BSi horizontal distribution**

The distributions of BSi at different layers in four seasons are showed in Fig. 3. It was divided into three layers, including surface, middle and bottom. The distribution of BSi showed distinct temporal and spatial variation. The surface water had the high BSi concentration in spring, autumn and winter basically in the Shandong Peninsula, which may be due to low salinity water



**Fig. 2.** *T-S* properties in South Yellow Sea. The color bar represents temperature.

from the Lubei coastal water. At the same time, the BSi concentration of the surface water in the vicinity of the Changjiang River was higher than that in the central waters of the southern Yellow



**Fig. 3.** The distribution of BSi of the surface, middle and bottom in spring, summer, autumn and winter.

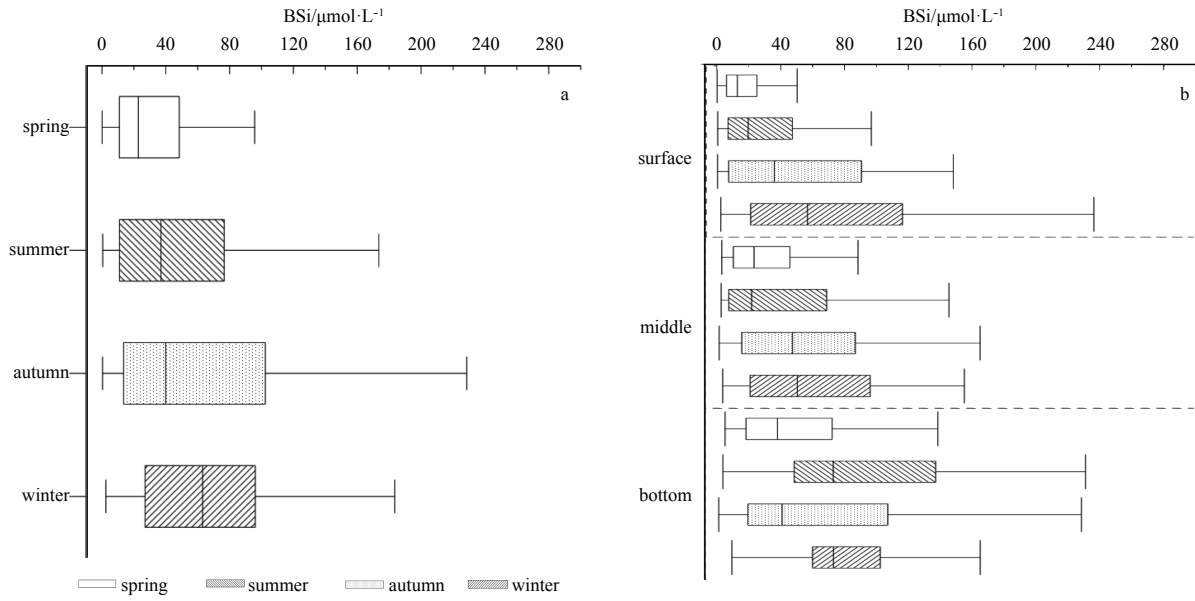
Sea, especially in summer. It may be affected by the large scale of the Changjiang River fresh water in summer. It was because the Changjiang River has a largest runoff in summer, and had a greater dilution effect on the salinity of the investigated sea area (Nelson and Goering, 1977). Meanwhile, a variety of organisms had also been brought to increase the amount of biomass in the waters near the Changjiang Estuary. The BSi content of the middle layer of water in spring, summer, autumn and winter was almost the same as that in the surface layer, and the regularity of the change tends to be the same. The BSi content of the bottom in spring and summer changed significantly. In spring, the content of BSi in the coastal sea was high, and the bottom water in summer appeared low BSi content in the middle area, high content of BSi on both sides, it was assumed that YSCWM had an effect on the results of the beginning of the summer due to the effect of the YSCWM in spring gradually. In winter, the BSi content of the central water body in the survey area was also increased, which may be affected by the Yellow Sea Warm Current (Nelson and Goering, 1977).

### 3.3 BSi vertical distribution

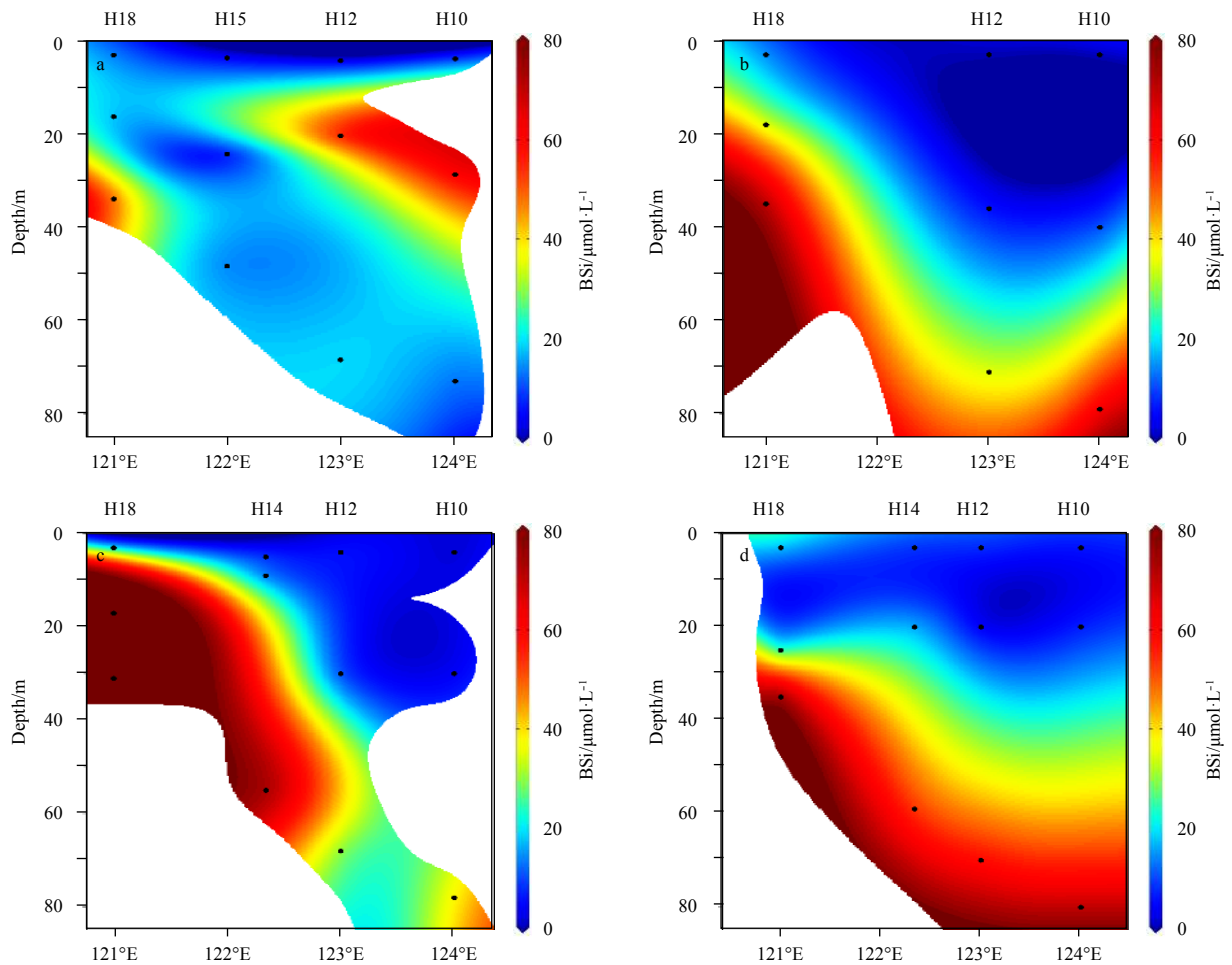
The contents of BSi in the surface, middle and bottom of

spring, summer, autumn, and winter are shown in Fig. 4. The range of BSi content in spring was 0.11–277.74  $\mu\text{mol/L}$ , with an average of 33.56  $\mu\text{mol/L}$ . The range of BSi content in summer was 0.48–198.36  $\mu\text{mol/L}$ , with an average of 50.62  $\mu\text{mol/L}$ . The range of BSi content in autumn was 0.37–235.70  $\mu\text{mol/L}$ , with an average of 56.57  $\mu\text{mol/L}$ . The range of BSi content in winter was 2.45–285.63  $\mu\text{mol/L}$ , with an average of 59.02  $\mu\text{mol/L}$ . Comparison of BSi contents in four seasons suggests that not only the total BSi content was the highest in winter, but also BSi content was the highest in all water layers in winter, no matter the surface, the middle and the bottom. Similarly, the BSi content in spring was the lowest and the BSi content in the surface, middle and bottom was the lowest in spring, which was due to the formation of the YSCWM in winter. At the beginning of spring, the YSCWM first appeared in the central sea of the Yellow Sea, and its power gradually strengthened, which affected the growth and reproduction of warm water phytoplankton to some extent. The number of phytoplankton in spring was obviously decreased, and the BSi content was also low in spring.

In order to further understand the vertical distribution of BSi, two typical sections including Section A1 and A2 were also investigated during spring, summer, autumn and winter. Section



**Fig. 4.** The concentration of BSi in spring, summer, autumn, and winter (a), and the contents of BSi in surface, middle and bottom of four seasons (b).



**Fig. 5.** The BSi of vertical distribution of Section A1 in spring (a), summer (b), autumn (c) and winter (d).

A1 (Fig. 1) across the eastern and western waters of the southern Yellow Sea and was located in the southern Yellow Sea along the 35°N, which was used to represent the effect of YSCWM on the

near-shore and central parts of the southern Yellow Sea. Section A1 contained Stas H18, H15, H12 and H10 in spring (Fig. 5a). Stations H18, H12 and H10 were included in Section A1 in summer

(Fig. 5b). Section A1 consisted of Stations H18, H14, H12 and H10 in autumn and winter (Figs 5c and d). Section A2 (Fig. 1) consisted of Stations BS1, B11, H09, H10, H26 and H27 along 124°E through the Yellow Sea in spring (Fig. 6a). There was the YSCWM in the middle of Section A2. In summer, it contained 11 stations, such as BS1, B10, H09, H10, H26, H28, H38, SY01, SY02, SY03 and SY04 (Fig. 6b). Stations B11, H09, H10, H26, H27 and H38 were included in Section A2 in autumn (Fig. 6c). In winter, Section A2 contained five stations, such as BS1, B10, H09, H10 and H26 (Fig. 6d).

It was found that the content of BSi in 10–40 m water body was low, and the high BSi content appeared in the nearshore and in the outer sea in Section A1 in spring (Fig. 5). In the vertical distribution, the BSi content appeared obvious stratification in summer and winter, which increased with the increase of depth. The YSCWM's role in the central water of the southern Yellow Sea was very obvious in summer, such as Stas H12 and H10. The BSi concentration in the 20–40 m water body was relatively low, which was mainly due to the effect of the low temperature and high salinity water of the YSCWM. The low temperature limited

the growth of the phytoplankton. With the increase of depth, temperature and salinity conditions were more suitable for the rapid growth of phytoplankton, so the concentration of BSi was also increasing. The vertical distribution of BSi in the water column of the study area decreased gradually from inshore to offshore regions, with the maximum BSi occurring at stations near shore with a water depth of 10–30 m in autumn. It could be seen that the role of the YSCWM remaining in summer had been gradually reduced, and its effect was negligible. The reason for the vertical distribution was due to the effect of Sta. H18 near shore. Distribution of BSi content caused by a series of siliceous organisms brought by the Subei coastal current. The vertical distribution of BSi concentration presented an obvious stratification in winter. The BSi concentration in the depth of 0–20 m water body was very low, but the bottom layer of sea water below 20 m was gradually affected by the Yellow Sea Warm Current, which brings some species of warm water into this study region, which makes the content of BSi increased and stratified evenly (Sun et al., 2014).

As shown in Fig. 6, it was found that the highest content of BSi

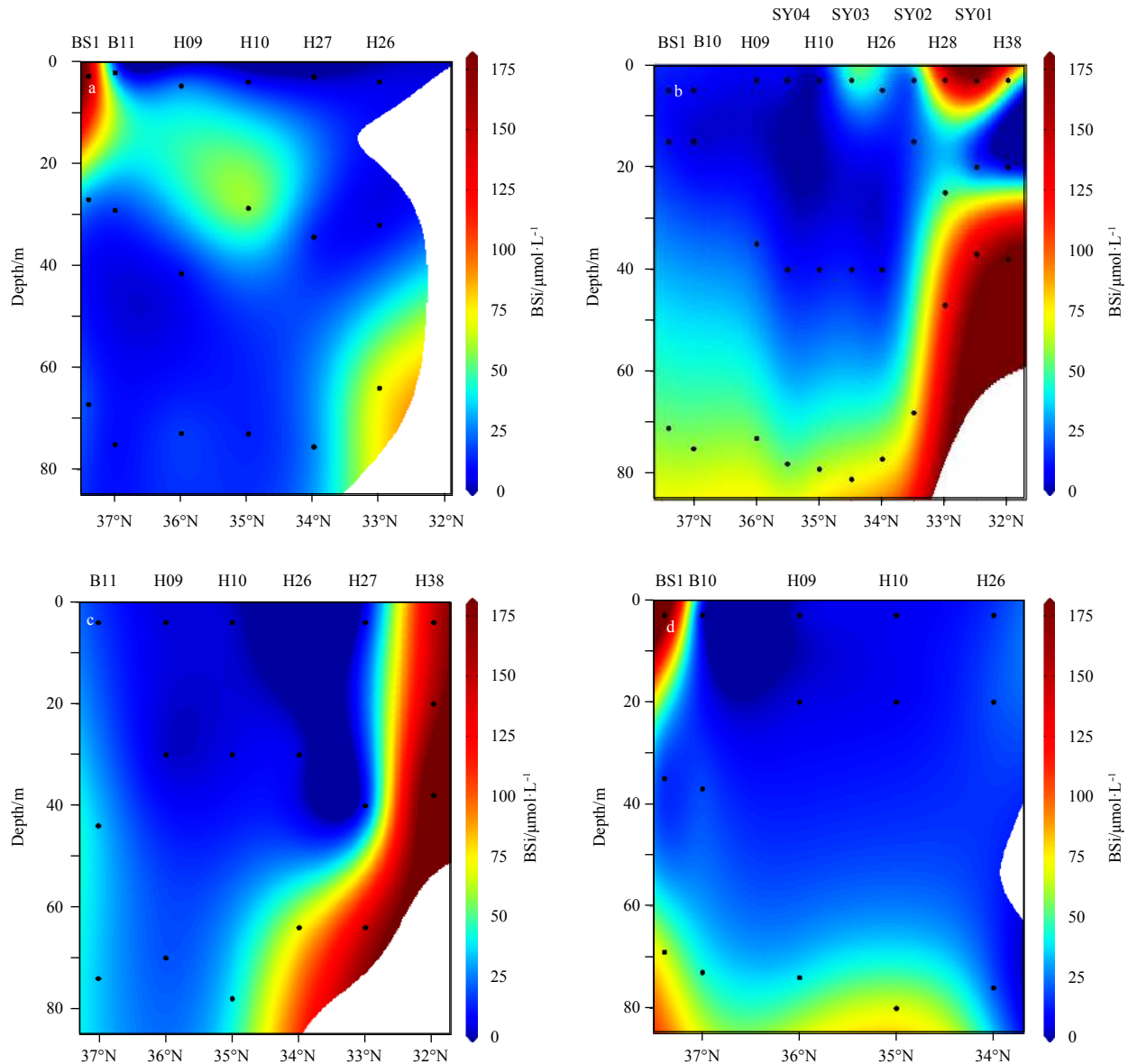


Fig. 6. The BSi of vertical distribution of Section A2 in spring (a), summer (b), autumn (c) and winter (d).

in the north of the southern Yellow Sea in Section A2. At the same time, it extended vertically to the middle of the southern Yellow Sea. The content of BSi in the middle layer of seawater was higher than that in other sea areas. It was because the YSCWM acted slowly and enhanced gradually, which affecting the growth and reproduction of phytoplankton to a certain extent (Cao et al., 2011). In summer, the distribution of BSi was obviously stratified. High concentration was mainly concentrated in the middle and bottom water controlled by the YSCWM. So we can see that the YSCWM has a significant effect on BSi storage. But it was found that the content of BSi increased gradually with depth, especially at 35°N from north to south direction in the investigation area in autumn. BSi content in the bottom layer diffused obviously. The concentration of BSi was spreading rapidly in surface and the middle layer from 33°N to 32°N, we speculated that it may be related to the input of the Yellow Sea Warm Current. The Yellow Sea Warm Current began to form in autumn. It carried a lot of high temperatures and high salinity water from the bottom to the middle of the Yellow Sea, resulting in the warming and salinity increasing process of seawater. It provided a suitable growth environment for BSi production and storage (DeMaster, 1981).

## 4 Discussion

### 4.1 The relationship between BSi and Chl *a*

Contents of BSi in the four seasons were positively correlated with Chl *a* concentrations (Fig. 7). There was a significant positive correlation between the surface water in the spring and in summer at the 0.01 level after the statistical correlation analysis. The reason for this result was that the YSCWM played an import-

ant role in the storage of BSi in spring and summer. The phytoplankton propagated rapidly in the surface water. Although the growth condition of the bottom water was better, the growth of phytoplankton was still limited by light in the bottom water (Exley, 2003).

A significant positive correlation between BSi content and Chl *a* content in the surface water was found in autumn and winter at 0.01 level. The correlation of BSi content and Chl *a* content in autumn was the weakest. In autumn, when the water layer was stratified, the vertical mixing degree of the surface water was more intense, and the vertical mixing coefficient below the thermocline decreased exponentially. At the same time, the nutrients transported from the bottom to the upper layer were reduced, the available nutrients in the surface were gradually consumed, and the phytoplankton in the deep layer can continue to grow (Schlüter and Sauter, 2000).

### 4.2 The relationship between BSi and T-S distribution

According to historical survey data, the study area was affected by multiple water masses, such as the coastal water mass, the central water mass, and the high salt water group (Jin, 1992). The coastal water mass was formed by the flow of fresh water mixed with the sea water, which was on the coast of the Yellow Sea within a depth of about 20–30 m such as the Lubei coastal water (Gong et al., 1996). These coastal water masses were characterized by low salinity throughout the year, turbid water, low transparency, and significant seasonal variation of temperature and salinity. For these water masses, their horizontal range in summer was larger than that in winter, but the thickness was shallow in summer and deep in winter. At the same time it also

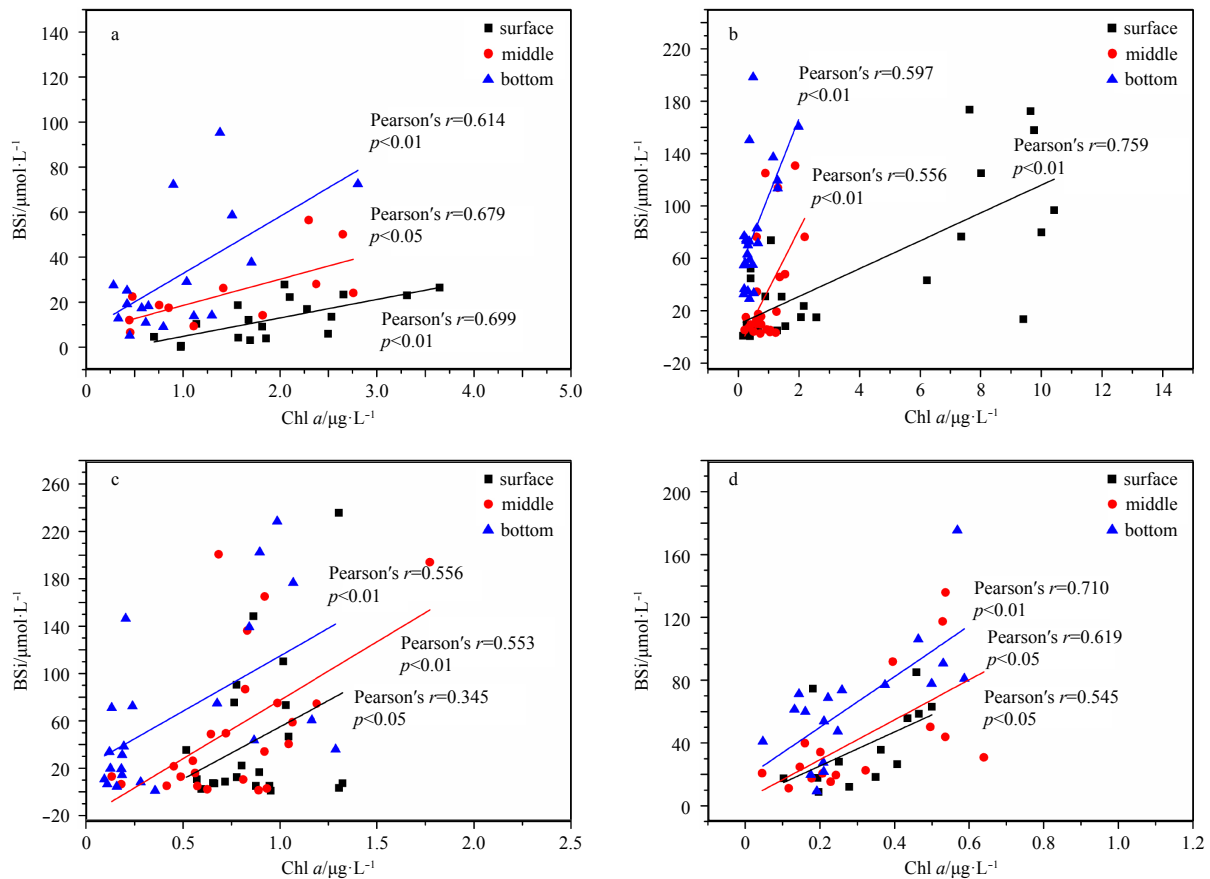


Fig. 7. Relationships between BSi contents and Chl *a* contents in spring (a), summer (b), autumn (c) and winter (d).

included the horizontal range of the water mass which was large in summer and small in winter, but the thickness of the water mass was shallow in summer and deep in winter (Jin, 1992).

The central water mass was formed at the central area of the Yellow Sea, and its southern tip extended into the East China Sea. This water mass was a mixture of the coastal water and offshore shallow sea water, which was formed under the influence of local hydrological meteorological conditions (Gong et al., 1996). In winter, the water mass was vertically homogeneous. The temperature was about 3–10°C and the salinity was about 32–34. In summer, the temperature and salinity were stratified throughout the water column because of the increasing temperature and reducing salinity. The central water in the Yellow Sea was obviously divided into upper and lower layers. The upper layer was characterized by high temperature and low salinity, ranging from 15 to 35 m. The lower layer was characterized by low temperature and high salinity water, which was called “the Yellow Sea Cold Water Mass (YSCWM)” (Jin, 1992). There was a clear stratification between the upper and lower water layers.

As shown in Fig. 8, high concentrations of BSi were presented in Stas H19, H22 and BS1 in spring. Stations H19 and H22 were close to the shore and they were affected by the coastal flow from the coast of North Jiangsu, which brought low brine and provided good conditions for the breeding of BSi. The high BSi content in Sta. BS1 may be affected by a series of effects from the Yellow Sea Warm Current. The BSi concentrations of Stas BS5 and B04 showed a high value due to the impact of Lubei coastal current. The high values of Stas H05, H10, H12 and H27 were because of the role of the YSCWM. In spring, the YSCWM began to affect the environmental conditions of these stations. High salinity and low temperature water bodies provided an excellent environment for the production of BSi.

In summer, Stas H35, H36, H37 and SY01 were located at the southernmost tip of the southern Yellow Sea near the Changjiang Estuary. The high temperature and low salinity environment resulted in high BSi content. It was affected by the Changjiang River fresh water, which had brought abundant nutrients suitable for the growth and reproduction of BSi from the land. High

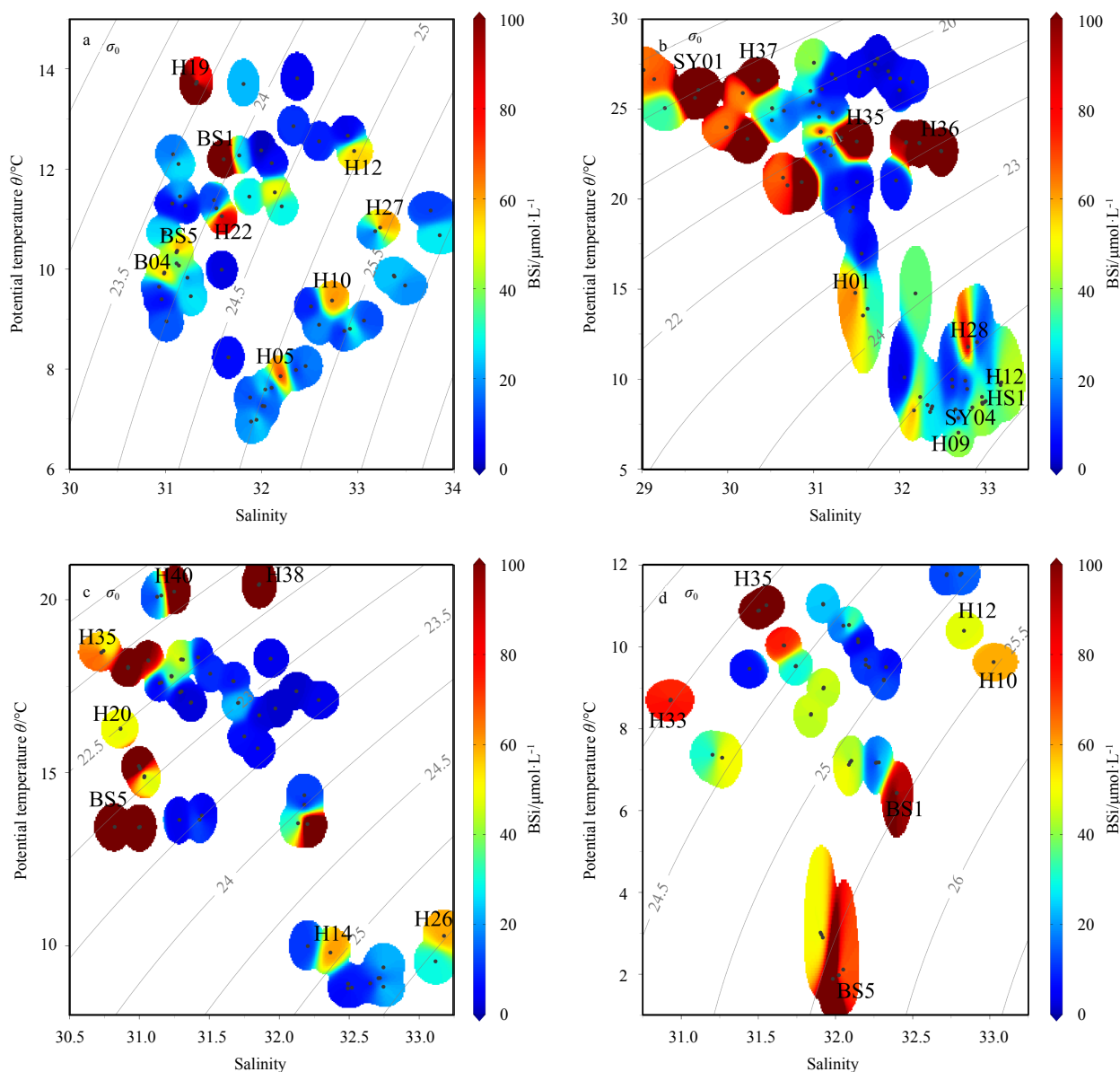


Fig. 8. The distribution of BSi under  $T$ - $S$  background in spring (a), summer (b), autumn (c) and winter (d).

levels of BSi were also observed at stations with low temperature and high salinity, such as H09, H12, HS1, H28, SY04 and other stations. These stations were located at the central location of the YSCWM, which were affected by the YSCWM. At the middle and bottom of these stations, there was a large number of BSi breeding.

In autumn, due to the effect of the Changjiang River, the concentrations of BSi were high in Stas H35, H38, H40 and other stations, which is similar to the result in summer. While a high BSi content appeared in Sta. BS5 because of the effect of the Lubei coastal current. Similarly, although the YSCWM was gradually declining, a few stations were affected by its high salinity and low temperature water bodies, such as Stas H14 and H26 (Ehrlich et al., 2010). Station H20 was affected by the coastal flow of northern Jiangsu Province.

In winter, Stas BS1, H10 and H12 showed high BSi levels due to a series of effects of the Yellow Sea Warm Current. The water body showed high temperature and high salinity. Station BS5 showed a high BSi content due to the impact of Lubei coastal current. Station H33 was affected by the coastal flow of northern Jiangsu Province. Station H35 was affected by fresh water from the Changjiang River.

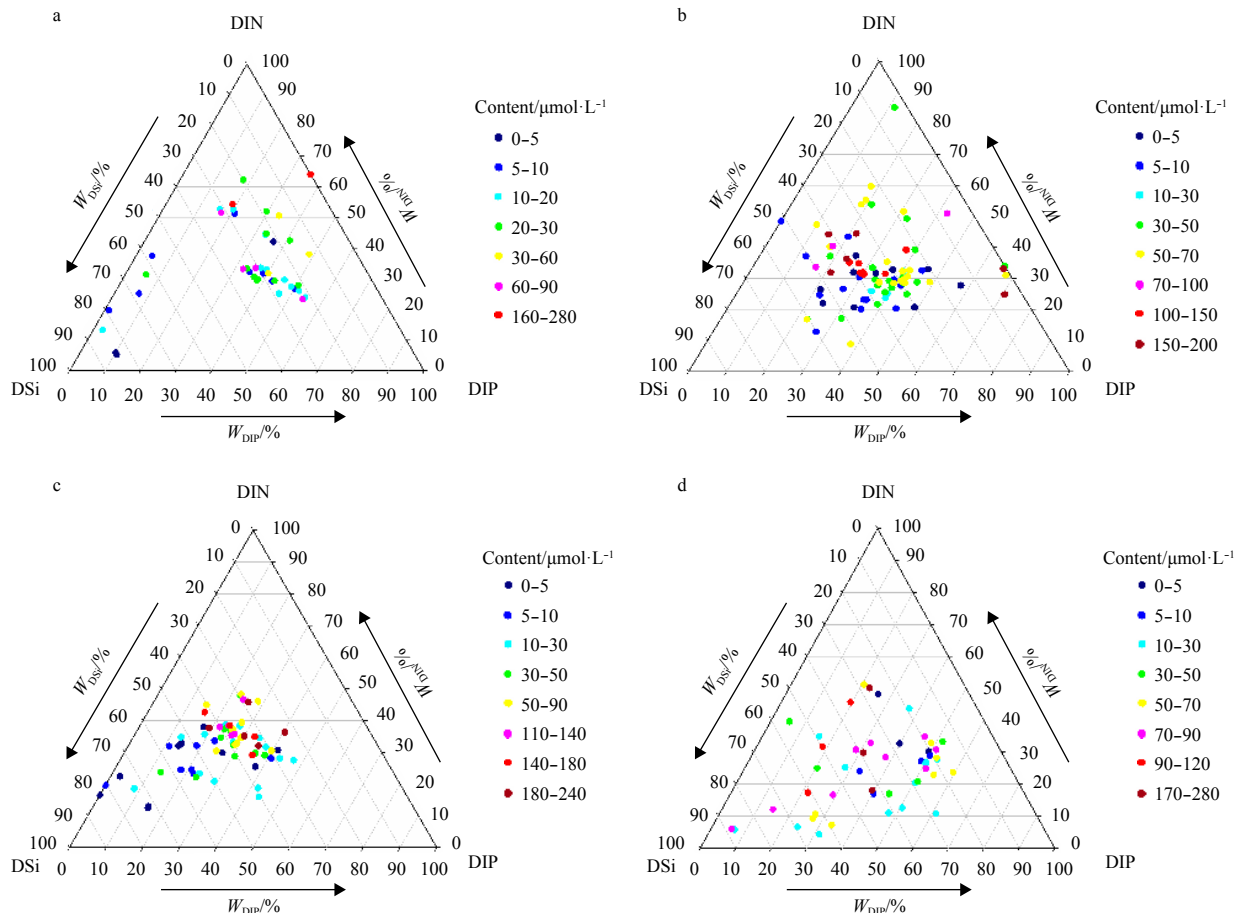
**4.3 The relationship between BSi and nutrients**

In spring, with the increase of BSi content, the action intensity of DSi concentration was concentrated in 30%–50%, the action intensity of DIP was concentrated in 50%–80%, and the action intensity of DIN was concentrated in 20%–40% (Fig. 9). In summer, with the increase of BSi content, the action intensity of

DSi concentration was concentrated in 20%–50%, and the action intensity of DIP was concentrated in 60%–90%, and the action intensity of DIN was concentrated in 50%–70% (Fig. 9). In autumn, with the increase of BSi content, the action intensity of DSi concentration was concentrated in 20%–40%, and the action intensity of DIP was concentrated in 60%–90%, and the action intensity of DIN was concentrated in 50%–70% (Fig. 9). In winter, with the increase of BSi content, the action intensity of DSi concentration was concentrated in 20%–50%, the action intensity of DIP was concentrated in 50%–80%, and the action intensity of DIN was concentrated in 60%–80% (Fig. 9).

It can be seen that the action intensity of DIP was strongest comparing with DSi and DIN in spring, summer and autumn, and DIP had a significant positive correlation with the content of BSi. The action intensity of DIN was second only to DIP. In winter, the common effect of DIP and DIN was the most important factor affecting the content of BSi. The content of DIP and DIN had a great effect on the content of BSI, and they had a significant positive correlation (DeMaster, 2002).

But the action intensity of DSi was not conspicuous in the southern Yellow Sea in the four seasons. Most siliceous organisms synthesized their own siliceous skeletons by absorbing silicates that dissolve in seawater. BSi and organic carbon caused a large proportion of BSi to be sinking and burial, and they can hardly participate in silicon recycling (Conley et al., 1993). Therefore, the lack of silicate in the South Yellow Sea water restricted the growth of phytoplankton (Takeda, 1998). Liu et al. (2016a, b) established a Si budget for the Bohai Sea and Yellow Sea on the



**Fig. 9.** The ternary plot of BSi as function of the relative proportions of three nutrient items ( $W_{DIN}$ ,  $W_{DIP}$  and  $W_{DSi}$ ) in spring (a), summer (b), autumn (c) and winter (d).

basis of DSi and BSi concentration measurements in the survey area. The results showed that BSi accounted for about 25% of the total reactive Si in the survey area. And there was a certain correlation between DSi and BSi. This was consistent with our conclusion. At the same time, the BSi distribution and our results were also very similar, only the specific position data was different, this may be due to the difference in the position setting and scope in the survey area.

## 5 Conclusions

The distribution of BSi content in the southern Yellow Sea showed obvious seasonal and spatial variations. The BSi distribution was mainly affected by the YSCWM, the Yellow Sea Warm Current, and the southern Yellow Sea coastal current water, etc. During the four seasons, the distributions of BSi showed similar patterns, which decreased from inshore to offshore sites. The contribution of BSi showed a trend of high in the southern area and low in the northern area. Comparison of BSi contents in four seasons suggests that both in the surface layer, the middle layer and the bottom layer of seawater, the BSi concentrations in winter were higher than other seasons.

The BSi concentrations at different stations were also related to the hydrological conditions, including temperature and salinity. There was a significant positive correlation between Chl *a* and BSi. It proved that diatom dominated phytoplankton communities in the Yellow Sea. So, BSi was very important to the biogeochemical cycle of silicon in the Yellow Sea. It can be seen that the action intensity of DIP was strongest comparing with DSi and DIN in spring, summer and autumn, and DIP had a significant positive correlation with the content of BSi. The action intensity of DIN was second only to DIP. In winter, the common effect of DIP and DIN was the most important factor affecting the content of BSi. However, the action intensity of DSi was not conspicuous in the southern Yellow Sea in the four seasons.

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