Acta Oceanol. Sin., 2015, Vol. 34, No. 6, P. 5–11
DOI: 10.1007/s13131-015-0681-0
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Chemicohydrographic characteristics of the Yellow Sea Cold Water Mass

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Received 3 January 2014; accepted 10 November 2014

Abstract

Based on the field data obtained during summer cruises in 2006, the overall perspective of chemical and hydrographic characteristics of the Yellow Sea Cold Water Mass (YSCWM) are discussed through the cross-YSCWM transect profiles and horizontal distributions of hydrological and chemical variables, with emphasis on the differences between the northern Yellow Sea Cold Water Mass (NYSCWM) and the southern Yellow Sea Cold Water Mass (SYSCWM). The results show that YSCWM is characterized by low temperature (<10°C) and dissolved oxygen (DO) concentration, high salinity (>32.0) and nutrient concentrations. Compared to the SYSCWM, the NYSCWM possesses lower values of temperature, salinity and nutrient concentrations but higher values of DO. Also its smaller variation ranges of variables (except for temperature) demonstrate that NYSCWM is more uniform than that of SYSCWM. In addition, thermocline is more intensive in the SYSCWM than that of NYSCWM. Furthermore, DO and Chl *a* maxima appear at the depth of 30 m in the SYSCWM, while these phenomena are not obvious in the NYSCWM.

Key words: Yellow Sea Cold Water Mass (YSCWM), horizontal distribution, vertical profile, chemicohydrographic characteristics

Citation: Xin Ming, Ma Deyi, Wang Baodong. 2015. Chemicohydrographic characteristics of the Yellow Sea Cold Water Mass. Acta Oceanologica Sinica, 34(6): 5–11, doi: 10.1007/s13131-015-0681-0

1 Introduction

The Yellow Sea (YS) is a semi-closed and shallow shelf sea with a trough of about 50 to 80 m in the central. It is linked with the Bohai Sea on the north and the East China Sea on the south (Qin, 1989). There is a prominent and important hydrological phenomenon—Yellow Sea Cold Water Mass (YSCWM) which has attracted extensive attention of oceanographers. It is a seasonal water mass appearing only in the summer half year (Li and Su, 1999) in the central bottom water with low temperature (<10°C) (Guan et al., 1963; Weng et al., 1989) which is remnants winter water, and its formation is related to seabed topography and depth (Nakao, 1977).

Many researchers have studied the physical aspects of YSCWM, especially the temporal and spatial variations of the YSCWM (Zhang et al., 2008; Oh et al., 2013). Also the YSCWM plays an important role in the distributions of bacterioplankton (Li et al., 2006) and zooplankton (Liu et al., 2012), as well as the distributions of chemical variables. There is a maximum value in the vertical profile of dissolved oxygen (DO) in summer (Gu, 1980), this is the earliest study of the biogenic elements in the YSCWM. In the subsequent researches, Diao (1986) and Wang (2000) further studied this phenomenon, and Wang (1999) also pointed out that YSCWM was the storage of nutrients from spring to autumn in the YS. In recent years, the researches on distribution characteristics of chemical variables in the YSCWM were incessantly deepened, including the distribution characteristics of chemical variables, such as Shi et al. (2009) and Zang et al. (2010) in the North Yellow Sea (NYS); DO (Yang et al., 2001; Xin et al., 2013), nutrients distribution and structure (Wang et al., 2003; Wei et al., 2010a; Fu et al., 2012) in the South Yellow Sea (SYS).

However, previous studies are limited to hydrological and chemical variables in the NYS or SYS separately, rather than the whole YSCWM. On the one hand, it still lacks an overall perspective of chemicohydrographic characteristics of the YSCWM using quasi-synchronous data, and understanding of the YSCWM is not enough comprehensive and intuitive; on the other hand, although the chemicohydrographic characteristics of the NYSCWM and SYSCWM have been documented separately, it is difficult to make a comparison of them because of the difference in the time of observation in previous works. Therefore, in order to get better understanding of the YSCWM, it is necessary to analyze their spatial heterogeneity and influencing factors by use of synchronous field data.

2 Sampling and methods

The data was collected by The First Institute of Oceanography, State Oceanic Administration (SOA) from 14th July to 5th August, 2006 in the SYS (142 stations) and Ocean University of China from 23rd July to 6th August, 2006 in the NYS (81 stations), respectively. Data from the two cruises were combined together.

Foundation item: The National Natural Science Foundation of China under contract No. 41106071; the National Basic Research (973 Program) of China under contract No. 2010CB428703; the Key Project of Young Marine Science Foundation of State Oceanic Administration of China under contract No. 2012503; the Key Project of Fundamental Research Funds for the First Institute of Oceanography, State Oceanic Administration under contract Nos GY02-2011T01 and GY02-2013T05.

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It is worth noting that four stations on the 37°N transect were surveyed by both cruises. The sampling stations in the YS were shown in Fig. 1.

2.1 *Field sampling and analysis methods*

Water samples were collected by the Niskin sampler in the depth of 2 m, 10 m, 30 m, 50 m and bottom layers. Sampling resolutions and analytical methods of dissolved oxygen (DO), pH, chlorophyll *a* (Chl *a*), phosphate, silicate, dissolved inorganic nitrogen (DIN, sum of nitrite, nitrate and ammonia), total organic carbon (TOC) and total suspended substance (TSS) were in accordance with marine chemical investigation procedures (Office of 908 Special Program, State Oceanic Administration, 2006). Detailed sampling and analysis methods in the NYS and SYS could be referenced in Zang et al. (2010) and Wei et al. (2010b), respectively. During the process of analysis, the national standard substances (produced by The Second Institute of Oceanography, SOA) were used for calibration. The precisions for the measurements of temperature, salinity, DO, pH, DIN, phosphate, silicate and TOC were 0.005°C, 0.005, 0.06 mg/dm^3, ±0.01, ±7.0%, ±10%, ±6.0% and ±2.0%, respectively. In the process of analysis, quantity of parallel samples and samples interpolation were not less than 10%. Measurements of samples interpolation must be in conformity with the specification. Otherwise, this batch of samples should be re-analyzed.

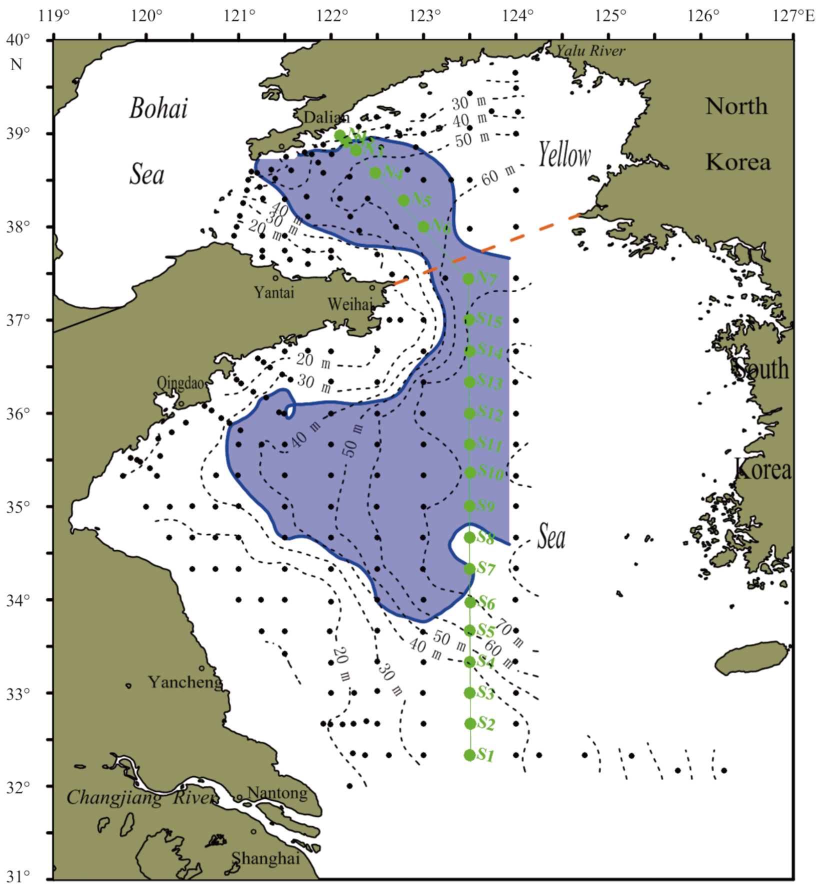

Fig. 1. Bathymetry in the YS and sampling stations (the dots) in the summer of 2006. The black dashed lines are isobaths, the red dashed line is the boundary between the North and South Yellow Sea, stations with green color are used to describe the vertical distribution from south to north, and the blue shadow refers to the range of YSCWM with temperature below 10°C in the bottom layer.

2.2 *Data analysis*

Because the surveying data was obtained from different scientific research units carrying on the SYS and NYS, it not only needed to remove the outliers from all the data, but also needed to test the significant difference between the two cruises. Therefore, Grubbs test method was carried out to eliminate the outliers (formula was as follows):

$$t = \frac{X_{\max\&\min} - \overline{X}}{S},$$

where $X_{\max\&\min}$ is the doubtable value, S mean the standard variation. If t-value is greater than critical value (corresponding values at α=0.01), the doubtable data should be removed.

Mean comparison is performed with the software SPSS16.0 to discriminate the significant difference between the data of two groups. The analysis result of data on the 37°N transect showed that there was no significant difference between the two sets of data at a significance level of α=0.05.

3 Horizontal distributions and vertical profiles of chemical and hydrological variables

Generally, the range of the YSCWM was the area covered by the isotherm of 10°C (Sun, 2006; Li et al., 2012). According to the surveying data, water with temperature below 10°C located in the depth deeper than 30 m. Therefore, the horizontal distributions of hydrological and chemical variables in bottom layer were discussed.

3.1 *Temperature and Salinity*

YSCWM reached its maximum in summer (Guan et al., 1985; Yu et al., 2006). The obvious feature of distribution was low temperature in the central, high temperature at surroundings. This pattern of distribution was similar in the NYS and SYS (Fig. 2a), but the geographical range of the bottom cold water of SYS was larger. The distribution pattern of salinity was consistent with that of temperature (Fig. 2b). According to the geographical location, the YSCWM could be divided into two parts, i.e., NYSCWM and SYSCWM. There were two differences between the two cold water masses. First of all, temperature (<6°C) at the cold center of NYSCWM was lower than that of the SYSCWM (<8°C). Second, due to the more significant influence of Yellow Sea Warm Current (YSWC) in the SYS in winter, salinity of residual water was generally greater than 32.5 in the SYSCWM except the area in the west boundary of the SYSCWM (Fig. 2b), while in NYSCWM the salinity was less than 32.4.

Vertical profiles of temperature and salinity were characterized by intensive stratification of the water column (Figs 3a and b). The water column could be divided into three parts from the surface to the bottom: the upper layer, thermocline and the lower layer. In the upper layer, water was characterized by high temperature and low salinity. Below the upper layer was the intensive thermocline with a thickness of about 20 m. Under the thermocline lied the full-size of YSCWM characterized by low temperature (<10°C) and higher salinity (>32.0). Two cold centers appeared at N5–N3 (38.29°–38.82°N) in NYSCWM and S13–S15 (36.34°–37°N) in SYSCWM where the temperature was lower than 7°C and 8°C, respectively. However, high value of salinity was observed in the area of S7–S10 (34.33°–35.36°N), which was not consistent with cold center, while in the NYS there was no obvious high salinity center. According to the vertical profile along the typical cross-YSCWM transect (Figs 3a and b), both of the average temperature (7.18°C) and salinity (32.26) in the NYSCWM were much lower than those in the SYSCWM (T=8.78°C, S=33.20). The intensity of thermocline was about 0.72 and 0.78°C/m for the NYS and SYS leading to the stronger stratification and more stable water column in the SYSCWM than that of the NYSCWM.

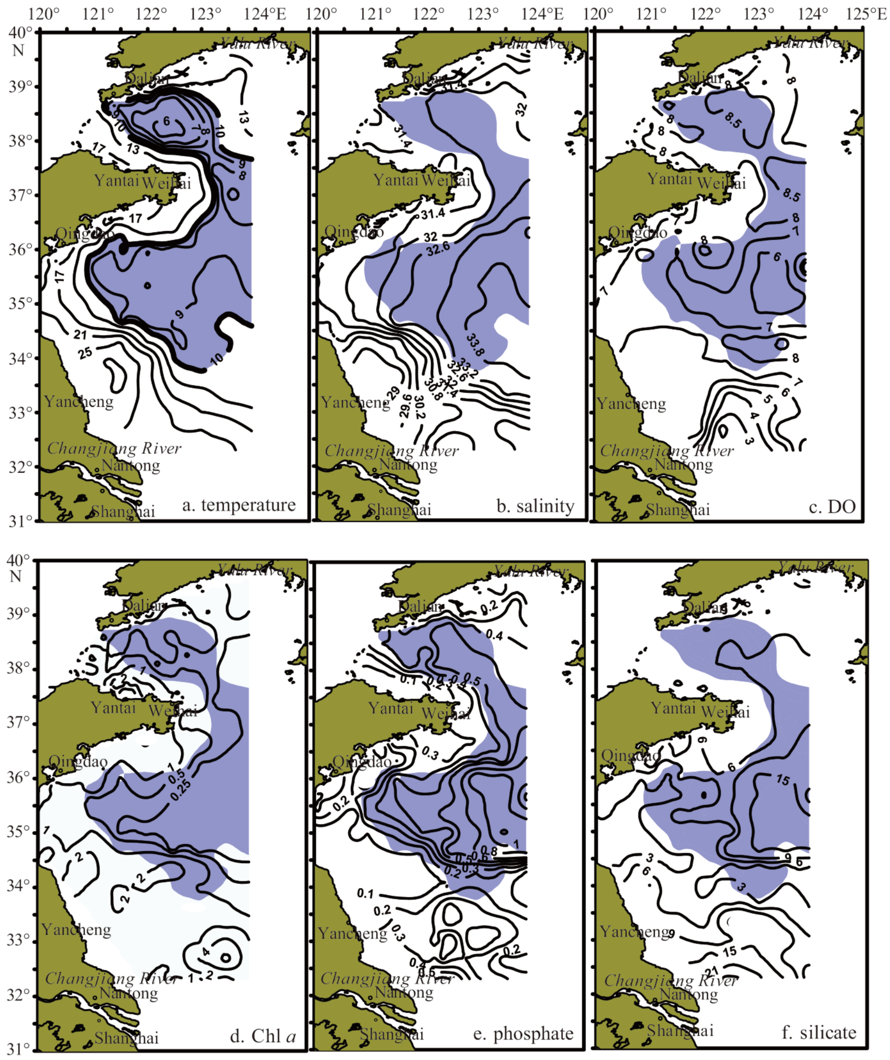

Fig. 2. Horizontal distributions of temperature (°C), salinity, DO (mg/dm³), Chl *a* (μg/dm³) and nutrients (μmol/dm³) at bottom layer in the Yellow Sea in summer of 2006 (the shadow refers to the range of YSCWM in the bottom layer).

3.2 *DO and Chl a*

Similar to the thermohaline distribution, there were closed contours of DO at bottom layer in the central of YS (Fig. 2c). However, the distribution patterns of DO in the bottom layer of SYS and NYS were just the opposite. The lowest value of DO (< 6.5 mg/dm^3) appeared in the central SYSCWM, but DO concentration was greater than 8.5 mg/dm^3 in the central NYSCWM. Distribution of Chl *a* was consistent with DO in the bottom cold water (Fig. 2d). Concentration of Chl *a* was higher than 0.25 μg/dm^3 in most area of the NYSCWM, but lower than 0.25 μg/dm^3 in the SYSCWM. As for the hypoxic area appeared in the northeast of Changjiang (Yangtze River) Estuary which was located out of the SYSCWM, Wang (2009), Wang et al. (2012) and Wei et al. (2010c) had carried on detailed descriptions, thus was not discussed in this study.

In the vertical profile of DO (Fig. 3c), there was maximum

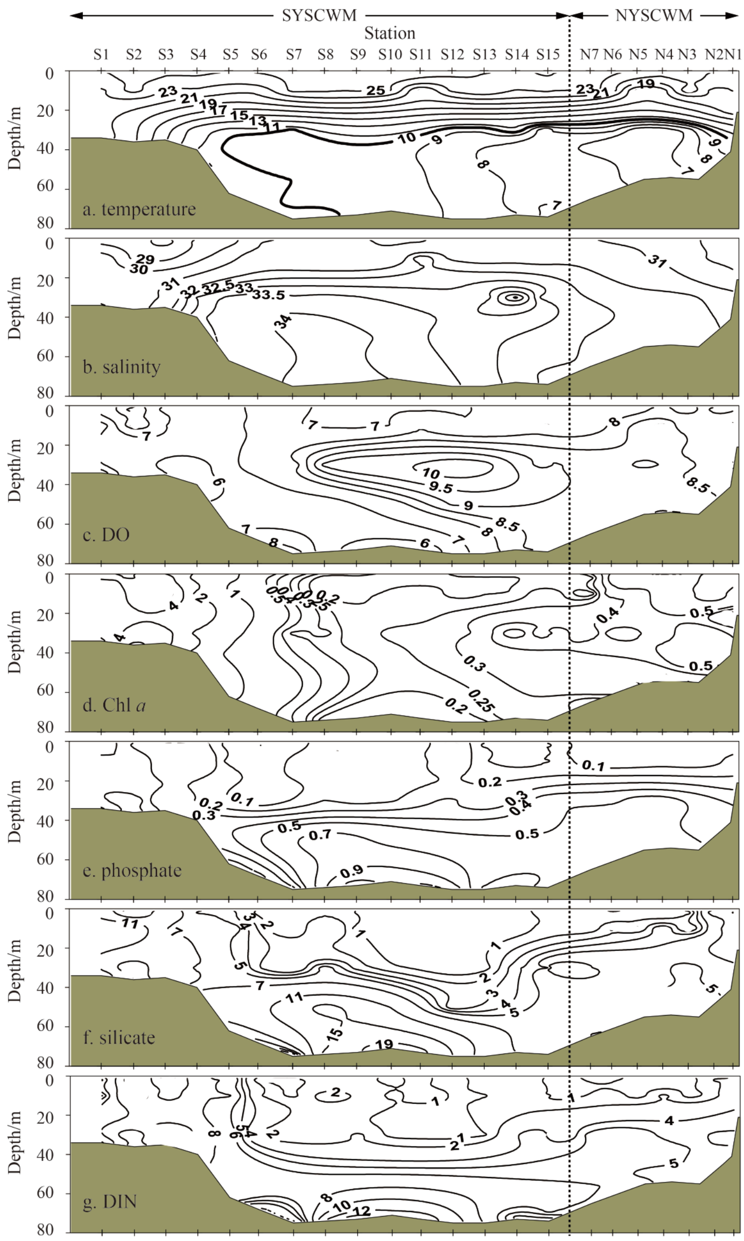

Fig. 3. Vertical distributions of temperature (°C), salinity, DO (mg/dm^3), Chl *a* (μg/dm^3) and nutrients (μmol/dm^3) in the transect across the YSCWM in summer of 2006 (the dotted line was the dividing line between the NYS and SYS).

(>10.0 mg/dm^3) at the depth of 30 m in the SYS from S8–S14 (34.67°–36.67°N). Similarly, the maximum Chl *a* existed at the same depth (Fig. 3d), which was the so-called subsurface chlorophyll maximum (SCM) (Yentsch, 1965; Lund-Hansen et al., 2006; Fu et al., 2009). Furthermore, in the SYSCWM, all of the maximum values of DO and Chl *a* appeared within the thermocline. Due to the suitable light availability and nutrient supply from the nutrient-rich bottom water, photosynthesis of phytoplankton was very intensive at this depth and it produced a large amount of oxygen. DO was reserved and accumulated to high values in this layer because of the presence of strong thermocline with stable vertical structure (Wang et al., 1999). This was also evidenced by the high DO saturation (average value 107.1%, n=7) of this depth. Therefore, DO maximum in the vertical profile appeared in the

SYS. However, different from the SYSCWM, the phenomenon of DO maximum in the vertical profile was not obvious in the NYS. Although SCM appeared at about 2–10 m, the depth was above the thermocline. DO was produced by phytoplankton photosynthesis released into the upper water. As a result, there was no DO maximum in the vertical profile in the NYS, but concentration of DO in the NYS (8.07 mg/dm^3) was greater than that of the SYS (7.08 mg/dm^3) in the upper water of cold water area. Further calculations showed that DO was unsaturated with an averaged DO saturation of 87.7% in the NYSCWM at 30 m layer of this transect.

3.3 *Nutrient*

Since the distribution pattern of DIN was quite similar to that of silicate, distributions of silicate and phosphate were selected to discuss the characteristics of nutrient distributions. In the bottom layer, the most obvious feature was the semi-enclosed contours with high values in the central YS. Nutrient concentrations in most of the surrounding area were lower than those in the central YS except for area in the southwest of YS, where strongly influenced by the Changjiang River Diluted Water (CRDW) with high nutrient contents (Wang, 1999; Wang et al., 2003; Wei et al., 2010b). Furthermore, because of the high concentrations of nutrient in the central bottom of the YS, the whole YSCWM could be regarded as the storage of nutrient of YS (Wang, 2000; Shi et al., 2009). In addition, nutrient concentrations in the SYSCWM were slightly higher than those in the NYSCWM. Thus it also indirectly indicated that large amount of the nutrient were stored in the SYSCWM, due to the higher nutrient contents and larger volume compared to the NYSCWM.

The vertical distributions of nutrient were influenced significantly by stratification of water column (Figs 3e–g). Nutrient were nearly depleted in the upper layer by the uptake of phytoplankton except the southern part of SYS (33°N), where was influenced by the input of CRDW as mentioned above. At the depth below thermocline, nutrient concentrations became greater with the increasing water depth, and the maximum concentrations of phosphate, silicate and DIN reached values greater than 1.0, 19.0, 12.0 μmol/dm^3, respectively, in the SYSCWM; while in the NYSCWM the maximum values of nutrient were higher than 0.5, 5.0 and 5.0 μmol/dm^3, respectively, which were much lower than those in the SYSCWM. Furthermore, the water area of high nutrient contents was consistent with that of low DO concentration in the SYS.

4 Chemicohydrographic characteristics of the YSCWM

Statistical analysis of all stations with temperature lower than 10°C at 30 m and bottom layers showed that salinity was less than 32.4 in the NYSCWM, but greater than 32.4 in the SYSCWM except the stations in the west boundary of the SYSCWM. Salinity of SYSCWM was dispersive and the variation range of salinity (3.0) was about three times greater than that in the NYSCWM (Fig. 4). T-S diagram also showed that the NYSCWM was more uniform in salinity than the SYSCWM.

Through the chemical element distributions on the T-S diagram of YSCWM in summer (Fig. 5), we found that contours of chemical elements were relatively dense in the SYSCWM compared to those of the NYSCWM. Distribution of DO showed that high values appeared in the stations with relatively low temperature and salinity (Fig. 5a). The concentration of DO was generally greater than 8.0 mg/dm^3 and the maximum value was 9.0 mg/dm^3 in the NYSCWM, but it was lower than 6.5 mg/dm^3 in the area with salinity greater than 33.5 in the SYSCWM. The DO maximum appeared in the stations with salinity lower than 33.5. For pH, Chl *a* and TOC, their distributions were consistent with DO in the SYSCWM. In the NYSCWM, the low pH and TOC values were accordance with the low temperature, but the Chl *a* was relatively uniform (Figs 5b–d). As for nutrient, phosphate, silicate and DIN possessed the similar distribution characteristics in the internal of the YSCWM (Figs 5e–g). In the SYSCWM, contents of nutrient increased with salinity, their distributions were contrary to that of DO. It suggested that with the consumption of DO by decomposition of organisms, pH value declined as well, and at the same time nutrients accumulated to high values in the SYSCWM. However, in the NYSCWM, distributions of chemical elements showed little change, indicating that chemical elements in the NYSCWM were mixed more evenly.

Table 1 shows the differences of chemical and hydrological variables of bottom water between SYSCWM and NYSCWM. Both average values of temperature and salinity in the SYSCWM were relatively higher than those of NYSCWM. Average concentration of DO in the NYSCWM (8.44 mg/dm^3) was much higher than SYSCWM (7.23 mg/dm^3). Nutrients and TSS were higher in SYSCWM than those in NYSCWM, especially for silicate. However, concentrations of Chl *a* and TOC were similar in the SYSCWM and NYSCWM. In addition to the temperature, variation ranges of other variables in the SYSCWM were larger than the NYSCWM. Differences of average values between 30 m and bottom cold water in the NYSCWM were much less than those in the SYSCWM, which implied that the internal water in the NYSCWM was more uniform than that of the SYSCWM. In conclusion, different strength of themocline was the key factor which led to the different characteristics of hydrographic and chemical variables in the NYSCWM and SYSCWM.

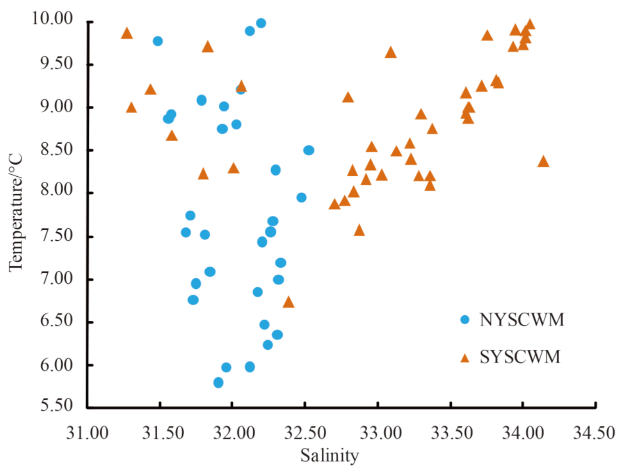

Fig. 4. The T-S diagram of YSCWM in summer.

5 Summary

Based on analysis of the horizontal distributions and cross-YSCWM transect profiles of biogenic and hydrological variables, the chemical and hydrographic characteristics of the YSCWM can be summarized as the following.

Generally, the YSCWM is low in temperature (≤10°C) but relatively high in salinity (>32.0), and it is relatively low in DO and pH values but high in nutrient concentrations in bottom water.

Specially, the spatial heterogeneity of chemical and hydrographic variables in the YSCWM shows some differences in chemicohydrographic characteristics between the NYSCWM and SYSCWM. The SYSCWM possesses relatively higher temperature and salinity than the NYSCWM, as well as their variation ranges. Due to the stronger thermocline, DO concentration is lower but nutrient concentrations are higher in the SYSCWM than those in the NYSCWM. In addition, the DO and Chl *a* maxima appear significantly at the depth of 30 m in the SYSCWM but not in the NYSCWM.

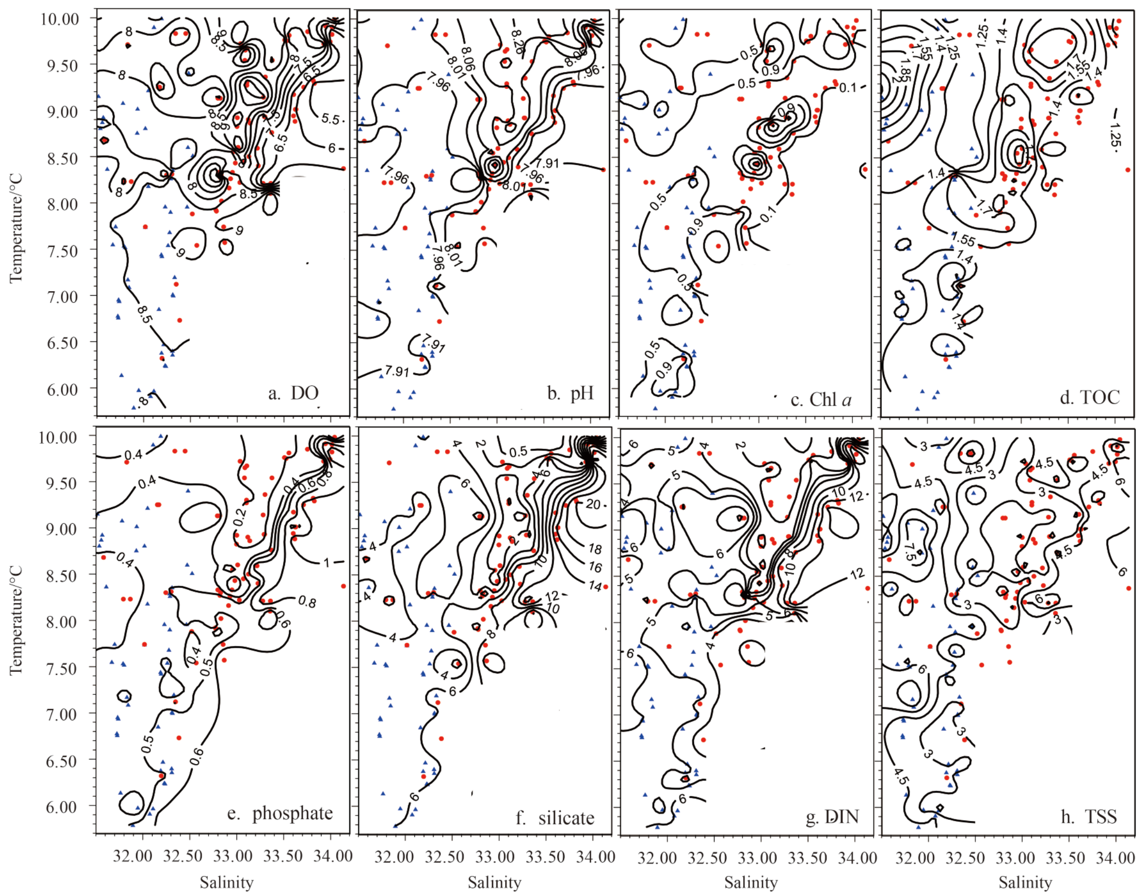

Fig. 5. The chemical element distributions (DO, mg/dm^3; Chl *a*, μg/dm^3; TOC, mg/dm^3; nutrients, μmol/dm^3; TSS, mg/dm^3) on the T-S diagram of YSCWM in summer. ● Stands for the stations of SYSCWM, and ▲ the stations of NYSCWM.

Table 1. Comparision of biogenic and hydrological variables between the SYSCWM and NYSCWM in the bottom water

	Parameter	*T*/°C	*S*	DO/mg·dm^{-3}	Chl *a*/ μg·dm^{-3}	Phosphate/ μmol·dm^{-3}	Silicate/ μmol·dm^{-3}	DIN/ μmol·dm^{-3}	TSS/ mg·dm^{-3}	TOC/ mg·dm^{-3}
SYSCWM	average±SD	8.85±0.74	33.06±0.78	7.23±1.06	0.47±0.57	0.58±0.33	8.68±6.12	7.15±4.35	5.15±2.60	1.50±0.31
	variation range	6.73–10.00	31.27–34.14	5.35–9.95	0.07–3.18	0.09–1.24	0.49–20.43	0.71–14.31	0.50–12.40	0.98–2.48
NYSCWM	average±SD	7.78±1.22	32.02±0.28	8.44±0.30	0.59±0.31	0.47±0.06	5.31±1.12	5.44±0.91	4.28±2.24	1.36±0.19
	variation range	5.79–10.00	31.48–32.53	7.59–8.99	0.18–1.22	0.29–0.56	2.19–7.63	4.01–7.97	0.90–9.50	1.04–1.65

Note: SD represents standard deviation.

Compared to the SYSCWM, NYSCWM is characterized by relatively lower temperature, salinity and nutrient concentrations but higher DO concentration, and the smaller variations of chemical and hydrological variables indicates the more uniform water of the NYSCWM. In conclusion, different intensity of thermocline and circulation feature are the main reasons, which induce the differences of chemical and hydrographic characteristics between the SYSCWM and NYSCWM.

Acknowledgements

The authors would like to appreciate Fu Mingzhu from the First Institute of Oceanography (FIO), The State Oceanic Administration (SOA) of China for providing Chl *a* data.

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