Inter-monthly regional variation of sea surface salinity and influencing factors in the East China Sea and the adjacent Northwest Pacific Ocean

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Abstract. Based on 1871-2010 monthly sea surface salinity (SSS) and flow field data, and the global seabed topography data, the inter-monthly regional variation of SSS in different regions and their influencing factors are discussed after climate zoning in the East China Sea (ECS) and the adjacent Northwest Pacific Ocean (ANPO). Results show that: (1) the study area can be divided into the area of the ECS, the Kuroshio area of the East China Sea (KECS) and the ANPO I area, II area and III area. (2) In the continental shelf area of the ECS, the inter-monthly regional variation of SSS is significant, the inter-monthly variation range of feature points is large and the difference of SSS value at each point is great. (3) In the KECS, the inter-monthly regional variation of SSS is small. The SSS at feature points is high and the inter-monthly variation is small. From the inlet to the outlet of the KECS, the SSS value gradually increases. (4) In the ANPO, the inter-monthly regional variation of SSS is the smallest, the SSS at feature points is high, and their inter-monthly variation is small. The SSS increases with increasing longitude at the same latitude, and decreases with increasing latitude at the same longitude.

1. Introduction

Climate change and its impact have become a hot spot of international concern. On the climate change study, the climate variability, process of change and temporal-spatial differentiation from inter-month to inter-decade, as well as its influencing factors and mechanism, are the key research fields of the Climate Variability and Predictability Research Program (CLIVAR), which is the core programme of the World Climate Research Programme (WCRP). Exploring the average inter-monthly climate state is the basis for further study of the inter-monthly to inter-decade climate change process and climate variability.

The ECS and its adjacent Northwest Pacific Ocean (ANPO) are important areas where affect the climate and environment of China and even East Asia [1]. The salinity, as a basic physical and chemical index of the ocean, is a quantitative indicator of the hydro-climatic-environment at the local or global oceanic condition [2].

The previous studies on SSS at the ECS are mostly limited to 20-30 years [3-6], or study the New Climate Base Period (NCBP) from 1981 to 2010, as proposed by the WMO Commission on Climatology [7]. There is no general research on the past long-term climate conditions, temporal-spatial differentiation and influencing factors.
Studying the inter-monthly mean climate state and its influencing factors of SSS in the ECS over a long time scale is the basis for further studying of the multi-scale climate change process and climate variability in China and East Asia.

In this study, SSS and current data from 1871-2010 of the ECS and the ANPO are used to divide the climate zones and explore the inter-monthly regional variation of SSS and its influencing mechanism.

2. Research area and Data

The research area includes the East China Sea (ECS) and its adjacent Northwest Pacific Ocean (ANPO) (21.25~33.25°N, 116.25~134.25°E).

The data of the sea surface salinity (SSS) and flow field come from the Simple Ocean Data Assimilation (SODA_2.2.4) developed by the University of Maryland (UMD) and Texas A & M University (TAMU) [8].

The topographic data comes from the 1-Minute Gridded Global Relief Data (ETOPO1) released by the National Geophysical Data Center of US (NGDC) [9].

3. Inter-monthly regional variations of SSS in the study area for 1871 to 2010

3.1 Inter-monthly distribution of SSS in the study area for 1871 to 2010

In order to reveal the monthly average regional distribution of SSS in the study area, the monthly average SSS data is extracted from January to December for 1871-2010 and the maps of average SSS distribution for 12 months are drawn.

Here, the months with maximum SSS (for March) and minimum SSS (for August) are shown only (Figure 1). It can be seen that:

The largest change region is found in the Yangtze River Estuary, while the obvious changes are found in the Pearl River Estuary, near Hangzhou Bay, Kyushu Island and Taiwan Island. These areas are mainly affected by runoff into the sea. The changes of SSS value and location in other months are gradually transit between March and August.

In general, there are some regional characteristics, from the continental shelf area of the ECS to KECS, and then the ANPO, the SSS value increases from small to large and the SSS changes from large to small.

3.2 Characteristics of annual range of SSS in 140 years for the study area

In order to analyze the regional variation amplitude and range of SSS in the study area, the annual range is counted out by the average SSS of August subtracting from March and the annual range chart of SSS in the study area is drawn (Figure 2).
From figure 2, the annual range of SSS in the study area is extremely uneven. It can be divided into the continental shelf sea area of the ECS, the KECS and the ANPO. Among them, the seasonal difference in the continental shelf of the ECS is the most significant, while that in the KECS and the ANPO is relatively small.

4. Climatic zoning and average inter-monthly differentiation of SSS at typical feature points in each climate zone

4.1 Climatic zoning
Considering that the ocean current is an important driver of material transportation and it can change the direction of ocean movement and salinity distribution. The vector data of surface current from 1871 to 2010 is further extracted and the map of surface current combining the SSS distribution for 140 years is drawn (Figure 3), to determine the climate condition zones and select the typical feature points at each climate zone.

From figure 3, there are three different flow field patterns in the ANPO with the boundary of 25°N and 29°N. Therefore, the climate structure of SSS in the whole area can also be divided into the continental shelf area of ECS, the KECS and the ANPO (including zone I, II and III).
4.2 The inter-monthly regional differentiation of SSS at typical feature points in different climate zones

According to the climate zones mentioned above, 21 typical feature points are selected in combination with the respective characteristics of each climate zones. The inter-monthly variation curves of the feature points in each sea area and their location distribution are displayed below.

4.2.1 The continental shelf area of the East China Sea (ECS). In the continental shelf area of the ECS (figure 4), there are three types of feature points:

1. The first type (D1, D2): The inter-monthly variation range of SSS is large, and the seasonal variation is obvious. The average SSS of D2 is lower than that of the other five points for each month in the past 140 years, mainly because it is the closest to the Yangtze River Estuary and is most affected by the fresh water of the Yangtze River. Compared with D1, which is also located in the impact area of the Yangtze River, the change trend of D1 and D2 is similar. However, from April to October, D1 is greatly affected by the North-South movement of the low salinity tongue from the Yangtze River, while D2 is always moving in the inner and outer periphery of the low salinity core from the Yangtze River. Therefore, the inter-monthly variation range of the SSS of D1 is larger than that of D2, especially from July to October.

2. The second type (D3): The inter-monthly variation range of SSS is larger, but the variation trend is completely opposite to the other five points. D3, which is located at the south of Hangzhou Bay, the SSS first increases and then decreases from April to October, and reaches the maximum in August. From October to next April, the variation of SSS is gentle, and the SSS is low in 12 months. Maybe from April to October, the tongue of the Yangtze River diluted water moves to the northeast, which restrains the southward movement of the North Jiangsu coastal current. In the same period, southeast monsoon gradually prevails. The coastal current in the ECS brings relatively high salinity water from south to north, and plus the influence of the rise of Taiwan warm current [10], which makes D3 a different trend of change.

3. The third type (D4, D10, D11): The SSS is higher and the variation range is smaller. The SSS variation range of D4 is the lowest among six points, and its SSS reaches the minimum in August. Compared with D10, both of them are located near the 34 PSU isohaline in the 140 year surface average salinity distribution map, and are also affected by the fresh water flowing into the sea. Therefore, the inter-monthly average value and the inter-monthly variation curve of SSS are close to each other. However, the variation of SSS of D4 from April to October is slightly smaller, which indicates that the influence of Pearl River diluted water to SSS in its surrounding sea area is far less than that of Yangtze River diluted water.

The inter-monthly variation of SSS at D11, follows the general variation trend of the feature points in the continental shelf of the ECS (except D3). But the minimum value of SSS concentrated in May and June, and gradually increases from June to September, one month ahead of the rest. It is closely related to the location of D11. The Taiwan warm current originates from the Taiwan Strait and the Kuroshio, and usually flows northward along the coasts of Fujian and Zhejiang to the Yangtze River.
When meeting with the coastal water which is formed outside the Yangtze Estuary, the Taiwan warm current turned to the northeast, or even to the east. Since May is the transitional period of the Yangtze River fresh water tongue moving from north to south, the Yangtze River diluted water mainly acts on the sea area near the Yangtze River Estuary. D11 is greatly affected by the Yangtze River diluted water at this time, and its SSS is low. From June to August, the Yangtze River fresh water tongue moves to the northeast, and its impact weakens. The influence of Taiwan warm current with higher SSS increases, so the SSS of D11 begins to increase.

Generally, since March, the runoff of the Yangtze River increases, and the scope of the Yangtze River diluted water gradually expands. After September, the runoff of the Yangtze River decreases, and the influenced scope of the Yangtze River diluted water in the east reduces to 123°E. Affected by this process, the SSS of 4 feature points are all high from October to next April. The SSS of the feature points from small to large are D2, D1, D11, and D10, which are mainly affected by the distance from the Yangtze River diluted water.

4.2.2 The Kuroshio area of the East China Sea (KECS). In the KESC (Figure 5), there are two types of feature points:

Figure 5. Inter-monthly variation curves of SSS at feature points in the KECS for 140 years.

The first type (D5, D6, D7, D9, D13, D14): The overall SSS value is higher, and the variation trend is close.

From April to October, the monthly average SSS of D5-D7 and D9, located on the main body of the Kuroshio, increases from the inlet to the outlet.

D5 is located near the Huoshaoliao, the "rain pole" in China. During summer and autumn, due to the proximity to the source of summer monsoon, the moist Pacific air-water is brought by the southeast summer monsoon forms dense rain here. When the typhoon lands, the terrain lifts, and abundant precipitation forms, besides, large terrain drop, short rivers, strong currents, and the lack of holding lakes together, cause most of the surface water to quickly drain into the ocean, which has a great influence on the reduction of SSS of D5. But, from October to next April, the SSS of D5 is higher than that of D6. This is due to the gradual strengthening of eddy activity in the sea area east of the Bass Strait in winter, which brings a part of the West Pacific high-salt water into the inlet of the Kuroshio.

The second type (D8, D12): From March to August, the inter-monthly SSS rate is large and the inter-monthly difference is obvious.

D8, where is located at the third turning of the Kuroshio Current, has the lowest average SSS in the typical feature points of the whole Kuroshio area, except that it is higher than D6 from January to March. From April to August, the SSS of D8 also shows the largest variation. D8 is close to the Yangtze River estuary and is affected by the Yangtze River diluted water, especially in summer, which has a greater influence on the SSS of the Kuroshio area than in other seasons. While, the average SSS of D9 at the outlet of Kuroshio is quite different from that of D8 at the same latitude. On the one hand, it is the effect of the Yangtze River diluted water on SSS to D8. On the other hand, D9 is located at the junction of the Kuroshio outlet and the Kuroshio extension current, which is also the edge of the vortex in the ANPO I
area. The high-salt seawater may come partly from the upwelling of high-salt water at the subsurface layer under the Kuroshio, and partly from the high-salt water of the Northwest Pacific.

The monthly average SSS of the second point (D12) located at the approximate PN section is generally lower than that of the third point (D13). Compared with the three typical feature points selected on the approximate PN section, the closer the side of the continental shelf, there is the lower the SSS value, and the greater the annual variation range of the SSS.

In general, the inter-monthly variation trend of average SSS of eight typical feature points in this area is consistent, with low SSS during summer and autumn, and high SSS in winter and spring. Except for D8 and D12, whose SSS decrease month by month since March. The other typical feature points are as follows: from January to April, the SSS is relatively high and gently decreases, among which, the month of D6 with highest SSS is January, that of D14 is in March and that of other feature points is in February. From April to August, the SSS decreases rapidly, and the lowest values are mainly concentrated in July and August (D6 is in September). From August to December, the SSS increases rapidly.

4.2.3 The adjacent Northwest Pacific Ocean (ANPO). In the ANPO (Figure 6, Figure 7, Figure 8), there are two types of feature points:

Figure 6. Inter-monthly variation curves of SSS at feature points in the ANPO for 140 years.

The first type (D15-D19, D21): The overall SSS value is high and the variation trend is similar. The 12-month SSS of the six feature points are all higher than that of the continental shelf area of the ECS and the KECS. The inter-monthly variation trend of SSS is relatively consistent. In general, the SSS value of each feature point reaches the maximum in March (D20 is in February), and reaches the minimum in July, August and September, the rest are transitional months. It’s maybe because the precipitation in the ANPO is concentrated in summer (July to September). There is less precipitation in the ANPO in winter and spring, so the SSS is high. D21 is located at the edge of the vortex in the ANPO II area, so it is very little affected by land and sea currents. The inter-monthly SSS variation of D21 can represent the overall variation of the inter-monthly SSS in the whole Northwest Pacific.

The second type (D14, D20): The SSS value is low; the difference is obvious especially in July and August. May be it is affected by the location, precipitation and other factors. See the analysis below for details.

Figure 7. Inter-monthly variation curves of SSS at feature points with the same latitude in the ANPO for 140 years.
The inter-monthly variation trend of SSS for D14, D15, D16 and D17 is basically the same, which are at the same latitude (22.25°N) (as shown in the figure 7).

Generally, the larger the longitude is, the higher the SSS for the 12 months is. Among them, the inter-monthly variation trend lines of SSS at D15, D16 and D17 are close. While the average SSS for 12 months of D14 is different from the above three points. D14 is a branch entrance of the Kuroshio that located at the Ryukyu Islands, but the Kuroshio Water with high salinity has little effect on it. On the one hand, it is at the turning position before the typhoon lands. In July to September, there are more heavy rains and the SSS value drops faster. On the other hand, it is close to D5, and is affected by abundant precipitation throughout the year in Huoshaoiao on the eastern part of Taiwan Island. Specially, the average SSS of D17 is lower than that of D16 from June to September.

Figure 7. The inter-monthly variation trend of SSS at feature points with the same latitude in the ANPO for 140 years.

Figure 8. The inter-monthly variation curves of SSS at feature points with the same longitude in the ANPO for 140 years. The inter-monthly variation trend of SSS for D17, D18, D19 and D20 is basically the same, which are at the same longitude (133.25°E) (as shown in the figure 8).

Generally, except for D17, the feature points with higher latitude has the smaller average SSS value during 12 months. Among them, the inter-monthly variation trend lines of SSS at D17, D18 and D19 are close. While D20 is different from the above three points. D20 is the marginal point of the Northwest Pacific, and its northwest is close to Kyushu Island. The reason for its lower SSS may be similar to D14, which is more likely to be affected by the terrain precipitation. Specially, except June, July and August, the average SSS of D17 is lower than that of D18 and D19.

To sum up the inter-monthly variation figure of SSS of the same latitude or longitude feature points in the Northwest Pacific (Figure 7, Figure 8), and according to the above rules, the average SSS of D17 is slightly lower than other feature points in the Northwest Pacific. However, the inter-monthly variation curves of SSS of all typical feature points in the Northwest Pacific tend to be consistent, and the variation range is very small.

5. Conclusion

SODA_2.2.4 marine hydrological climate environment data set and seabed topography depth data are used to analyze the monthly average SSS and flow field distribution characteristics in the ECS and the ANPO for 1871 to 2010. The climate zones of SSS are divided. The inter-monthly variation and regional differentiation of SSS are analyzed and the influencing factors are discussed. The results are as follows:

(1) According to the regional distribution of SSS and combined with topography and previous research, in the ECS and the ANPO, it can be divided into three climatic regions of SSS, namely the continental shelf area of the ECS, the KECS and the ANPO. Combined with the characteristics of the flow field, the ANPO can also be divided into three sub zones, namely ANPO I area, II area and III area.

(2) In the continental shelf area of the ECS, the regional variation of SSS is great, and the inter-monthly variation of SSS is significant. At the Yangtze River Estuary, near Hangzhou Bay and near Pearl River Estuary, the SSS is quite different from that of other areas in the same sea area. D11, where is located at PN section, the minimum value of average SSS appears in May and June, and gradually increases from June to September, one month ahead of the rest. This not only reflects the influence of
the North-South movement of the Yangtze River diluted water, but also is related to the Taiwan warm current from the south.

(3) In the KECS, the inter-monthly regional variation of SSS is smaller and the salinity value changes little. The trend of isohaline is consistent with the Kuroshio current path. Only in the coastal of Kyushu Island, the annual range of SSS is relatively large, which is influenced by the continental shelf area of the ECS and its own runoff into the sea. From April to October, the average SSS of D5-D7, and D9, where are following Kuroshio current path, gradually increases from the inlet to the outlet of the KECS. However, at the third turning point of the Kuroshio, the SSS value of D8 is low, it is the impact from the Yangtze River diluted water. Because D5 is close to the south side of Taiwan Island and is greatly affected by the land diluted water and precipitation, the SSS of D5 is lower than that of other feature points along the Kuroshio path, especially in summer. From October to next April, the eddy activity in the area east of Bashi Strait gradually strengthens, and part of the Western Pacific high salinity water inflows the Kuroshio inlet, which increases the SSS of D5.

(4) In the ANPO, the distribution of SSS is uniform, and the inter-monthly regional variation of SSS is very small. At the same latitude, the SSS increases with the increase of longitude; while at the same longitude, the SSS decreases with the increase of latitude.

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