Kuroshio Axis Variation and Its Impact on Sea Level Change of East China

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Abstract: A close relationship is existing between the Kuroshio axis variation of the East China Sea and East Sea sea level change. Based on AIPOcean 1.0 DataSet, this paper developed the principal axis extraction procedure, analyzed the response mechanism of East China Sea level change to the Kuroshio axis variation in depth, and obtained that: ①Being mainly influenced by the combined influence from monsoon, terrain, Changjiang diluted water etc., to the north of 26°N, the East China Sea Kuroshio axis is inclining to the west in winter and spring, while inclining to the east in summer and autumn; at northeastern Taiwan axis bend point, affected by the monsoon and the terrain, its deviation is just the opposite; ②The East China Sea Kuroshio axis is mainly located within 0-250m, mostly distributing at tide layer at 1, 3, 4, 9, accounting for 72%. The Kuroshio mainstream is shrinking and narrowing with the depth, as a result of which most of the Kuroshio flow, quality and momentum transport concentrate at the middle and upper layer. ③With the increase of the principal axis velocity, the right side of sea level shows a downward trend while the right side of sea level rises as a whole. Since it is close to the Kuroshio source area, Kuroshio water with high velocity at the entrance to Kuroshio drives the left and right sides of sea level rising. In the north transport process, it will exchange material and energy with the East China Sea continental shelf water continuously. Its flow velocity will begin to decline as getting to the middle of Kuroshio, and both the left and right sides of sea level will show a slow decline or invariant feature.

Keywords: East China Sea, Kuroshio axis, Sea level change.

1. Introduction

The Kuroshio is a strong ocean current at the north Pacific western border, which is characterized by high temperature, high salinity, narrow stream, great flow velocity, and large flow rate[1, 2]. It is known as one of the two biggest currents in the world, enjoying the equal popularity with the Gulf Stream [3, 4]. It is originated from the North Equatorial Current, carrying high temperature and high salinity water to the east of Taiwan, passing through the submarine ridge at the east of 50°E and flowing into the East China Sea. It flows to the northeast direction along with the outer East China Sea continental shelf, to the northeast direction along with south bank of Kyushu, Honshu and other islands in Japan, and then to the east at about 141°E, 35°N[5]. Kuroshio spans about 15 latitudes from north to south and about 40 longitudes from east to west. The part flowing through the East China Sea is called East China Sea Kuroshio which occupies an important position in the whole Kuroshio system.

The East China Sea Kuroshio is an important part of the Kuroshio system. Its flow velocity is strong and stable. The principal axis velocity is up to 100-150cm/s and the maximum flow velocity is approximately 180cm/s. The velocity structure is given priority to single-core, often accompanied by dual or multi-core structure [6, 7]. One half of the maximum flow velocity of East China Sea Kuroshio (namely the core) is located on the surface to 50m, to the surface layer. And the other half is located at much deeper position, from 100-200m[8]. Countercurrent almost exists at the right side of Kuroshio all the year round. Large countercurrent may form flow core as well.

The Kuroshio, as the western boundary current of the north Pacific subtropical circular current, has an important influence on China's offshore circulation and sea level, SST abnormality at the East China Sea Kuroshio sea area is a key factor affecting summer atmospheric circulation and precipitation in China. The East China Sea Kuroshio takes interaction with the East China Sea continental shelf water at the widest mid-latitude shelf of the world and performs matter and energy exchange and transformation, which have strong influence on China’s offshore circulation and have become the main power of China’s offshore circulation variation[9, 10]. The flow velocity, flow rate and stream of its principal axis are of great significance on sea level change of the East China Sea, especially the Kuroshio area. The position offset of Kuroshio also has strong impact on the east Asian climate, the distribution of Marine sediments at this region and the surface productivity.

Researches show that Kuroshio flow changes are closely related to both the left and right sides of sea level of Kuroshio, height difference between the left and right sides of sea level and the sea level change of the whole Kuroshio drainage basin [11]. When Kuroshio flow increases, the overall sea level rises. However, the left side of sea level will be lower than the right side of sea level, and height difference between the left and right sides of sea level will increase. The sea level change will lag behind the Kuroshio flow rate change about half a year. In addition, previous studies have found that [12], during the Kuroshio big bend process, the Kuroshio flow, temperature-salinit and atmosphere will have corresponding changes which will lead to obvious rising of sea level. The Kuroshio big bend refers to the U or V type bending of the Kuroshio path at the south sea area to Honshu in Japan [13]. When the Kuroshio appears big bending, the sea level may become abnormal due to the increase of the Kuroshio flow. When the Kuroshio bending plays as the main factor, the sea level will rise and has a higher sea level value; while when it is given priority to ENSO, the sea level will drop and has a lower sea level value.

The previous studies mainly focus on Kuroshio flow rate, flow velocity and principal axis. A further research is to be performed on the relationship between the East China Sea Kuroshio axis position offset, the yearly, quarterly, and monthly variation tendencies of principal axis flow direction and vertical distribution, velocity zonal change rule and the sea level on both sides of principal axis change responding to flow velocity changes etc.. Based on the reanalysis data of AIPOcean1.0 [14], the paper extracted the velocity data, defined the scope and boundary of East China Sea Kuroshio according to the flow velocity, determined the maximum velocity line is as the Kuroshio axis; independently researched and developed the principal axis extraction procedure, performed comparative study on sea surface height data on both sides of the principal axis and analyzed the response mechanism of East China Sea level change to Kuroshio axis variation in depth.

2. Boundary determination and principal axis extraction of East China Sea Kuroshio

2.1 Boundary determination

To research change law of the principal axis of East China Sea Kuroshio area and its relationship with the sea level changes, the east and west boundaries of East China Sea Kuroshio have to be determined firstly and then to draw the principal axis of East China Sea Kuroshio. From the start-up phase of the Kuroshio research in the 1870s, many scholars used the aerial data and proposed many methods to determine the Kuroshio east and west boundaries. For example Sun Xiangning et al. [15] (1991) proposed that the isotherm distribution at layer 200m from 15-18℃ is quite similar to the Kuroshio path. Thus the 15℃ isotherm can be determined as the inner (left) boundary of Kuroshio and the 18℃ isotherm can be determined as the outer (right) boundary of Kuroshio; Yu Fei et al. [9] (2002) proposed that the
Kuroshio boundary is equivalent to the biggest area of the level of temperature gradient at 100 or 200m layer, thus the 20℃ isotherm above 100m layer or the 18℃ isotherm above 200m can be adopted to present it.

This paper selected East China Sea as the research scope, referring to the Kuroshio boundary determination method proposed by Kang Jiancheng et al. [16] (2013) to define the slope toe line of eastern slope of Okinawa trough and the slope break 500m of Ryukyu islands chain as the east boundary of East China Sea Kuroshio within the scope of 22°N-33.5°N, 120°E-130.5°E; and the 160m isobath of East China Sea continental shelf as the west boundary of East China Sea Kuroshio (Figure 1).

Figure 1 East China Sea Kuroshio Boundary

The part shown with bond solid line is the selected East China Sea Kuroshio boundary.

2.2 Principal axis extraction method

For the general flow path of the main body of East China Sea Kuroshio, most of the predecessors are based on aerial data, depicting the general flow direction of flow axis by utilizing the Max. flow velocity. The general flow direction of the East China Sea Kuroshio path has been clean until now. But aerial velocity data resolution is relatively low, the error is bigger, and the maximum velocity line obtained is relatively coarse. The paper conducted orthogonal synthesis on radial and zonal velocity data of the Kuroshio area to extract north orientation data; Considering that multiple points may occur at the same latitude as simply extracting the maximum values, the maximum values of each point at different depth of the study area space will be extracted firstly to draw an isobathic chart. By using Matlab software, we develop the principal axis drawing, extract principal axis data procedure, draw the year by year and multiple years' average yearly, quarterly and monthly principal axis moving trends of East China Sea Kuroshio.

3. Flow path change and vertical distribution law of the East China Sea Kuroshio

3.1 Temporal and spatial variation of principal axis flow path

Many scholars carried out studies on flow direction of Kuroshio axis and generally believed that Kuroshio axis flows along the outer continental shelf, being restricted by terrain, path and flow pattern of Kuroshio are basically stable [9, 17], and that the overall seasonal change is not obvious, faster in spring and slower in autumn. It is a western narrow strip boundary flow with fairly stable flow principal axis [4, 18]. However, the flow principal axis will have some offset to the right side with the increase in depth, with almost no flow change at vertical direction[15]. The anticyclonic type of small bending seasonal variation may occur in northeastern Taiwan and the position adjacent to Tokara Strait, which makes Kuroshio axis presenting as a snake shape stable structure [19]. Strong interaction exists between East China Sea Kuroshio and East China Sea continental shelf water, especially at the entrance (in northeastern Taiwan) and export (northern Kuroshio bending). The Kuroshio water will be divorced from the main trunk and flow to the continental shelf, mainly emerging at Taiwan’s northeast sea area and Kyushu southwest sea area, secondly at the middle section of Kuroshio (28°N) [9].

In this paper, based on the research and development of the principal axis drawing and data extraction procedure, multiple years’ average quarterly principal axis flowing direction diagram is obtained (Figure 2). It can be seen that bounded to Kuroshio axis, there is a significant difference between both sides of sea level, lower at the left and higher at the right and that the overall trends of four seasons are consistent, the reason for which may be that the AIPOcean1.0 date is as model simulated data that pays more attention to middle or large scaled sea level changes and a bit rough on the description effects after local sea level change data averaging and smoothing. But the description of the general trend of the change of sea level is accurate.
Figure 2 Quarterly Kuroshio Principal Axis Flow Direction Diagram of East China Sea. (Dotted line as line of reference)
The Kuroshio axis flow is basically stable throughout the year, and bending occurs in northeastern Taiwan and Kyushu southwest sea areas. Taiwan's northeast sea level is higher compared to other sea areas of the East China Sea throughout the year, which is mainly caused by the following two reasons: the first one is that being affected by terrain, the Kuroshio will flow to northeast through Taiwan Strait; the second one is that it is located at the entrance to the east China sea of the Kuroshio and that the Kuroshio water with high temperature and high salinity just enters the East China Sea, resulting in increase in the sea water temperature and sea level; moreover, the Kuroshio will have bending at these two points. Li Kunping [13] (1993) believes that when big bending forms at Kuroshio, the seawater temperature will present a relatively higher value and the sea level will rise obviously, presenting a high value.

3.2 Principal axis vertical distribution rule

From statistic analysis of distribution proportion at each layer of principal axis data extracted from different depths according to the Vertical Layer and Depth Corresponding Table, from the annual change trend, the values at the principal axis (Max. flow velocity) are mainly distributed at the first 10 layers (namely no deeper than 250m), mostly distributing at tide layer 1, 3, 4, 9, accounting for 72%. From the point of seasonal change, they are mainly distributed at layer 3, 4, 5, 9, accounting for 67.8% in spring and winter and all the points are distributed at the upper 11 layers; and mainly distributed at the surface layer (the first layer), accounting for 52.1% and 65.6% respectively in summer and autumn and all the points are distributed at the upper 11 layers; it is consistent with the conclusion that the velocity of extremum is located at the surface layer to 250m layer, which is proposed by Miao Yutian et al. (1984); and it is basically in line with the conclusion that most of the Max. flow velocity (namely the core) of East China Sea Kuroshio are located at the surface layer deeper to 50m and the other half are located at 100-200m depth proposed by Wu Zhiyan [20-22] (2008). The Kuroshio mainstream is shrinking and narrowing with the depth, as a result of which most of Kuroshio flow, quality and momentum transport concentrate at the middle-upper layer.

4. Relationship between East China Sea Kuroshio axis flow velocity and sea level changes

Through researches on the relationship between the change of principal axis flow velocity and sea level, we can determine the corresponding relationship of sea level to the change of flow velocity and flow path, can also perform in-depth analysis of causes of sea level changes and reveal the influence mechanism of East China Sea Kuroshio to sea level change. Most of the previous researches basically adopt extracting a certain velocity range, for example 40cm/s[21,23], 51.4cm/s[24-25] etc. as the width of Kuroshio mainstream and generally take the Max. flow velocity line of Kuroshio as the flow core. The paper extracted the Max. flow velocities of Kuroshio, drew up a line to obtain the Kuroshio axis (flow core) and performed contract analysis by extracting the flow velocity values at the principal axis, the surface abnormal values corresponding to each point at principal axis, surface abnormal values corresponding to left and right boundaries (Figure 3).

Generally, along the flow direction of East China Sea Kuroshio, sea level presents characteristics of being lower at left side and higher at right side (right boundary) > principal axis > left boundary). The first half of the right boundary will gradually increase with the latitude rise, and with a Max. rising rate at the entrance to Kuroshio while the change trend of the second half is not obvious and has slow dropping at the exit; the first half of the left boundary will present fluctuated changes with the latitude rise, while the change trend of the second half is not obvious and has slow dropping at the exit section of Kuroshio. The sea surface height corresponding to principal axis has a dropping trend at the east of Taiwan and variation trend of the rest of entire process is relatively stable. The flow velocity of the Kuroshio axis presents the characteristic of rising first and then dropping. From the entrance to the middle section, the flow velocity is increasing all the time and than is slowly dropping with a little bit rising at the exit. The Max. flow velocity always appears at the biggest terrain slope at the south of East China Sea [4, 25].

![Figure 3. Comparison of Principal Axis Velocity with Seal Levels of Left and Right Boundaries and Principal Axis (Based on multiple years' average data)](image)

The paper divided the whole flow process of Kuroshio axis into 6 phases (Figure 3), namely phase A to F to analyze the corresponding relationship of the principal axis flow velocity to sea level change. During phase B, D, F, with the increase in flow velocity of the principal axis, the left side of sea level shows a trend of dropping while the right side of sea level is overall rising which is consistent with the conclusion proposed by Chen Meixiang (2009). In phase A (the entrance of East China Sea Kuroshio), however, since it is close to the Kuroshio source area, Kuroshio water with high temperature and high salinity will go through the Luzon Strait, Taiwan Strait and then turn to northeast. The flow velocity of Kuroshio is fast there and will drive both of the left and right sides of sea level rising. During phase C, E, the flow velocity is dropping. Both the left and right sides of sea level will show a slow decline or invariant feature. In the north transport process of Kuroshio, it will exchange material and energy etc. with East China Sea continental shelf water continuously. Its flow velocity will begin to decline after the middle of Kuroshio.

The specific volume of sea level change plays an important role in East China Sea level change. This paper will analyze the specific volume of sea level change during sea level change of East China Sea Kuroshio. According to the researches [11], the specific volume of sea level is rising in the whole East China Sea Kuroshio drainage basin. Compared with distribution trend of specific volume sea level and general distribution trend of sea level, the difference around Kuroshio is bigger; while comparing the sea level rising trend at both sides of Kuroshio with the specific volume sea level, it is not obvious; the specific volume change trend of sea level far away from the Kuroshio is similar to that of the sea level.
In comparison of seasonal change trend and annual change trend of the left and right boundaries, the principal axis sea level abnormality and the principal axis flow velocity aforementioned, it can be found that the trends are basically the same. But the seasonal changes of each element are different, the change law of which in spring, summer, autumn and winter are studied in depth in this paper. By comparing we can see that the seasonal variation of left and right boundaries and sea level above principal axis is characterized as autumn>winter>summer>spring; left boundary at the first half of the principal axis is more violent and shows the tendency of slow decline at the latter half; the right boundary rises from the entrance to Kuroshio to the sea level in the northeast of Taiwan, and then the rising trend slows down, and the seasonal difference in sea level at the latter half is obvious; the seasonal change law of principal axis is relatively complex: the fluctuation and variation at the first half is obvious while continuously decreasing at the latter half; the seasonal change of flow velocity at the same latitude is not great; the surface abnormal values corresponding to the principal axis show that the seasonal change of sea level at the same latitude is great and the variation trend is basically consistent with that of the principal axis flow velocity.

5. Conclusion

(1) The Kuroshio axis flow is basically stable throughout the year, relatively smooth at the middle flow path and bend in northeastern Taiwan and Kyushu southwest sea areas. The East China Sea Kuroshio has obvious offset feature along with seasonal change.

(2) The multiple years' average data of East China Sea Kuroshio shows that most of the values (Max. flow velocity) are mainly distributed at the first 10 layers (no deeper than 250m), most distributing at layer 1, 3, 4, 7, accounting for 72%. From the point of seasonal data, they are mainly distributed at layer 3, 4, 5, 9, accounting for 67.8%, and all the points distribute at the first 11 layers; in summer and autumn, they mainly distribute at the surface layer (the first layer), accounting for 52.1% and 65.6% respectively, and all the points distribute at the first 11 layers; the Kuroshio mainstream is shrinking and narrowing with the depth, as a result of which most of the Kuroshio flow, quality and momentum transport concentrate at the middle-upper layer.

(3) The seasonal variation of the left and right boundaries and sea level above the principal axis is characterized as autumn>winter>summer>spring; the left boundary at the first half of the principal axis is more violent and shows the tendency of slow decline at the latter half; the right boundary rises from the entrance to Kuroshio to the sea level in the northeast of Taiwan, and then the rising trend slows down, and the seasonal difference in sea level at the latter half is obvious; the seasonal change law of the principal axis is relatively complex: fluctuation and variation at the first half is obvious while continuously decreasing at the latter half; the seasonal change of flow velocity at the same latitude is not great. The flow velocity of principal axis presents the characteristic of rising first and then dropping. From the entrance to the middle section, the flow velocity is increasing all the time and then is slowly dropping with a little bit rising at the exit. The Max. flow velocity always appears at the biggest terrain slope of the south of East China Sea.

(4) At the entrance to East China Sea Kuroshio, since it is close to the Kuroshio source area, Kuroshio water with high temperature and high salinity will go through the Luzon Strait, Taiwan Strait and then turn to northeast. The flow velocity of Kuroshio is fast there and will drive both of the left and right sides of sea level rising. At the middle sea area of the Kuroshio, with the increase in the principal axis velocity, the left side of sea level shows a downward trend while the right side of sea level rises as a whole. The height difference increases at both sides of principal axis. In the north transport process of East China Sea Kuroshio, it will exchange material and energy with the East China Sea continental shelf water continuously. Its flow velocity will begin to decline after the middle of the Kuroshio, the principal axis velocity will slow down and both the left and right side of the sea level will show a slow decline or invariant feature.

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