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Seasonal variability of Kuroshio intrusion northeast of Taiwan Island as revealed by self-organizing map*

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Abstract The self-organizing map method is applied to satellite-derived sea-level anomaly fields of 1993–2012 to study variations of the Kuroshio intrusion northeast of Taiwan Island. Four major features are revealed, showing significant seasonal variability of the intrusion. In general, the intrusion increases (decreases) with a high (low) sea-level anomaly at the edge of the East China Sea shelf in winter (summer). Open-ocean mesoscale eddies play an additional role in modulating the seasonal variation of the intrusion. Further analyses are needed to study eddy-Kuroshio interaction dynamics.

Keyword: Kuroshio intrusion; self-organizing map; mesoscale eddies

1 INTRODUCTION

The Kuroshio Current (KC) is the strongest western boundary current in the western Pacific. It flows poleward along the east coast of Taiwan Island, transporting warm tropical water toward high latitudes. Satellite images show that the KC is often associated with energetic meanders and eddies merging east of Taiwan Island (John et al., 2001; Zhang et al., 2001). In the East China Sea (ECS), the steep slope acts as a strong potential vorticity barrier that constrains water exchange between the KC and ECS. Kuroshio intrusion activities mainly occur in two regions, northeast of Taiwan Island and southwest of Kyushu Island, as shown by numerous studies (Nitani, 1972; Lie and Cho, 2002; Isobe, 2008; Ma et al., 2009).

The current system and associated variations northeast of Taiwan Island are complex. The Kuroshio intrusion northeast of Taiwan Island is traditionally referred to as a quasi-steady current, especially in winter. It is called the Kuroshio Branch Current (KBC), with long-term mean transport ~1.4 Sv (Isobe, 2008). The KC axis migrates seasonally northeast of Taiwan Island, shifting shoreward in fall and winter, and seaward in spring and summer (Ma et al., 2009; Liu and Gan, 2012). Similar seasonality is observed in terms of KBC intensity, which is stronger in winter and weaker in summer. Oey et al. (2010) attributed the seasonal variation to the cross-shelf baroclinicity change associated with surface cooling, and Guo et al. (2006) showed that seasonality of the Kuroshio onshore flux along the entire ECS shelf is primarily balanced by local wind stress. Recent studies proposed that the mesoscale eddies are important in modulating the Kuroshio intrusion northeast of Taiwan Island. Gawarkiewicz et al. (2011) suggested that more (less) onshore intrusion is associated with low (high) Kuroshio transport and cyclonic (anticyclonic) eddy activities east of Taiwan Island. Based on 20-year historic drifter tracks, Vélez-Belchí et al. (2013) demonstrated that cyclonic eddies from the western Pacific can indeed introduce some large Kuroshio intrusions. A cold eddy or sometimes multiple cold eddies (Sun and Xiu, 1997; Tang et al., 2000) are

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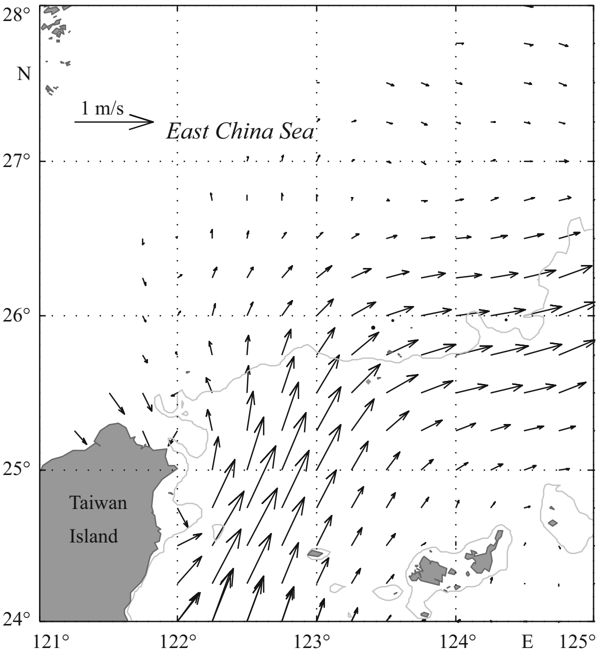

Fig.1 Twenty-year average geostrophic currents based on AVISO absolute dynamic height

A scale vector of 1 m/s is also shown. Only currents with depths greater than 100 m are shown. Gray line represents 200-m isobath.

frequently observed northeast of Taiwan Island. Eddy activity induces local upwelling and provides a major mechanism of nutrient delivery to support primary production in the ECS (Gong et al., 1997; Sassa et al., 2008; Sassa and Tsukamoto, 2010).

Clearly, the flow pattern northeast of Taiwan Island can be impacted by both local seasonal surface atmospheric forcing and mesoscale eddies east of the island. The spatial and temporal variabilities of such features need further investigation. Moreover, whether there is any linkage between the Kuroshio intrusion induced by local seasonal surface atmospheric forcing and intra-seasonal mesoscale eddy activities remains unclear. In this paper, we apply self-organizing map (SOM) analysis, an effective method for feature extraction and classification to further quantify spatiotemporal variability of the Kuroshio intrusion northeast of Taiwan Island based on satellite-derived sea-level anomaly (SLA) data, and discuss the potential contribution of the intra-seasonal mesoscale eddies to seasonal variation of the Kuroshio intrusion.

2 DATA AND METHOD

Gridded SLA data from Archiving, Validation and Interpretation of Satellite Oceanographic (AVISO) (http://www.aviso.oceanobs.com/) during January 1993 to December 2012 were used for SOM analysis. The Kuroshio itself is much stronger than its variation northeast of Taiwan Island. Therefore, compared with the geostrophic current, the geostrophic current anomaly was expected to exhibit variations more clearly. AVISO SLA is a blended product from all available altimeter satellite surface topography (Jason 1 and 2, Envisat, ERS, Topex/Poseidon). Spatial and temporal resolutions are 1/4° and 7 days, which is sufficient for resolving mesoscale eddy activities with research quality (Chelton et al., 2011). The resulting geostrophic velocity anomalies derived from the SLA are used to describe flow patterns.

The SOM is an unsupervised neural network method based on competitive learning (Kohonen, 1982, 2001). It extracts dataset features by projecting high-dimensional data into low-dimensional (usually two-dimensional) space and, in so doing, it effectively preserves input data information because of the topology-preserving technique. Since SOM has been demonstrated to have many advantages over conventional methods (such as Empirical Orthogonal Functions) for feature extraction (Liu et al., 2006a), the method has been used widely in the study of meteorology and oceanography (Liu et al., 2006b; Liu and Weisberg, 2011; Jin et al., 2010; Tsui and Wu, 2012; Xu et al., 2013). The tunable SOM parameters must be specified prior to the neural network training process. Parameterizations are set to a rectangular lattice, "sheet" map shape, linearly initialized weights, batch training method, and "ep" neighborhood function with radius 1 according to Liu et al. (2006a), to produce an accurate representation of feature extraction. We define the map size as 2×2 to represent the strong seasonal variations of the Kuroshio intrusion. A series of sensitivity experiments with varying map sizes (2×3, 3×3, and 3×4) were also conducted, and the basic SLA patterns remained similar to the result based on a 2×2 map size. In addition to the four SLA spatial patterns, a 20-year time series of best matching unit (BMU) was obtained for classifying the type/category of each SLA snapshot.

3 RESULT

To highlight the variations of the Kuroshio intrusion northeast of Taiwan Island, the domain range was selected to be between 121°–125°E and 24°–28°N. Only data over the area with water depth greater than 100 m were used in SOM analysis, to improve geostrophic current analysis (Liu et al., 2006b). The 20-year mean geostrophic current (Fig.1) shows that

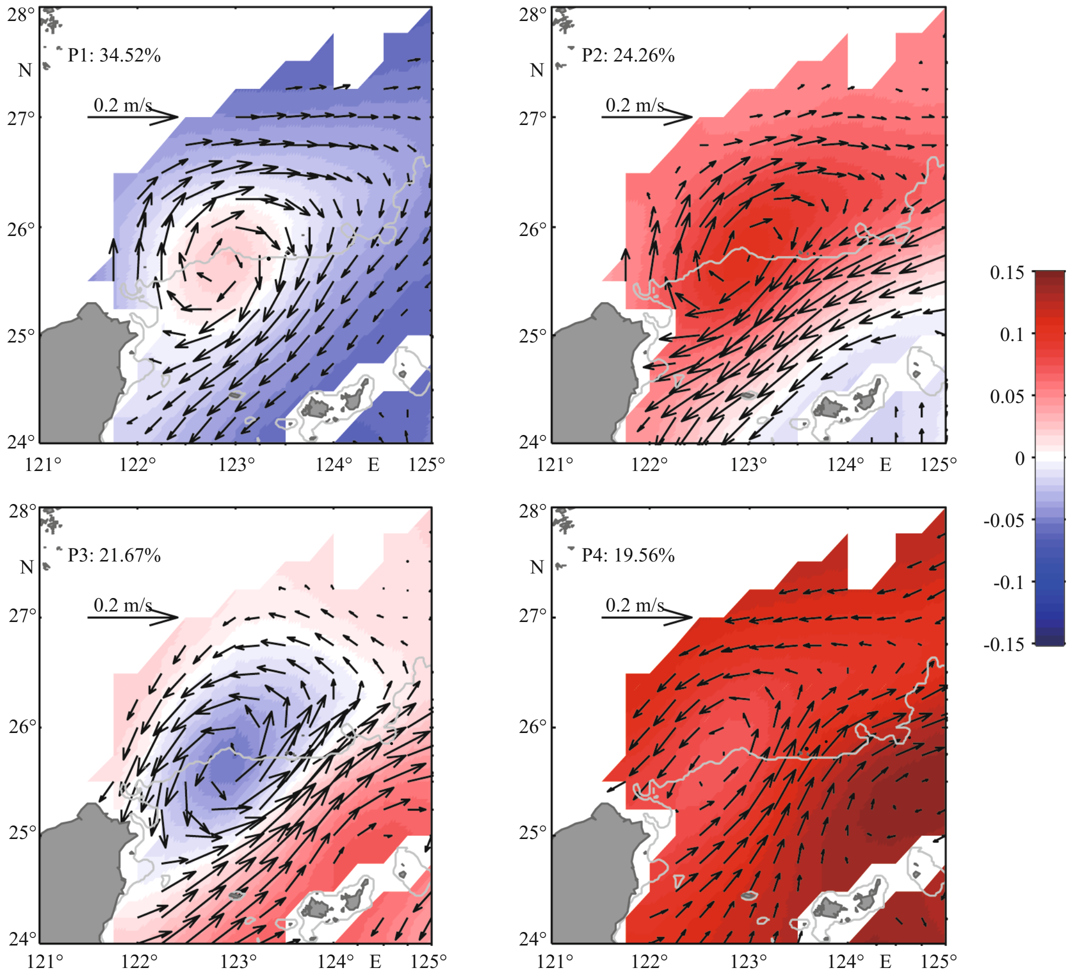

Fig.2 Four 2×2 self-organizing map (SOM) patterns (P1–P4) of AVISO SLA field during 1993–2012

Color shading depicts SLA (in meters) and arrows indicate corresponding geostrophic velocities. Frequency of occurrence is shown in percent. Gray contour in each panel is 200-m isobath.

the KC collides with the ECS shelf break. A portion of the current passes the 200-m isobath and intrudes onto the ECS shelf around 123°E. The majority of this current turns clockwise and rejoins the KC in deep water further east.

The four extracted SLA patterns (P1–P4) and corresponding geostrophic current anomalies are shown in Fig.2. The current anomaly on the ECS shelf generally shows out-of-phase variation with the KC anomaly in the deep water region. Patterns P1 and P2 show similar anticyclonic circulation anomalies (i.e., intrusion) northeast of Taiwan Island. The current on the ECS shelf is increased, while the KC in the deep water is decreased. In other words, along the 200-m isobath, the Kuroshio intrusion is increased (decreased) west (east) of 123°E. The anticyclonic circulation anomaly not only indicates a more shoreward Kuroshio intrusion, but also westward migration along the 200-m isobath. Patterns P3 and P4 show a similar but cyclonic circulation anomaly northeast of Taiwan Island. Along the 200-m isobath, the Kuroshio intrusion is decreased (increased) west (east) of 123°E. The cyclonic circulation anomaly indicates a weaker intrusion and eastward shift of its position along the 200-m isobath.

Frequencies of occurrence (FO) of P1–P4 are 34.5%, 24.3%, 21.7% and 19.6%, respectively. Together, the FO of strong Kuroshio intrusion patterns (P1 and P2) is 58.8%, compared with 41.2% for the weak patterns (P3 and P4). To further understand the four patterns and their monthly variability, long-term average FOs of each pattern were calculated for each month (Fig.3). Both P1 and P4 show remarkable seasonality; P1 mainly occurs from January through April, and P4 mainly from July through October. The strong Kuroshio intrusion patterns (P1 and P2) dominate from October through April, and the weak patterns (P3 and P4) from June through September.

This seasonal variation of the intrusion is consistent with the findings of other studies (Ma et al., 2009; Liu and Gan, 2012). Because of seasonal surface atmospheric forcing on the shelf, the KC axis migrates seasonally (Guo et al., 2006; Oey et al., 2010). The KC axis is near the ECS shelf break in winter and far from that shelf break in summer. Therefore, the current anomaly shows a cyclonic or anticyclonic circulation structure at the edge of the ECS shelf, as shown by the above four patterns.

Although P2 shows a geostrophic current anomaly pattern similar to P1, two characteristics are different. First, the mean SLA across the entire domain is higher in P2 than in P1. Second, P2 shows a stronger KC decrease than P1. P3 and P4 also have two different characteristics. First, the mean SLA over the entire domain is higher in P4 than in P3; second, P3 shows a stronger KC increase than P4. Seasonal variation of KC transport east of Taiwan Island is relatively weak, and prominent KC variation east of Taiwan Island is dominated by a 100-day intra-seasonal fluctuation associated with mesoscale eddies propagating from the open ocean (Johns et al., 2001; Zhang et al., 2001). Analysis by Gawarkiewicz et al. (2011) suggested that more (less) onshore intrusion is associated with low (high) Kuroshio transport and a cyclonic (anticyclonic) eddy pattern east of Taiwan Island. Although FOs of P2 and P3 have individual peaks in November and June, they are comparable in other months. This is consistent with the intra-seasonal character of mesoscale eddy impact. These evidences all suggest that, except for current anomaly patterns in their dominant seasons, P2 and P3 may also reveal the impact of intra-seasonal mesoscale eddies on the Kuroshio intrusion.

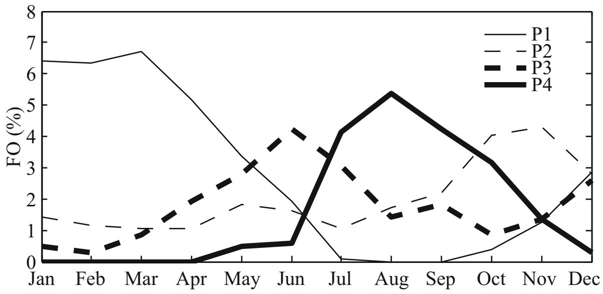

Fig.3 Monthly frequency of occurrence (FO) for SOM patterns P1–P4

The 20-year time series of BMU is shown in Fig.4. Considering only the seasonal cycle as suggested by the monthly FOs (Fig.3), the sequence of pattern evolution is expected to be P1→P3→P4→P2→P1. However, the evolution is irregular between P1 and P4 over these years, further suggesting the importance of mesoscale eddy impact on the Kuroshio intrusion at the intra-seasonal time scale. For example, in 1993, the sequence of pattern evolution was

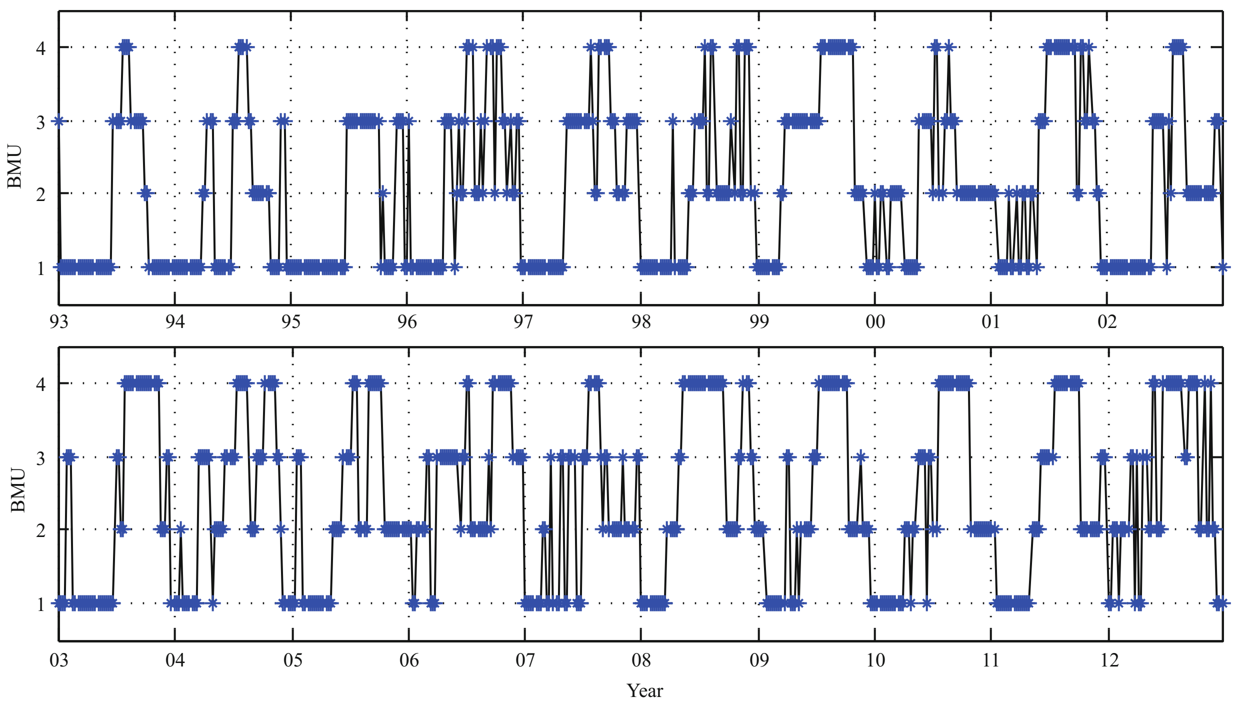

Fig.4 Evolution of best matching unit (BMU) for the four SOM patterns in 1993–2012

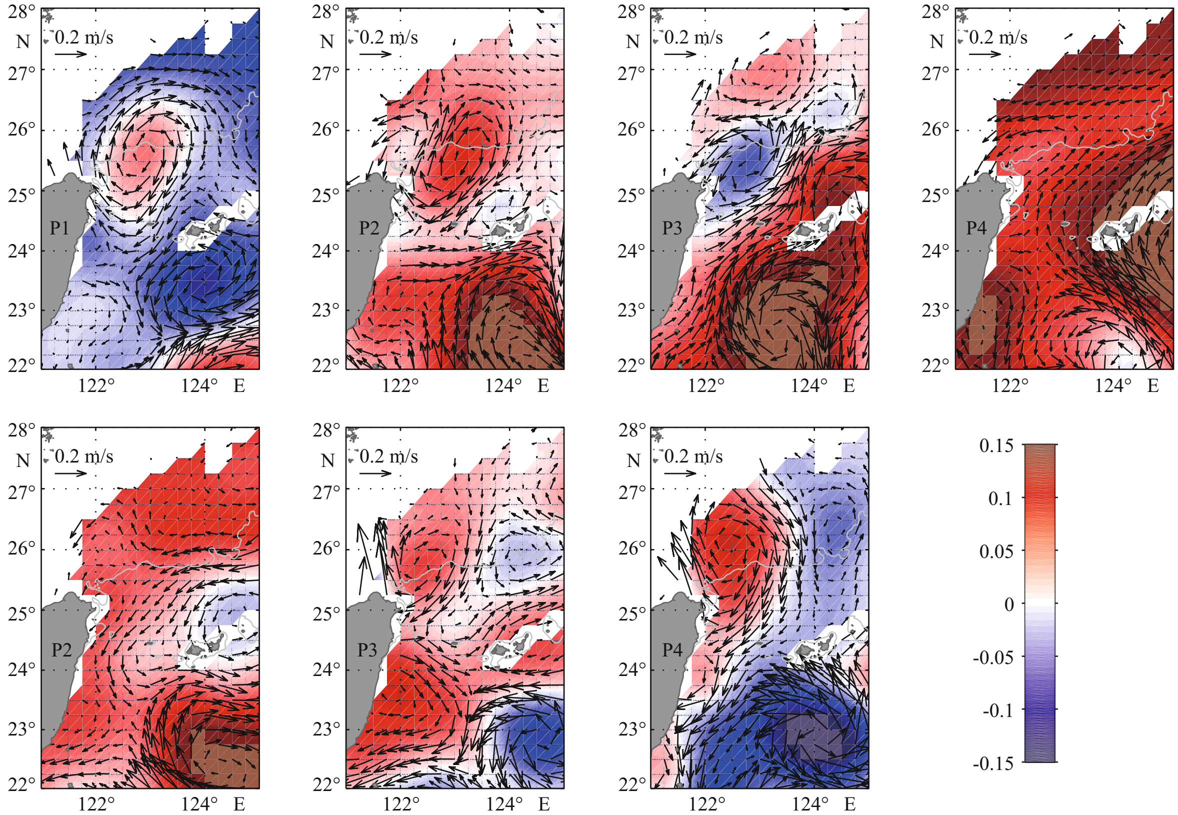

Fig.5 Mean SLA (in meters; color shading) and corresponding geostrophic velocities (arrows) during the period of each continuous SOM pattern in 2011

P1→P3→P4→P3→P2→P1. In 1999, the sequence was P1→P2→P3→P4→P2→P1, and in 2011, it was P1→P2→P3→P4→P2→P3→P1. Here, we choose year 2011 to elucidate SLA evolution (Fig.5). This shows remarkable seasonal SLA variation; the spatial mean SLA is positive in the summer half-year and negative in the winter half-year. In addition to this seasonal evolution, the intra-seasonal mesoscale eddies also had a strong influence on circulation structure variation northeast of Taiwan Island. The arrival of a cyclonic eddy around Ishigaki Island weakened the KC east of Taiwan Island and increased the Kuroshio intrusion northeast of Taiwan Island (P1 and P2). The arrival of an anticyclonic eddy around Ishigaki Island strengthened the KC east of Taiwan Island and weakened the Kuroshio intrusion northeast of Taiwan Island (P3 and P4). As a result, the evolution between P1 and P4 is complicated by the intra-seasonal mesoscale eddies.

4 DISCUSSION

Four current anomaly patterns northeast of Taiwan Island were extracted from 20-year AVISO SLA data, using the SOM. This revealed the dominant seasonal Kuroshio intrusion variation in a reasonable manner. Previous studies showed that the KC axis migrates onshore in winter and offshore in summer, leading to a larger Kuroshio onshore intrusion in winter. The mechanism was argued to be associated with local sea surface atmospheric forcing, the local monsoon (Guo et al., 2006) and seasonal surface heat flux (Oey et al., 2010). The four patterns also showed that the Kuroshio intrusion increases (decreases) with a high (low) sea-level anomaly at the edge of the ECS shelf in the winter (summer) half-year, while the KC decreases (increases) in the deep water region northeast of Taiwan Island.

Second, P2 and P3 indicated the possible impact of mesoscale eddies on the Kuroshio intrusion. These eddies are important in modulating both KC transport east of Taiwan Island (Johns et al., 2001) and Kuroshio intrusion northeast of Taiwan Island (Gawarkiewicz et al., 2011; Vélez-Belchí et al., 2013). To further illustrate the relationship between the Kuroshio intrusion and KC east of Taiwan Island, the mean SLA field in a larger domain (120°–128°E, 20°–28°N) was calculated during corresponding times of each SOM pattern (Fig.6). Northeast of Taiwan Island, the high

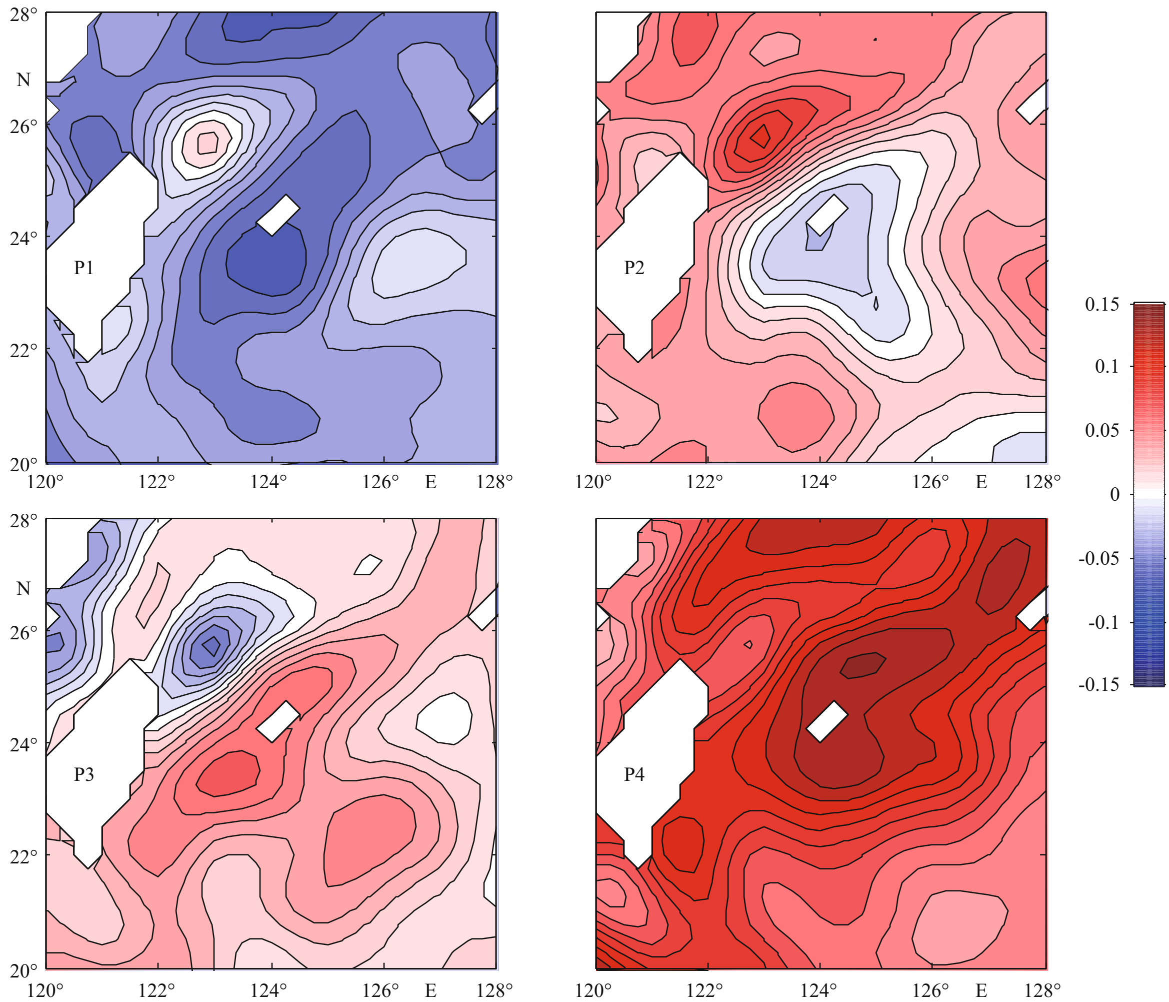

Fig.6 Mean SLA (in meters) during each SOM pattern

Contour interval is 0.01 m.

sea-level anomalies in P1 and P2 and low anomalies in P3 and P4 persisted. There is an explicit low (high) SLA east of Taiwan Island in P2 (P3), which confirms that P2 and P3 exhibit the impact of mesoscale eddies on the Kuroshio intrusion. The interaction between the KC and a cyclonic (anticyclonic) eddy east of Taiwan Island induce a Kuroshio intrusion increase (decrease) and lead to a high (low) SLA northeast of Taiwan Island. The cyclonic (anticyclonic) eddy shows the same effect as winter (summer) surface atmospheric forcing. As mentioned above, because of the impact of intra-seasonal mesoscale eddies, the circulation pattern evolution strongly oscillated between winter (P1) and summer (P4).

P1 occurs mainly in winter with low SLA east of Taiwan Island. P4, which occurs mainly in summer, corresponds to a high SLA east of the island (Fig.6). Although the two patterns occur seasonally, corresponding SLA structures east of Taiwan Island are similar to those (P2 and P3) induced by mesoscale eddies. The influence of such eddies on the KC east of Taiwan Island is on an intra-seasonal time scale (Johns et al., 2001; Zhang et al., 2001). The Kuroshio intrusion induced by these intra-seasonal mesoscale eddies may also modulate its seasonal variation. In the open ocean, the overall number of cyclonic eddies is the same as that of anticyclonic eddies over 16 years (Chelton et al., 2011). In the subtropical zonal band of the North Pacific Ocean, Liu et al. (2012) also calculated eddy generation and termination numbers, indicating no significant difference between cyclonic and anticyclonic eddies in terms of seasonal variation. Therefore, the reason why the Kuroshio intrusion increase (decrease) northeast of Taiwan Island favors a low (high) sea-level anomaly east of Taiwan Island in winter (summer) remains unclear.

The interaction between the KC and mesoscale eddies not only depends on eddies from the open ocean, but also on KC characteristics and its surrounding ocean environment in the western ocean boundary region. There is no prominent number difference between open-ocean cyclonic and anticyclonic mesoscale eddies on the seasonal time scale and KC transport shows weak seasonal variability. Therefore, the possible reason for seasonal favoring of a sea-level anomaly east of Taiwan Island is seasonal variation of the local ocean environment. The thermocline in the open ocean has a dominant seasonal variation (Zhang et al., 2009), being deeper (shallower) and weaker (stronger) in winter (summer). A cyclonic eddy may have a stronger impact on the KC and cause the Kuroshio intrusion increase northeast of Taiwan Island with winter ocean stratification. The anticyclonic eddy may have greater influence on the KC and cause the Kuroshio intrusion to decrease northeast of Taiwan Island with summer ocean stratification. These preliminary hypotheses require further debate or confirmation.

5 CONCLUSION

By applying SOM analysis to a satellite-derived sea-level anomaly field northeast of Taiwan Island during 1993–2012, four coherent sea surface current anomaly patterns were extracted, revealing seasonal Kuroshio intrusion variation and the impact of open-ocean mesoscale eddies east of Taiwan Island. The results coincide with earlier studies, demonstrating that the SOM method is a robust means for studying the Kuroshio intrusion northeast of Taiwan Island. In general, the Kuroshio intrusion increases (decreases) with a high (low) sea-level anomaly at the edge of the ECS shelf in winter (summer) northeast of Taiwan Island. The interaction between the KC and a cyclonic (anticyclonic) eddy east of this island could induce Kuroshio intrusion increase (decrease) and lead to a high (low) SLA northeast of the island, with the same impact as winter (summer) surface atmospheric forcing. The results also show that mesoscale eddies had a role in modulating seasonal variation of the Kuroshio intrusion northeast of Taiwan Island. One possible reason is local seasonal ocean stratification variation, but more detailed analyses of in situ observations and studies of dynamic mechanisms are needed.

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