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Variabilities of the sea level anomalies in the upstream areas of the Kuroshio Current

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Variabilities of the sea level anomalies in the upstream areas of the Kuroshio Current

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Abstract. The relationship between The Kuroshio velocities and Sea Level Anomalies (SLA) in the upstream areas (between Taiwan and Yonaguni Island) is investigated based on satellite altimetry observation. Mean of the SLA data from 2005-2008 show that in the northeast of Taiwan tends to form strong eddy activity. Furthermore, the type of eddy that forms in the upstream areas is difference every season, cold (warm) eddy more exists in summer (winter). The speed of the Kuroshio in the upstream areas is determined by combination of High-Frequency (HF) radar and Copernicus Marine Environment Monitoring Service (CMEMS) data. These two are exhibited that Kuroshio speed become faster (slower) in summer (winter). High positive correlation of the Kuroshio speed and SLA are found in between Yonaguni and Iriomote Island. When the Kuroshio speed in the middle of HF radar areas (123.375° N) became faster, it coincided with transition of warm eddy to cold eddy in the northeast of Taiwan and vice versa.

1. Introduction

Kuroshio also called Japan Current, is the strong surface current of the North Pacific Ocean gyre, flowing past Taiwan and Ryukyu Island in Japan. Lately, satellite altimetry data with high resolution used frequently to improve the understanding of this phenomenon. In the East of Taiwan, Sea Surface Height Anomaly (SSHA) observed by satellite altimetry are found to be well correlated with the Kuroshio transport, both offshore and onshore Kuroshio meandering could be generated by the negative anomaly which are simultaneously with the low Kuroshio transport based on the World Ocean Circulation Experiment (WOCE) PCM-1 [1]. Prior study recognized mesoscale eddy southeast of Taiwan later on would encourage seaward (or coastward) of the Kuroshio east of Taiwan 40 days later [2]. Westward propagating warm eddies from 18°N to 23°N may form a large Kuroshio meander and then, the meanders led to a large 100-days transport fluctuation in the East Taiwan Channel [3]. El Niño/Southern Oscillation (ENSO) and Pacific decadal oscillation (PDO) have an influence on these variabilities of the Kuroshio [4,5].

Furthermore, ocean circulation in the upstream areas of the Kuroshio have been widely recorded in another several observations, such as variability of the SLA around northeast of Taiwan using short and long term datasets [6,7], study of the Kuroshio axis by High-Frequency (HF) radar [8] and the Kuroshio intrusion role in atmospheric variability [9]. Northeast of Taiwan has a unique geography setting that consist of the continental shelf and slope, where eddies are frequently forms. In northeast of Taiwan, cyclonic eddy found more exist in summer than winter [10]. Low sea level anomaly is one indicator that represents cyclonic eddy [11]. This eddy associated with cold dome, and would be disappeared caused by seasonal migration of the Kuroshio axis [12].

Enhancement of quality on satellite altimetry resolution in recent decades, make accuracy of the Kuroshio's observations also increased. For example, SLA reanalysis data from Copernicus Marine Environment Monitoring Service (CMEMS) derived from Mean Sea Surface (MSS) which already filtered from residual noise and small-scale signal. Since May 2017, geostrophic velocities data (MADT-UV) delayed time from AVISO processed and distributed by CMEMS. Geostrophic velocities are one of important product of satellite altimetry which obtained from the first derivative of sea surface height [13]. But it should be noted, in order to improve accuracy much better, it should not only rely on satellite altimetry data but also another instrument with higher spatial resolution. High-Frequency radar is one of reliable instrument which provide ocean currents data by send radio waves and measure scattered signal from the surface ocean [14]. In general, two HF radars needed and would be placed at a certain distance to produce the current velocity map. In Yonaguni and Ishigaki Island, there is a pair of High-Frequency radar that have been observing sea surface current in the upstream areas since 2001. Combination of these two-instrument expected to providing comprehensive explanation of variability of the SLA and Kuroshio.

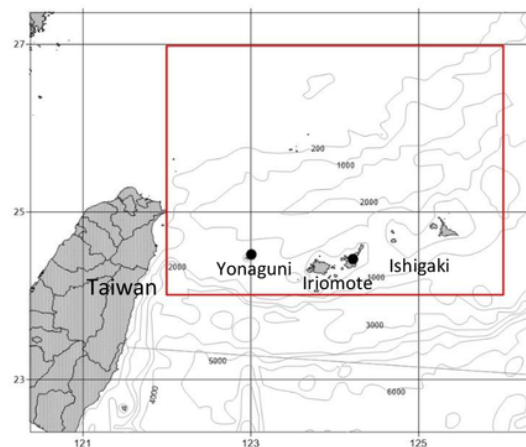


Figure 1. Observation location map with bathymetry contours (200, 1000, 2000, 3000, 5000 and 6000 m), black dots represent the location of HF radar at Yonaguni and Ishigaki Island. Red box is northern and eastern boundary for HF radar observation.

In this paper, we determine speed of the Kuroshio and SLA in summer and winter. Seasonal averaged of the SLA maps present the tendency of eddy that to be formed, particularly in the northeast of Taiwan. The Kuroshio speed data are obtained by High-Frequency radar and satellite altimetry. Meanwhile, seasonal mean of the Kuroshio reveals difference feature that will be occurred during the season. Finally, correlation map of these parameter also shown, both these parameters affected each other and led to the formation of eddy northeast of Taiwan.

2. Materials and Methods

Table 1 describes the data that used in this paper in brief, one of them is satellite altimetry data (i.e. geostrophic velocity and SLA). Copernicus Marine Environment Monitoring Service (CMEMS) distributes delayed time SLA data which is generated by combination of several satellite altimetry mission (JASON-1 and 2, ENVISAT, ERS-1 and 2). Computation of raw SLA, cross validation, filtering and sub-sampling and generation of by-products process, all

Table 1. HF Radar and Satellite Altimetry Data Specifications.

Data	Spatial Resolution	Temporal resolution
HF Radar	7 km x 7 km	30 minutes
Satellite (Geostrophic Current)	± 27 km x 27 km	Daily
Satellite (SLA)	± 27 km x 27 km	Daily

have been done in order to generating the SLA product [15]. Spatial resolution of SLA data from January 2005 to December 2008 are $0.25^\circ \times 0.25^\circ$ ($\pm 27 \text{ km} \times 27 \text{ km}$). The SLA was derived from the difference between sea surface height (SSH) and mean sea surface height (MSSH).

$$SLA = H - R_{obs} - \Delta R_{Geo_{corr}} - MSSH \quad (1)$$

Where H is representative of absolute sea surface height, R_{obs} is the distance from spacecraft antenna to sea surface that already corrected, $\Delta R_{Geo_{corr}}$ is geophysical corrections (e.g. tides, atmospheric delay and sea state bias) and MSSH is the ocean surface height above satellite altimetry reference ellipsoid over a certain time.

Geostrophic velocity was obtained from first derivative of the sea surface height (SSH). The data are used as representation of the Kuroshio speed, the zonal (u) and meridional (v) component of geostrophic velocity can be derived from equation 2. In which, g is gravitational constant, the Coriolis parameter $f = 2\Omega \sin\phi$, where Ω is the angular speed of the earth rotation and ϕ is the latitude, h is SSH that obtained from altimeter.

$$u_s = \frac{g}{f} \frac{\partial h}{\partial y}, \quad v_s = \frac{g}{f} \frac{\partial h}{\partial x} \quad (2)$$

A pair of Long-Range High-Frequency Ocean Radar are operated by The National Institute of Information and Communication (NICT) Japan, placed on Yonaguni and Ishigaki Island. The Long-Range High-Frequency Ocean Radar (hereafter HF radar) is a kind of a doppler radar which are aimed at monitoring surface current in the upstream areas. The HF radar produced surface current components with 7 km spatial interval and covered approximately 200 km. Eastward and northward current component every 30-minutes temporal interval from April 2005 to August 2008 use in this paper. Strong typhoon was happened in the late of September 2006 and led to interference in HF radar result, thus we omitted the data in that month.

The investigation of seasonal variability of the Kuroshio current and SLA in the present study are performed by computing the average value from December to February for winter and June to August for summer season. Seasonal variability of the Kuroshio from HF radar and satellite altimetry will be compared and expected to show variabilities more clearly. The SLA were used to detect eddies, in particular northeast of Taiwan.

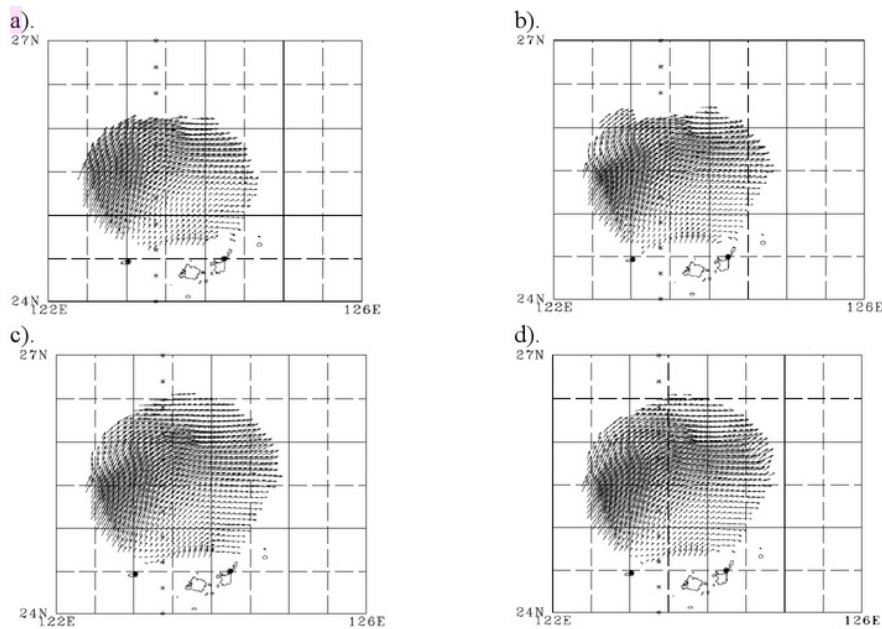
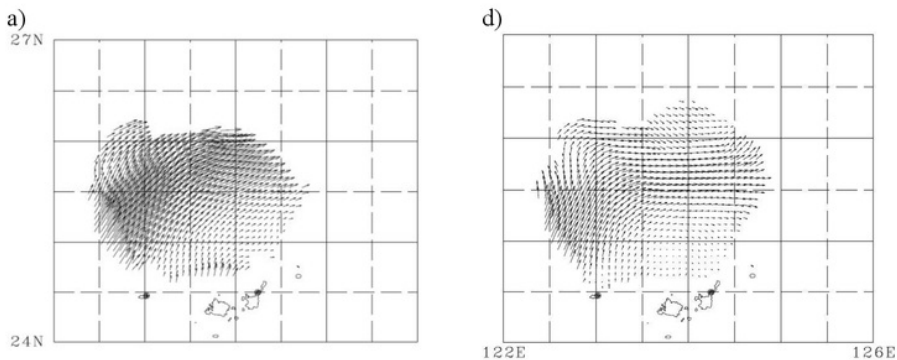


Figure 2. Mean annual of the Kuroshio speed in 2005 (a), 2006 (b), 2007 (c), 2008 (d). The point marks indicate the position of HF radar. The meridional line at 123.375°E as reference for observation of the Kuroshio is also plotted by a star line.

3. Results

3.1. Variabilities of the Kuroshio by HF Radar and Satellite Altimetry

In order to facilitate within monitoring of variabilities of the Kuroshio, we need to determine specific point or line that passed by the Kuroshio consistently. Based on HF radar and altimetry data, meridional line at 123.375°E assumed as specific line for the Kuroshio observation. Figure 2 indicates the Kuroshio continuously crosses at 123.375°E which is represented by the length of vector. The latitude for the Kuroshio observation boundaries are confirmed by Fig. 5, in which these boundaries have a purpose to perceive variabilities of the Kuroshio by satellite altimetry.



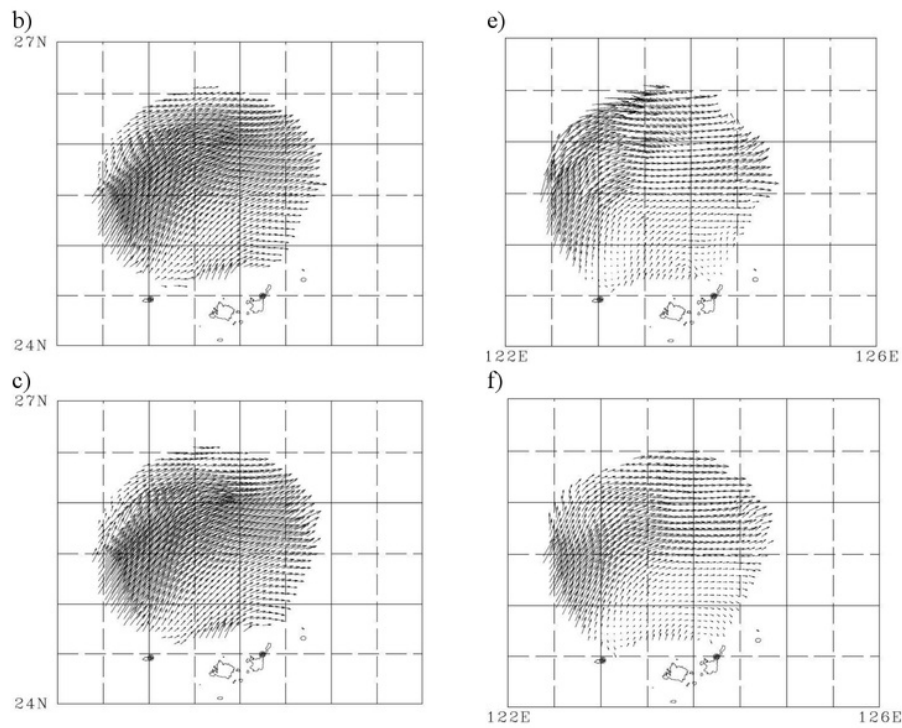


Figure 3. Mean seasonal variabilities of the Kuroshio by HF Radar in summer 2006 (a), 2007 (b), 2008 (c) and in winter 2006 (d), 2007 (e) and 2008 (f). The dotted marks are the same as Fig. 1.

The seasonal variabilities of the Kuroshio by HF Radar are exhibited in Fig. 3. Vector in summer seem more length and crowded than in winter, it means the Kuroshio speed shows a tendency to be faster in summer and slower in winter. In winter, the vectors that represent strong current are seen shift northward, meanwhile in summer move to southward. It indicates when summer (or winter) the Kuroshio shifted southward (or northward), These have been reported in prior studies in which the Kuroshio led northward on to shelf of the East China Sea in winter [16]. Actually, the shifting is clearest in 2007, but unclear in other years. Although shifts of the Kuroshio are unclear in 2006 and 2008, stronger (or weaker) remained clear.

Variabilities of the Kuroshio with magnitude above 0.3 by satellite altimetry data are extracted in Fig. 4. The results look exactly the same as maps that are produced by HF radar. The Kuroshio tends to be faster (slower) in summer (winter), but with the advantages northward and southward shifts of the Kuroshio are more clearly visible. All of figure in winter (bottom panel) indicates that the Kuroshio moves northward, meantime in summer (upper panel) moves southward. The Kuroshio intrusion reportedly increased as the Kuroshio shifted northward in winter [6].

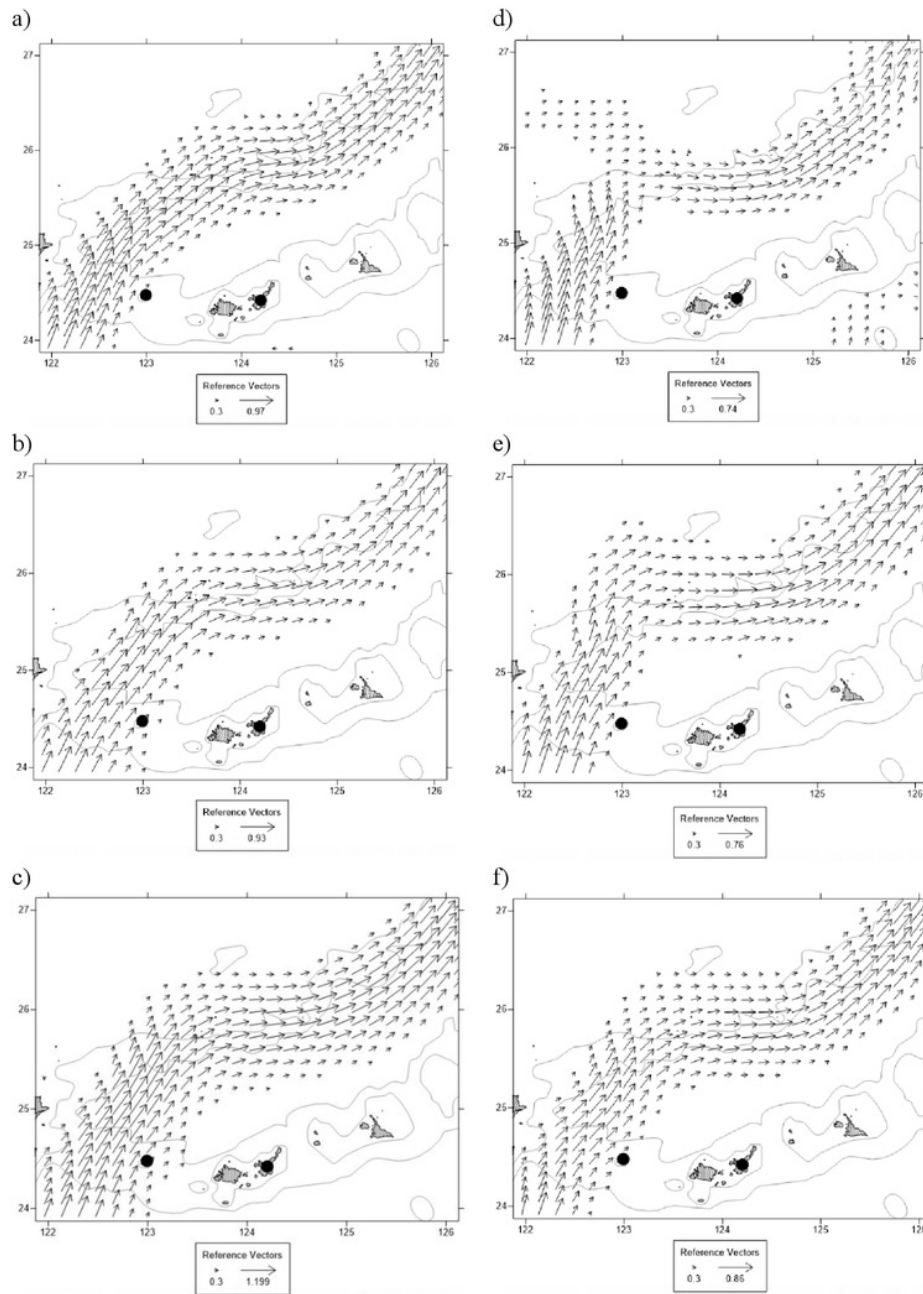


Figure 4. Mean seasonal variabilities of the Kuroshio by satellite altimetry in summer 2006 (a), 2007 (b), 2008 (c) and in winter 2006 (d), 2007 (e) and 2008 (f), superimposed on the bathymetry contours (200 and 1000 m). The magnitudes under 0.3 are removed from data for convenience. The dotted marks are the same as Fig. 1.

Since variability of the Kuroshio was shown clearer by satellite altimetry, therefore in order to better understand about the Kuroshio, we have constructed Hovmöller (latitude-time) diagram at meridional line 123.375°N using time series data of geostrophic velocity from satellite altimetry. Hovmöller diagram is a common ways of plotting oceanography data, in order to display the pattern. Hovmöller diagram in Fig. 5 reveals variabilities of the Kuroshio by satellite altimetry for 4 years. As well as Fig. 3 and Fig. 4, variabilities of the Kuroshio tend likewise to be moved northward (or southward) in winter (or summer). However, the shifts of the Kuroshio in Fig. 5 described more clearly. When the Kuroshio speed is faster (or slower), the Kuroshio shifts southward (or northward). Hovmöller diagram Fig. 5 shows the Kuroshio can reach out speeds over 0.9 m s^{-1} in summer, and weakened to less than 0.3 m s^{-1} in spring or winter. Nevertheless, there are exception which the Kuroshio speed exceeds 0.6 m s^{-1} in January 2008. It will be discussed in the next chapter.

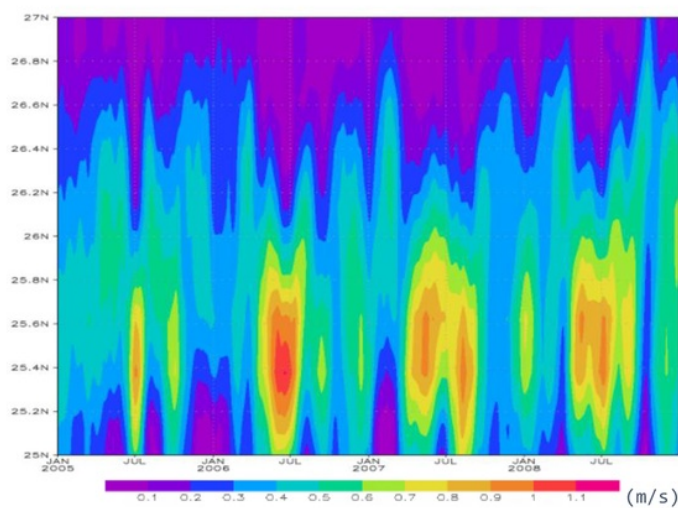


Figure 5. Hovmöller (latitude-time) diagram of variabilities of the Kuroshio speed by satellite altimetry data from 2005-2008 at meridional line 123.375°E with 35-days low pass filtered. Latitude (time) is indicated by X-axis (Y-axis).

3.2. Variabilities of the SLA Northeast of Taiwan

Figure 6 exhibits mean seasonal of the SLA during winter and summer from 2005-2008. The SLA northeast of Taiwan in continental slope indicates lower (or higher) in summer (or winter). This simultaneity also implies that there is a tendency to form cold dome in summer (Fig. 6b), especially at meridional line 122.625°E. The SLA inside the ring is higher (or lower) than surrounding in winter (or summer), denotes the emergence of warm (or cold) eddy. Meantime, in the centre of HF radar observation area (between Yonaguni and Ishigaki Island) is surrounded by the negative SLA in winter (Fig. 6b) and the inverse is the positive SLA in summer.

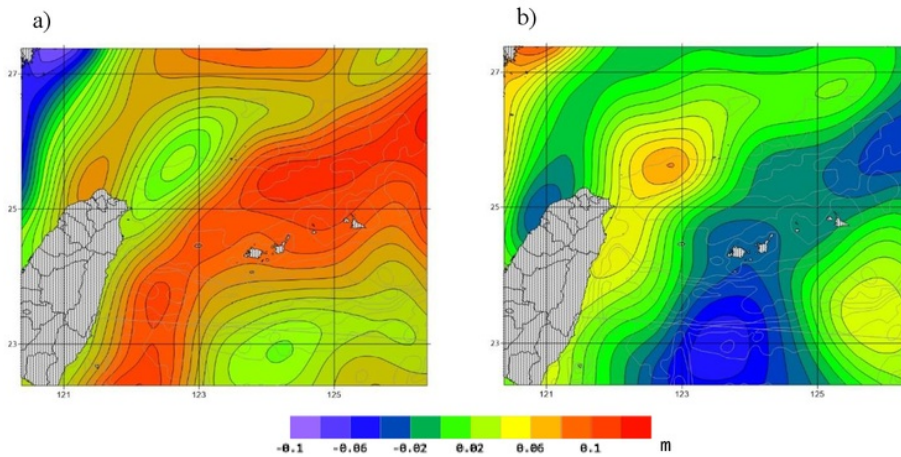


Figure 6. Mean of the SLA in summer (a) and in winter (b) from 2005-2008, contour intervals are 0.01 m.

Mean of the Kuroshio speed for one week is displayed by the upper panels of Fig. 7. Fig. 7a describes the surface current speed when the positive SLA appears in northeast of Taiwan in Fig. 7c and 7d, whereas Fig. 7b is for Fig. 7e and 7f. The Kuroshio moved northward in March 2008, it is quite different with the Kuroshio speed in May 2008 which shifted southward. In May 2008 (or March 2008), the Kuroshio speed became faster (or slower) when shifted southward (or northward) as mentioned earlier. That motion occurred simultaneously with the positive and negative SLA northeast of Taiwan.

To better understanding about SLA and Kuroshio correlation. We choose occurrence on spring 2008 to observe, when transition from weak to strong Kuroshio took place. The transition from warm to cold core in northeast of Taiwan is shown by Fig. 7c to 7f (middle and bottom panel), positive (or negative) SLA are appeared on west of the red boxes that represent Fig. 7a and 7b boundaries. These SLA existed at meridional line 122.625°E in which the core of the SLA located along the continental slope. As that reason, meridional line at 122.625°E determined as the SLA observation line for Fig. 8. Beside the SLA transition northeast of Taiwan, from 18th to 19th of March 2008 seen that the SLA located at 22.375°N joined the SLA east of Taiwan and towards HF radar observation areas. Furthermore, at 19th of March the SLA northeast of Taiwan are associated with these SLA (Fig. 7d). Like the prior statement, previous study mentioned that warm eddies southeast of Taiwan related to other eddies within the HF radar observation areas [2]. Meanwhile, from 8th to 9th of May 2008 shown by Fig. 7e and 7f, the SLA from southeast of Taiwan are moved out and merged with the SLA southwest of the red boxes. When the Kuroshio speed is slower (or faster) in Fig. 7a (or Fig. 7b), the SLA between Iriomote and Ishigaki Island turned out higher (or lower). Figure 7 overall implies that southern and stronger (or northern and weaker) Kuroshio triggered the negative (or positive) SLA northeast of Taiwan.

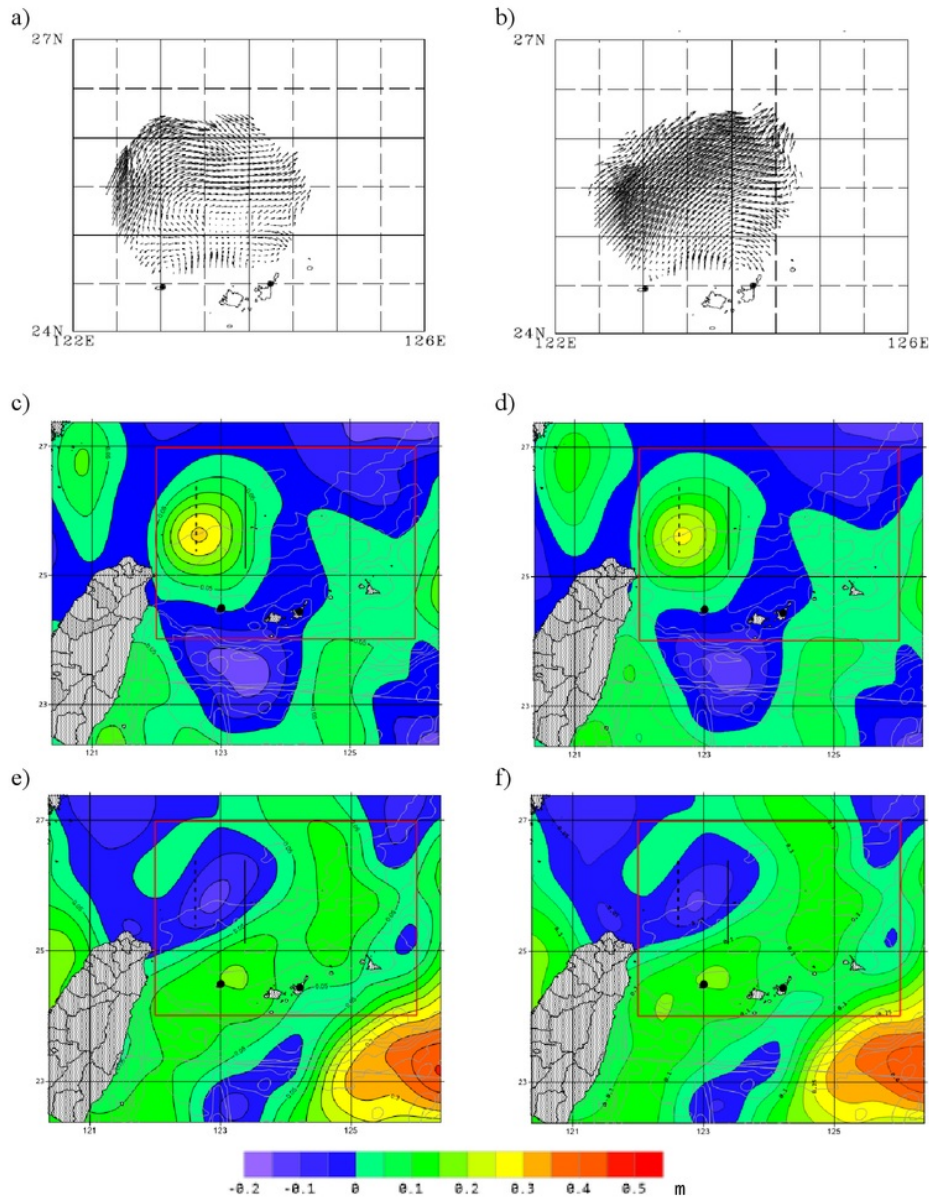


Figure 7. Mean of the surface current speed from 14-21 March 2008 (a), and 7-14 May 2008 (b). The SLA maps on 18 March 2008 (c), 19 March 2008 (d), 8 May 2008 (e) and 9 May 2008 (f). Black dots and red boxes in the lower panels are the same as Fig. 1. The contour intervals are 0.05 m.

In order to support the above paragraph statement, the Kuroshio speed and SLA from 2005-2008 are plotted as Fig. 8. In order to reduce noise from satellite altimetry, all geostrophic components and SLA data were smoothed by 35-days low-passed filtered. These two are found to be well correlated, as the

SLA is higher (or lower) when the Kuroshio speed become slower (or faster). Namely, the SLA northeast of Taiwan seems to be lower (or higher) in summer (or winter). However, abnormal occurrence was happened in winter 2008 where the SLA has a tendency become lower. The lowest state of the SLA was happened in May 2007 and then followed by January 2008 as the second.

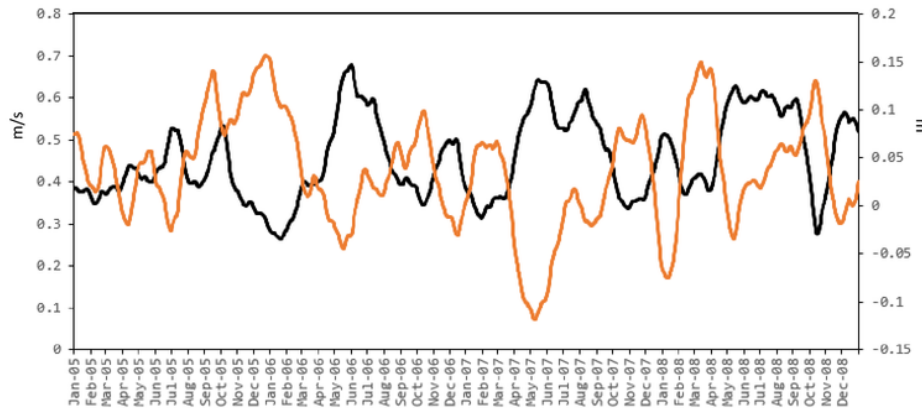


Figure 8. Time series of the Kuroshio speed (black line) and SLA (red line) with 35-days low pass filtered. The Kuroshio speed is the mean of geostrophic velocities from satellite altimetry that across black line (123.375°E) in figure 6, whilst the SLA derived from average value at broken line (122.375°E). Y-axis in the left (or right) indicates value of the Kuroshio speed (or the SLA).

Bottom panel on Fig. 9 displays the Kuroshio speed same as Fig. 8, but data in 2005 have removed for convenient. The boxes from the bottom to the top pose latitude-time plot of the SLA (35-days low passed) along northeast of Taiwan in latitude 25.125°N to 27.25°N range at longitude from 123.875°E - 122.375°E . The SLA inside the ring is higher (or lower) than surrounding which indicates the appearance of anti-cyclonic (cyclonic) eddy. Those figures indicate that dominant eddy which forms in northeast of Taiwan or at 122.375°E propagate eastward towards the centre of HF radar observation. Furthermore, the eddies reach the maximum state at 122.875°E and then weakened as it is approaching the Kuroshio meander. In the longitude 123.875°E , the eddies would be merged and disappeared gradually by the Kuroshio. Most of northeast of Taiwan eddies have periods of 30-45 days before they disappear. Figure 9 also shows when the Kuroshio speed is faster (slower), the SLA is carried away by the meander is higher (lower), meanwhile the SLA along continental slope tends to be lower (higher).

To investigate the relationship of both parameters, we have constructed a correlation between a time series of the Kuroshio speed and SLA data from 2005-2008, in the upstream areas as Fig. 7(c) to 7(f). Correlation coefficient derived from calculations that performed on each grid point. Calculations are not only done with the SLA on the same date, but also 20 days after and 20 days, 40 days before, as suggested in previous studies [2].

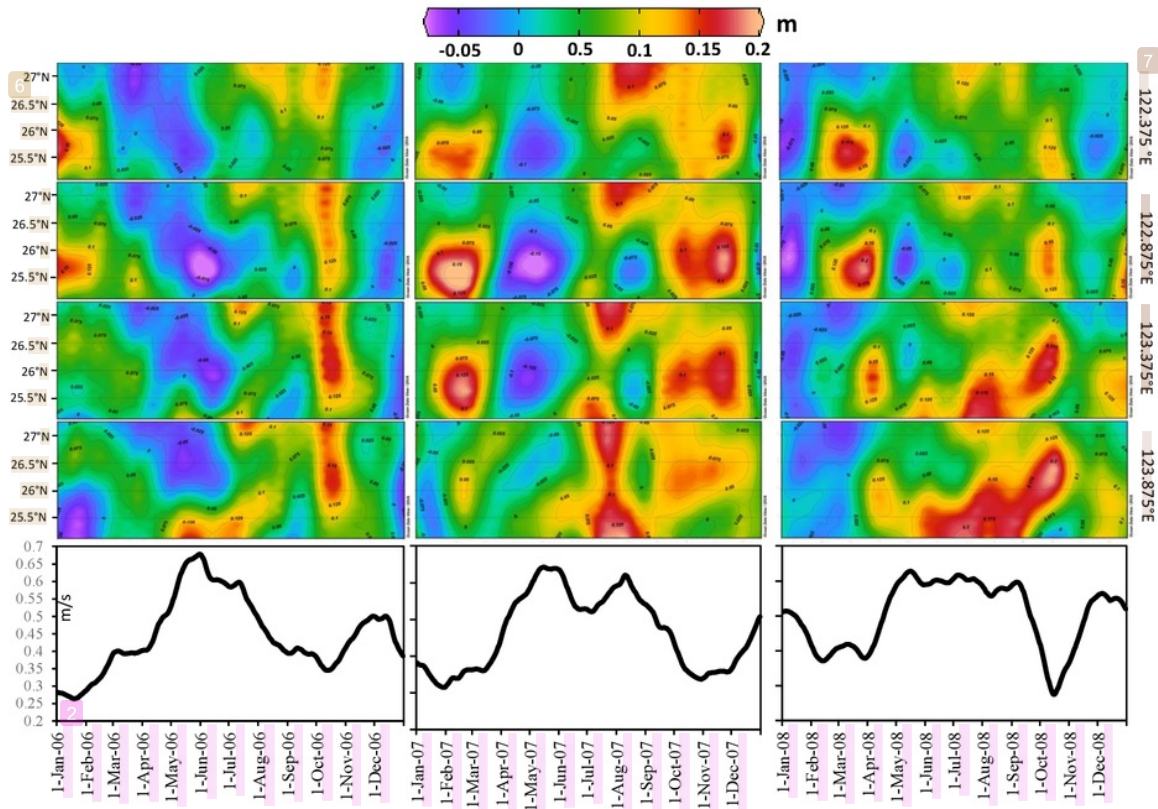


Figure 9. Bottom panel: The Kuroshio speed same as Fig. 7 and Hovmöller (latitude-time) plots of variabilities of the SLA northeast of Taiwan from 2006-2008 (35-days low pass filtered) for longitudes 123.875° to 122.375°E. The contour intervals are 0.05 m.

In Fig. 10(c) every positive (or negative) correlation indicates that the SLA at location is higher (lower), while the Kuroshio speed tends to increase (or decrease). Before calculating the correlation, both geostrophic velocity and SLA data were smoothed by 35-days low-passed filtered to reduce small-scale noises. When there are no temporal lags, negative correlation is found in the continental slope. In the northeast of Taiwan also found positive between a pair of negative correlation, this looks similar to Fig. 7(d) in which the positive SLA is surrounded by negative SLA. Positive correlation centred between Yonaguni and Iriomote Island. Negative correlation emerges in the continental slope with the SLA 20 days before (Fig. 10b) and still exists with the SLA 20 days after (Fig. 10d), while two small areas of positive correlation are found at 23°N southeast of Taiwan when correlation is accounted with the SLA 40 days before (Fig. 8b). Furthermore, these correlations are seen mixed up and form a larger area western Yonaguni Island with the SLA 20 day before. The positive correlation near east coast of Taiwan still exists, but it disappears at meridional line 123°E. The movement of positive correlation areas with temporal lags implies that anti-cyclonic (cyclonic) eddy southeast of Taiwan through 122.5°-123°N stimulates the Kuroshio speed, which tends to be faster (or slower) at centre of HF radar observation, followed by the emergence of cyclonic (anti-cyclonic) eddy northeast of Taiwan that indicated by negative correlation.

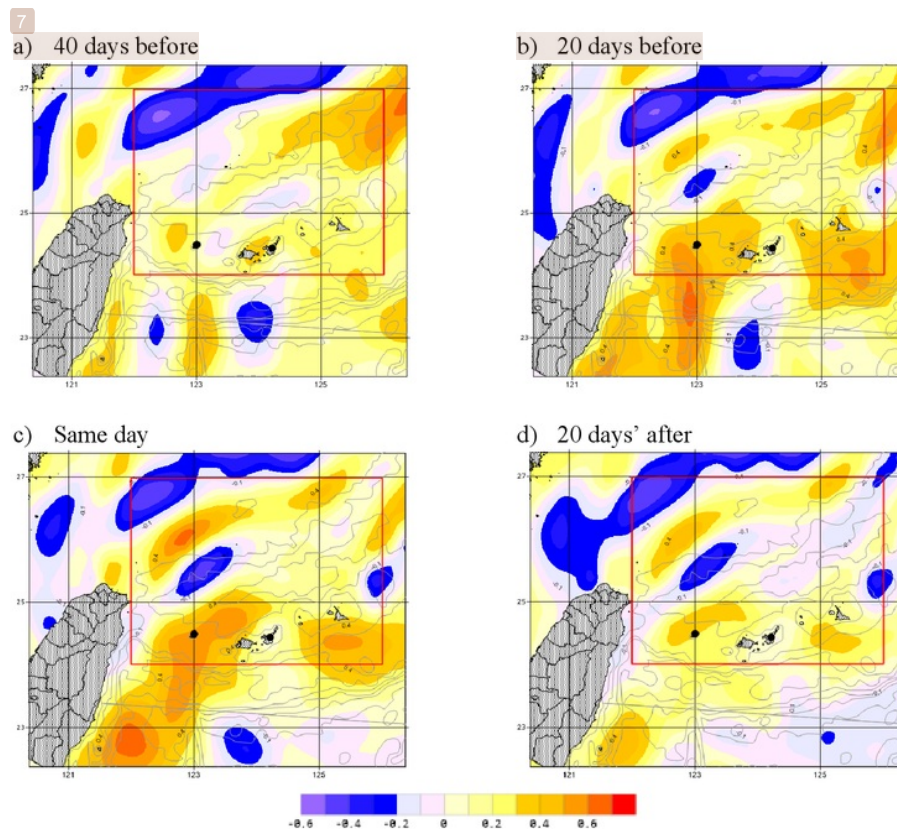


Figure 10. Cross correlation map of 35 days' low pass filtered the Kuroshio speed and SLA 40 days before (a), 20 days before (b), at the same day (c) and 20 days after (d) with 0.1 contour intervals. Dotted marks and bathymetry contours are the same as Fig. 1.

4. Summary and discussion

The combination of HF radar and altimetry data shows seasonal variabilities of the Kuroshio speed in the upstream areas, in particular along 123.375°N. The Kuroshio speed is being faster in summer and slower in winter (Fig. 3 and Fig. 4). Monsoon system becomes the main factor that causes these variabilities. In summer (or winter), the Kuroshio speed may be increased (or decreased) due to southwesterly (or northeasterly) wind effect [17]. However, several prior studies have been recording the strengthening (or weakening) of the Kuroshio speed in summer (or winter) [2,18,19].

The Kuroshio tends to move northward in winter and southward in summer (Fig. 3 and 4), but from the HF radar is not clear the following factor that generates the shift. We may be able to make a preliminary statement as mentioned in the above paragraph, therefore we need accurate evidence to prove it. Variability of the Kuroshio by satellite altimetry describes the shifts of the Kuroshio more clearly (Fig. 5). As expected from Fig. 3 and 4, the southward (or northward) Kuroshio takes place in summer (or winter), especially in July (or February). It seen that the Kuroshio shifts northward when the speed decreased, meanwhile southward shift is followed by increased speed. In fact, southward and northward shifts of the Kuroshio have been reported in prior studies [2,12,16].

In summer (or winter), the SLA northeast of Taiwan has a tendency to be formed cold (or warm) eddy which are depicted by the SLA inside the ring is lower (or higher) than surrounding. This is in line

with [10] that found the number of cyclonic eddies are more significant in summer than in winter. In addition to the SLA, cold dome also one indication of the emergence of cyclonic eddy that comes up mainly in summer and associates with upwelling [20]. The SLA northeast of Taiwan seems contrary to the Kuroshio speed (Fig. 8). The SLA is lower (or higher) in summer (or winter), while at the same time the Kuroshio becomes faster (or slower). Even though, there is any exception when the Kuroshio shifted southward and stronger which led to the SLA to be lower, in January 2008. We try to figure out climatological factors that cause these abnormal conditions. Furthermore, El Nino-Southern Oscillation (ENSO) appears as one of the leading factor that estimated to be mastermind of. In 2007-2008, there was a moderate La Nina phenomenon. In the winter when La Nina occurred, surface current speed that crossed near northeast of Taiwan will be faster than usual as suggested in prior studies [5]. However, ENSO is not the only cause of variability of the Kuroshio, so it needs to be investigated further.

Figure 9 depicts eastward propagating of eddy in the northeast of Taiwan. The successive phenomena of the formation to disappearance of the eddy are described as follows: As mentioned above, when the Kuroshio speed is being faster (slower), cold (warm) eddy sets to form at 122.375°E and then propagates eastward towards the Kuroshio meander. On its way, cold (warm) eddy reaches its maximum state at 122.875 and would undergo weakening processes afterwards. As approaching the Kuroshio meander, cold (warm) eddy would merge/interact with the stronger (weaker) Kuroshio. Furthermore, cold (warm) eddy disappears gradually through mixed up with the higher (lower) SLA which is carried by the meander.

By taking into account correlation of the Kuroshio speed and the SLA with temporal lag, the Kuroshio speed in the centre of HF radar location looks to be influenced by eddy southeast of Taiwan, as reported in prior study [2]. Eddy southeast of Taiwan (along 123°E) propagates into the Kuroshio meander and any possibility merges with another eddy along coastline of Taiwan 20 days later, actually eddy southeast of Taiwan is westward propagating eddies from western Pacific and would significantly reduce the Kuroshio transport [3], then the merged eddy propagates together with the meander. Furthermore, the meander arrives at HF radar observation areas 40 days later with decreased (or increased) of the Kuroshio speed, followed by anti-cyclonic (or cyclonic) eddy northeast of Taiwan. When there are no temporal lags, negative correlation is found in the continental slope (Fig.10c). It begins to emerge 20 days before (Fig. 10b) when westward propagating eddy appears in east of Taiwan and still exists 20 days after (Fig. 10d). It indicates that the centre of cyclonic (or anti-cyclonic) eddy appears along continental slope, those events have been recorded in previous studies [6]. In this case, the Kuroshio intrusion in the continental slope plays a main role [21], increased (or decreased) of intrusion coincides with the emergence of cold (or warm) eddies [20]. The appearance of negative correlation from 20 days before to 20 days after implies the dominant eddies that form northeast of Taiwan, have a period of approximately 40 days, in line with Fig. 9 which implies that the eddies have periods of 30-45 days. Along 123°E meridional line is the main path of eddy southeast of Taiwan, towards the centre of the HF radar observation area. It is indicated by positive correlation that appears in the 40 days before (Fig. 10a) then will be vanished 20 days after the same day (Fig. 10d). Positive correlation in the east of Taiwan (Fig. 11c) explains that the appearances of warm (cold) propagating eddy in east of Taiwan, will be increased (decreased) the Kuroshio speed also. Hsu et al., 2016 was mentioned that the Kuroshio speed dropped approximately 84% of the seasonal average under the appearances of cyclonic eddy. The movement of negative correlation north of Taiwan indicates SLA at location not too much influenced by the Kuroshio. In the area is more affected by Taiwan warm current and China coastal current.

The present study only describes and represents specific mesoscale areas, especially predefined reference lines, either longitude or latitude limits. The formation of eddy northeast of Taiwan needs to be investigated further using HF radar, which is capable of produce surface current data with high spatial resolution. It is important to remove tidal components, wind-driven Ekman current component and inertial oscillations [2,8], in order to generate small scale variations of the Kuroshio on the shelf slope northeast of Taiwan.

Acknowledgments

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