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Research Article

ENVIRONMENTAL CHANGES IN THE SOUTH CHINA SEA

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ABSTRACT
A time series of surface temperature, salinity, precipitation and chlorophyll data were used for the Luzon Strait region in determining environmental changes caused by Kuroshio intrusions into the South China Sea. Data were analyzed with the System for Multidisciplinary Research and Applications (NASA Giovanni). Salinity data reveal that December of the yearly cycle is the time of major high salinity influx from the Kuroshio into the South China Sea.
Seventeen years of observations for temperature showed an increase of around 0.5^{O}C, and for salinity data that was available for a period of about four years, an increase of 1.4 psu was observed. Data on chlorophyll show elevated concentrations north of Luzon Island and indicate upwelling and eutrophication by river discharge that builds a strong chlorophyll gradient against the adjacent Kuroshio water. Elevated chlorophyll values were also observed along the southern coast of Taiwan with cold water indicating the upwelling region. The time series show the periodic occurrence of Kuroshio intrusion into the South China Sea in the form of surface loops and eddies through the Luzon Strait. It is concluded that superimposed to the seasonal variations in temperature, salinity and chlorophyll, are inter-annual variations that can be attributed to ENSO cycles and are therefore most probably related to large changes in atmospheric circulation during the El Niño phase.

Keywords: *Luzon Strait, Kuroshio, Monsoonal Changes, Remote Sensing*

INTRODUCTION
The South China Sea (SCS) is an important fishing ground, and an understanding of the dynamics, in particular, the interaction between the western Pacific Ocean and the South China Sea, serves for a better management of the marine ecosystem. This argument is highlighted by fast changes in fishery. Paul and Liang (2019) showed that following a rapid increase of fishing in the 1980s and early 1990s, catches from the South China Sea stagnated. The cause of the massive expansion of the fisheries in the SCS is due to the increased populations in the surrounding countries and their need to sustain the population.
As the South China Sea is located in the monsoon region, it undergoes frequent environmental changes and the seasonal monsoons determine the variations in the wind direction, and typically, the wind during summer is weak from the southwest whereas the monsoon from the northeast is stronger during boreal winter. Seasonal changes in the hydrography of the water masses around the Philippines are in response to both the northeast monsoon and the southwest monsoon. Accordingly, the circulation pattern reverses its direction and, therefore, the exchange of water between the South China Sea and the western Pacific is also dominated by fluctuation and changes of the monsoons (Wyrtki, 1961).
The Luzon Strait connects the Philippine Sea and the South China Sea and is about 350 km wide with a maximum depth of about 2500 m. All other channels connecting the South China Sea with water from the western Pacific Ocean are either narrow or shallow and less important with respect to transport of water from the Pacific. The Kuroshio dominates the hydrography around the Luzon Strait. It originates from the westward flowing North Equatorial Current and as the Kuroshio flows northward with a slight westward incursion through the deep channels of Luzon Strait, it occasionally turns partly westward. It modifies with its entrainment and development of mesoscale eddies the surface characteristics, and a clockwise cycle of four patterns causes significant intra-seasonal variation for the east branch (Sun *et al.*, 2018, Wang *et al.*, 2020). The seasonal character of transport through the Luzon Strait seems to be a common feature as observed by Qu (2000) who derived from hydrographic observations, a maximum transport of

5.3 Sv in January - February and a minimum of 0.2 Sv in June–July. Velocity observations near the surface made by Centurioni *et al.*, (2004), with satellite-tracked drifters, confirmed the seasonal character of currents that pass from the Philippine Sea through the Luzon Strait into the South China Sea with a mean speed of about 0.4 to 0.7 m s^{-1}.

In view of the complexity in the hydrography and importance of water exchange between the Pacific and the South China Sea, it is challenging to obtain further information on the dynamics in the Luzon Strait and neighboring seas with time series (Ho *et al.*, 2004). Remote sensing observations of chlorophyll have been reported for the South China Sea before but they were restricted to the southwest of the Luzon Strait (Tang *et al.*, 1999). Therefore, it is the intent to present and analyze surface observations of temperature, chlorophyll and salinity that were collected by satellites during the last decades. Compared to the South China Sea, the Kuroshio is characterized by an oligotrophic environment and carries low concentrations of chlorophyll and therefore, the level of chlorophyll is an additional parameter used in this study for documenting environmental changes in the Luzon Strait and neighboring seas.

MATERIALS AND METHODS

Remotely sensed surface temperature, salinity, precipitation and chlorophyll were used with the main emphasis on establishing the response of the marine environment to monsoonal and inter-annual changes. The data were accessed from the System for Multidisciplinary Research and Applications (NASA Giovanni). Giovanni is constructed for the analysis of Earth remote sensing data products on weather, climate, atmospheric composition and dynamics, oceanography and hydrological processes. Most data sets used in this study cover a timeframe of more than ten years except for the measurement of sea surface salinity that was available only for the period September 2011 to May 2015. SeaWiFS had only a short life span from July 4, 1997 to December 11, 2010, although the instrument provided useful data and they are included in this study. All other data sets were available for 2008 through 2018. Three areas were selected for the study. The first site was selected to generate some general hydrographic information on the region that covers the area of the northern part of the Philippine Sea 114.0 E, 17.8 N to 124.0 E, 23.0 N, and included the Luzon Strait. The second area covers the coordinates 120.1 E, 18.4 N to 121.1 E, 22.3 N and was selected for a more detailed description of the Luzon Strait; and the third site was located at 114°E, 16° N to 124°E, 23°N.

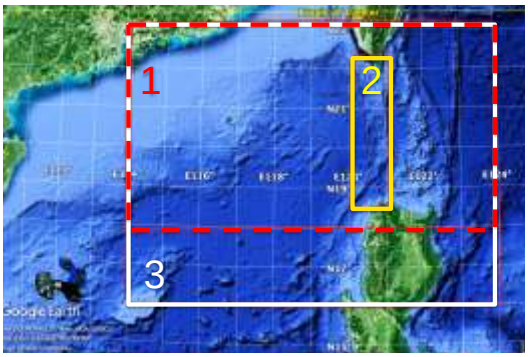

Figure 1: Positions of the investigated areas in the South China Sea, Philippine Sea and Luzon Strait. Insert 1: 114.0°E, 17.8°N to 124.0°E, 23.0°N; insert 2: 120°N, 18.4°N to 121.1°E, 22.3°N; insert 3: 114°E, 16° N to 124°E, 23°N.

Not all data sets were complete to cover the areas over a longer time span, but efforts were made to timely match best the various parameters. As many satellite missions were experimental, they do not provide continuous observations, but this study takes advantage of long periods of observations including data that do not necessarily coincide with the major data set that is provided by the MODIS mission. In

particular, the chlorophyll data were occasionally limited due to persistent cloud coverage and therefore, monthly averaged data were not always complete.

RESULTS AND DISCUSSION

The Luzon Strait and the neighboring region east and west of the Strait undergo seasonal changes that are mainly dominated by the dynamics of the Kuroshio. Figure 2 shows an example of the yearly cycle of temperature and chlorophyll as well as two selected seasons in image format. The data show that higher chlorophyll concentrations are associated with lower temperature although during summer, intermediate maxima may occur as well. The image that covers the season from October to January shows the intrusion of warm water from the Kuroshio into the Luzon Strait. Temperature and chlorophyll concentrations show a well-developed gradient between the Kuroshio and the water in the Strait but during summer, the temperature gradient is reduced and warming of the surface leads to patterns that make it difficult to identify the boundary of the Kuroshio.

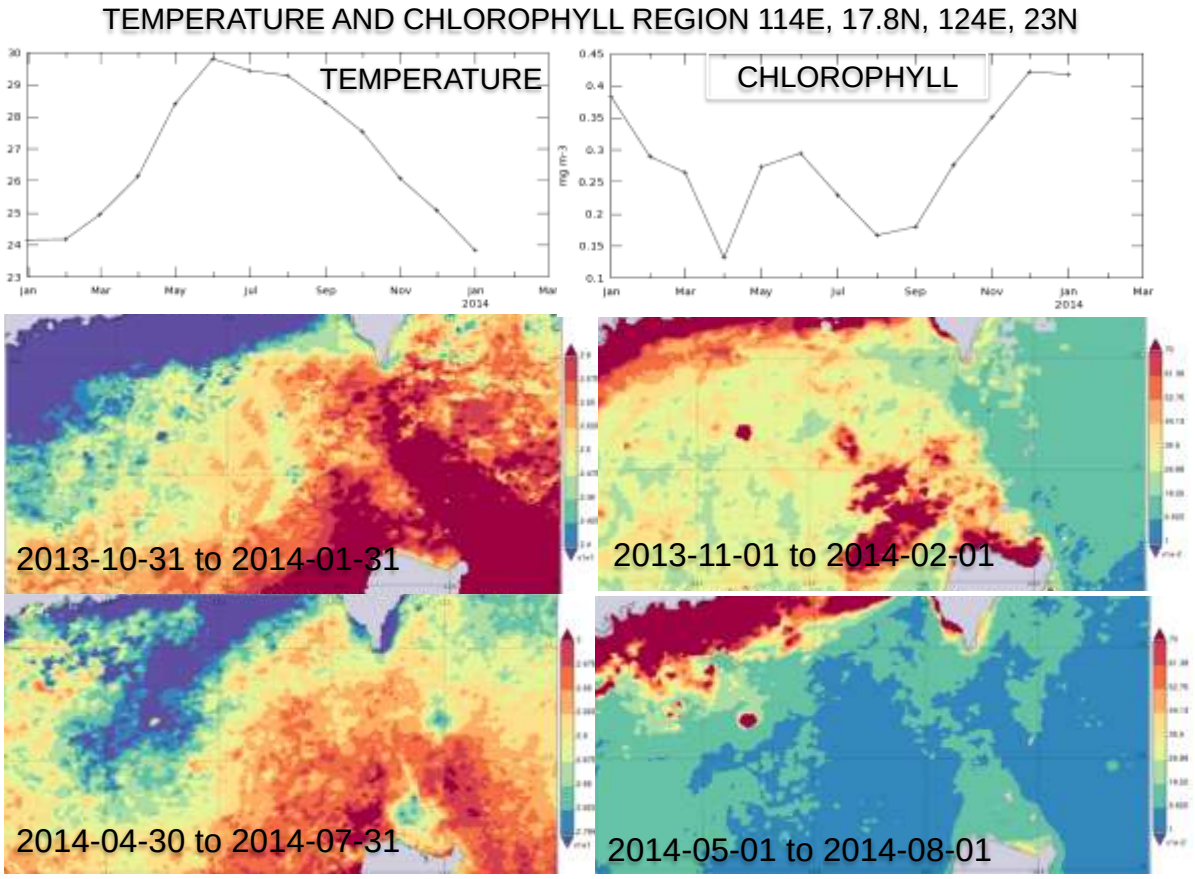

Figure 2: Selected seasonal composite of temperature and chlorophyll concentrations for 2013/2014 in the region north of Luzon Island as shown in Figure 1, insert 1.

All available salinity data are graphed for the same region, as in Figure 2. The results are shown in Figure 3 and reveal a yearly cycling indicating an increase of about 1.4 psu over the whole time frame of the data set. This increase in salinity is observed during the strong El Niño 2015-2016 (Null 2020), and it can be assumed that transport from the Kuroshio intrusion region was the possible cause for higher salinity values.

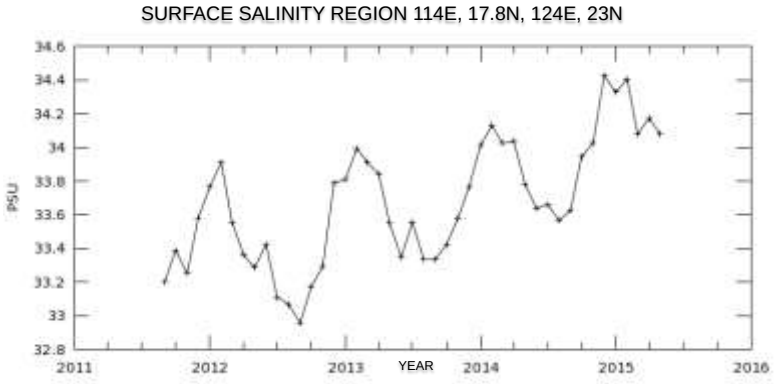

Figure 3: Monthly sea surface salinity in the Philippine Sea/South China Sea for the 2011-2015 duration of the salinity study in the region east and west of the Luzon Strait, north of Luzon Island, as shown in Figure 1, insert 1.

Luzon Strait

The climatology for chlorophyll and temperature in the Luzon Strait, shown in Figure 4, indicates the location wherein the average major surface processes take place. At around 21^{o}N, at a mean temperature of approximately 28^{O}C, low chlorophyll concentration is related to the average boundary position of the occasional Kuroshio intrusion whereas the elevated chlorophyll concentration north of Luzon Island indicates eutrophication that is caused most probably by river discharge.

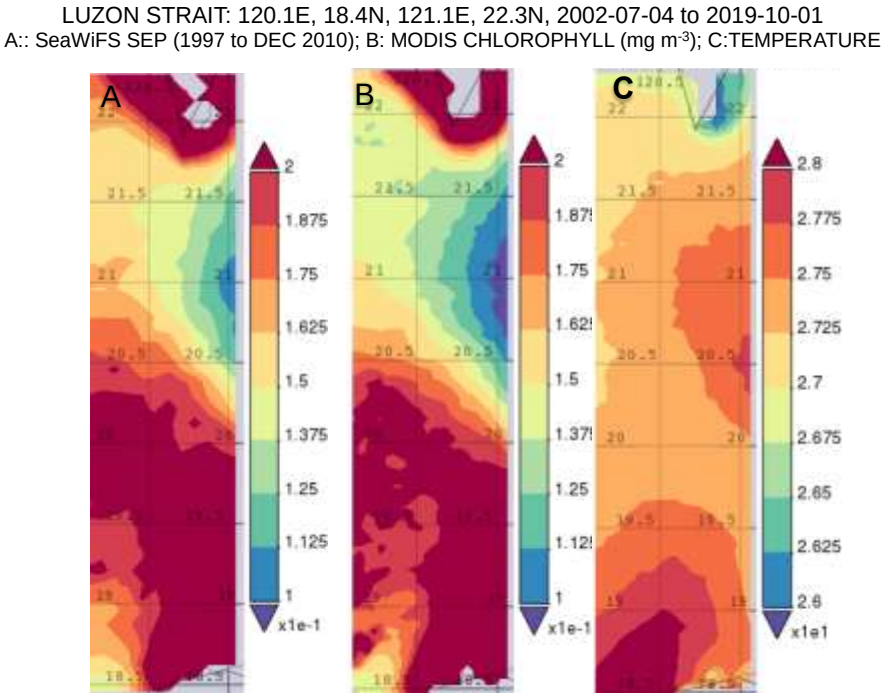

Figure 4: A: SeaWiFS chlorophyll concentration from September 1997 to December 2010. B: MODIS chlorophyll concentration from July 2002 to October 2019. C: Temperature in the Luzon Strait from July 2002 to October 2019. The covered region is shown in Figure 1with insert 2.

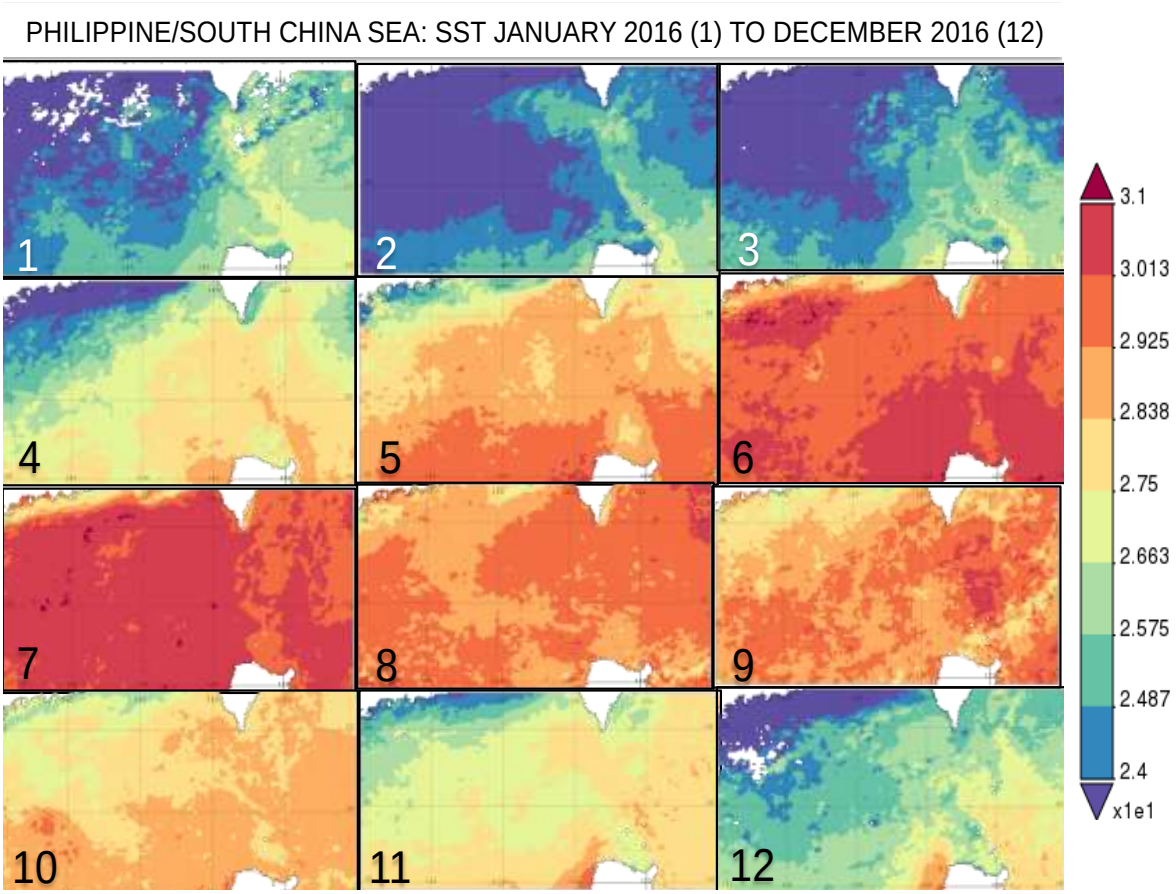

Figure 5: Yearly cycle of monthly averaged sea surface temperature over the Philippine Sea/South China Sea in 2016 for the region covered in Figure 1, insert 1. Numbers in the figure refer to the corresponding months, and the same color annotations for temperature scale have been used for all images.

Monthly observations of surface temperature shown in Figure 5 reveal the seasonal fluctuation of temperature gradients that are phase-locked with the monsoons. That means that at the beginning of the year, the Philippine Sea has warmer surface water compared with the colder South China Sea, and the Kuroshio is best recognized in the January image. In the February image, it can be seen that Kuroshio water enters south of Taiwan through the Luzon Strait into the South China Sea with an indication of eddy formation progressing in a westward direction. In March, the Kuroshio still forms a strong thermal gradient with the adjacent water masses, and there is an indication of eddy building. From January to March, a near-coastal filament appears north of the coastal region of Luzon that is interpreted as an isolated narrow jet from the Kuroshio. The fading northeast monsoon leads to an accumulation of heat in a shallower mixed layer from late spring to early summer that eventually warms the sea surface, and temperature gradients start to diminish from June to October when the Kuroshio can hardly be recognized by surface temperature alone. Averaged surface temperature has its maximum in June/July and declines in subsequent months with the development of the northeast monsoon. This decline is the result of deepening of the mixed layer by the southwest monsoon and marks the end of the heat accumulation despite the incoming surface heat flux (Qu, 2001). Toward the end of the summer season, cooling of the region develops and the sea surface temperature gradients allow again a better recognition of the Kuroshio.

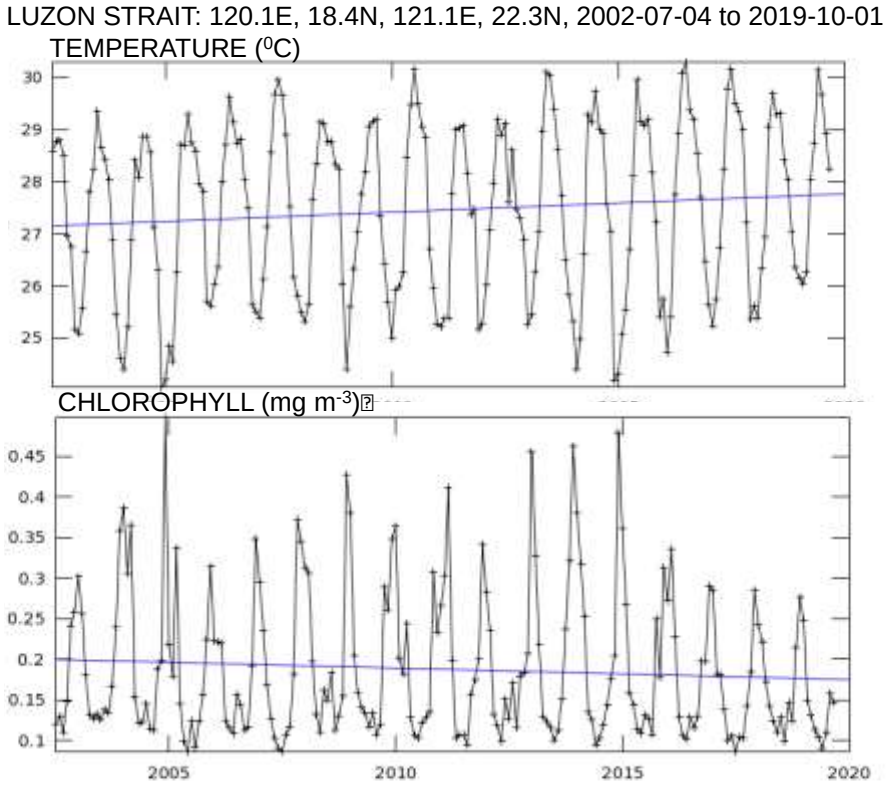

Figure 6: Monthly changes of temperature and chlorophyll concentrations in the Luzon Strait. The area covered is shown in Figure 1 as insert 2. The lines are based on linear regression of data from July 2002 to October 2019.

The biological system responds to the seasonal cycles as well as to inter-annual changes that are recognized in monthly temperature and chlorophyll data as shown in Figure 6. Almost every summer, intermittent chlorophyll peaks are observed and the increase in concentration starts shortly after the onset of the Northeast monsoon, although chlorophyll maxima do not necessarily coincide with the peak temperature. During the 17-year observations, a linear regression of the data showed for temperature an increase of around 0.5^0C while chlorophyll shows a slight decrease. This development follows a cooling trend that was reported by Caruso *et al.*, (2006), and for the NE South China Sea, they found a sea surface temperature decrease of 0.15^0C y^{-1} for the time 1998 to 2005. That means that around 2004 a large-scale change appeared in the observed region.

A branch of the Kuroshio occasionally deviates its course in a northwestward direction to the South China Sea through the Balintang Channel in the Luzon Strait. Images shown in Figure 7 reveal two branches of the Kuroshio located on the western and eastern sides of the Batanes Islands, in the Luzon Strait. In addition, shedding of eddies has been visualized in more detail with temperature measurements based on averaged data over approximately eight days, as shown in Figure 7. At the beginning of January, the Kuroshio warm water is well recognized and starts to bifurcate by January 15 to 22. The process of bifurcation continues until February 7, 2016 when an isolated warm eddy is visible and its displacement south of Taiwan, in a northwest direction, can be recognized from February 21 to 28, 2016. The coverage for the period, February 28 to March 15, 2016, shows a reorganization of the Kuroshio surface structure, and it is apparent that the process of bifurcation is one of the possible processes in eddy building that can be estimated to be around six weeks.

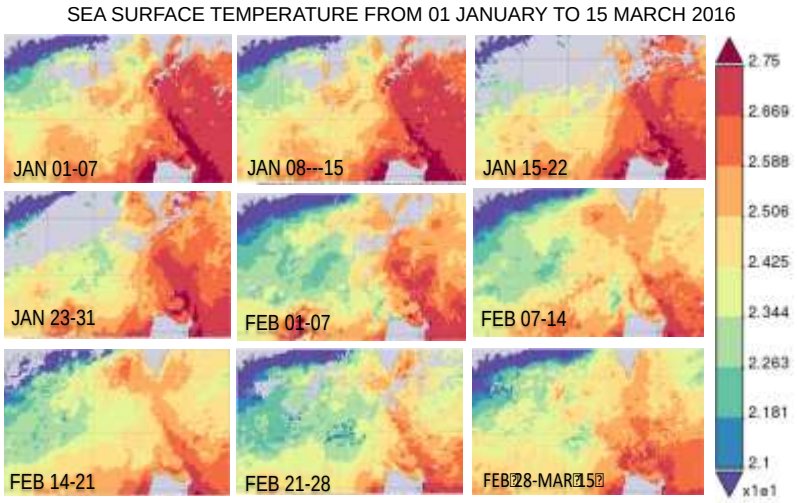

Figure 7: Sea surface temperature observations based on 8-day composites show bifurcation of the Kuroshio from January to February 2016. The area covered is shown in Figure 1 as insert 3. The northern edge of Luzon Island and the southern part of Taiwan are shown in grey. Note that persistent cloud coverage in the region is also indicated as grey.

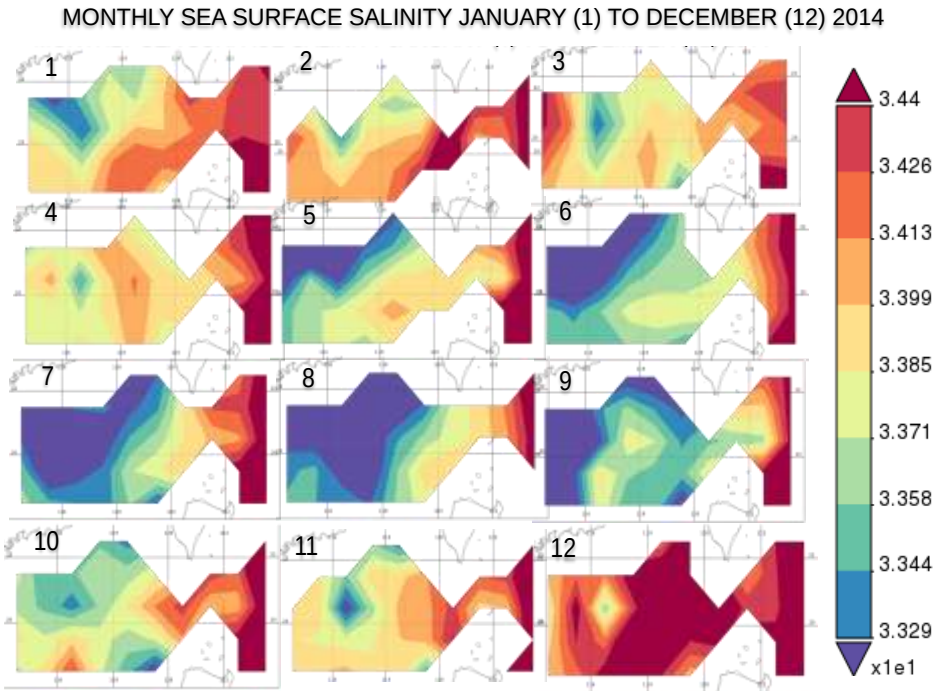

Figure 8: Salinity measurements (psu) covering the area over the Philippine Sea/South China Sea in 2014 for the region shown in Figure 1, insert 1. Numbers in the figure refer to the corresponding months. The color scale for salinity was annotated in ten steps in order to have the best contrast for each image during the year 2014. The data are based on one-degree and one-month average, respectively.

The intrusion of Kuroshio water into the South China Sea has been tracked with salinity measurements that are shown in Figure 8. Although the salinity data used in this study have coarse spatial and temporal resolution and are only available on a monthly average over several years, they have the advantage of large-scale quasi-synoptic surface coverage that has not been documented for the region before. December is the time of major high salinity influx from the Kuroshio but the intrusion of Kuroshio water reduces during the following months, and slight freshening occurs in the western part of the South China Sea where lower salinity values are observed until September. Due to the coarse ground resolution of the salinity measurements, however, eddy formation can hardly be recognized although patches with slightly elevated salinity are visible west of the Luzon Strait from December to April and are indicative of eddy intrusion into the South China Sea. However, eddies may even move farther west as has been shown by tracking a warm eddy that originated from the Luzon Strait and migrated westward along the 500-m isobaths and could be traced until it approached the east of Hainan Island (Wang *et al.*, 2020).

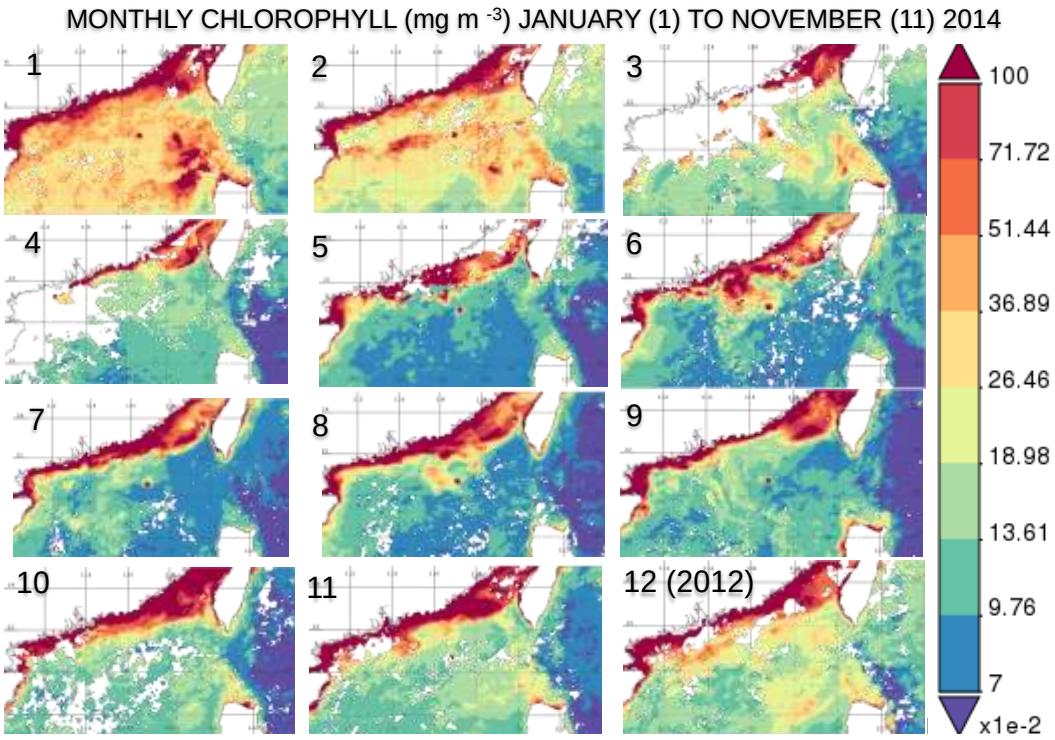

Figure 9: Chlorophyll distribution covering the area over the Philippine Sea/South China Sea in 2014 for the region shown in Figure 1 as insert 1. The area was extended slightly 114.0 E, 17 N to 124.0 E, 25 N, to compare with the salinity data that had a resolution of one degree only. Numbers in the figures refer to the corresponding months. Observations in December 2014 were strongly obscured by clouds; therefore, data for December 2012 were incorporated.

The salinity data in Figure 8 can be compared with the corresponding chlorophyll distribution in Figure 9. Blooming and low temperatures throughout the year characterize the region with lowest salinity values along the continental shelf of southern China, in the vicinity of Guangdong and Fujian Provinces. Low temperatures as shown in Figures 6 and 7 indicate possible upwelling conditions that elucidate the high chlorophyll values shown in Figure 9, with its highest values between July and October. This observation

is in agreement with reported summer upwelling as a regular phenomenon from June-September (Ndah, *et al.*, 2016; Yan *et al.*, 2015). The Kuroshio is recognized by its low chlorophyll concentrations and builds a strong gradient with water from the Luzon Strait. December and January show wide blooming over the Strait and the South China Sea. At the northern tip of Luzon Island, it was found that frequent blooming is associated with river discharge and entrainment of coastal water into the western boundary of the Kuroshio. This process is recognizable for the whole year but is significantly elevated during the season from December to March. It is reasonable to assume that local upwelling is also introduced by the local bathymetry, local winds and the impact of geostrophic flow of the Kuroshio. A support for this is given with Figure 10 that shows that lower temperatures were frequently found close to the coastal region of northern Luzon Island. The same figure also demonstrates the fast changes of sea surface temperature patterns by the intrusion of Kuroshio water into the Luzon Strait through eddy formation.

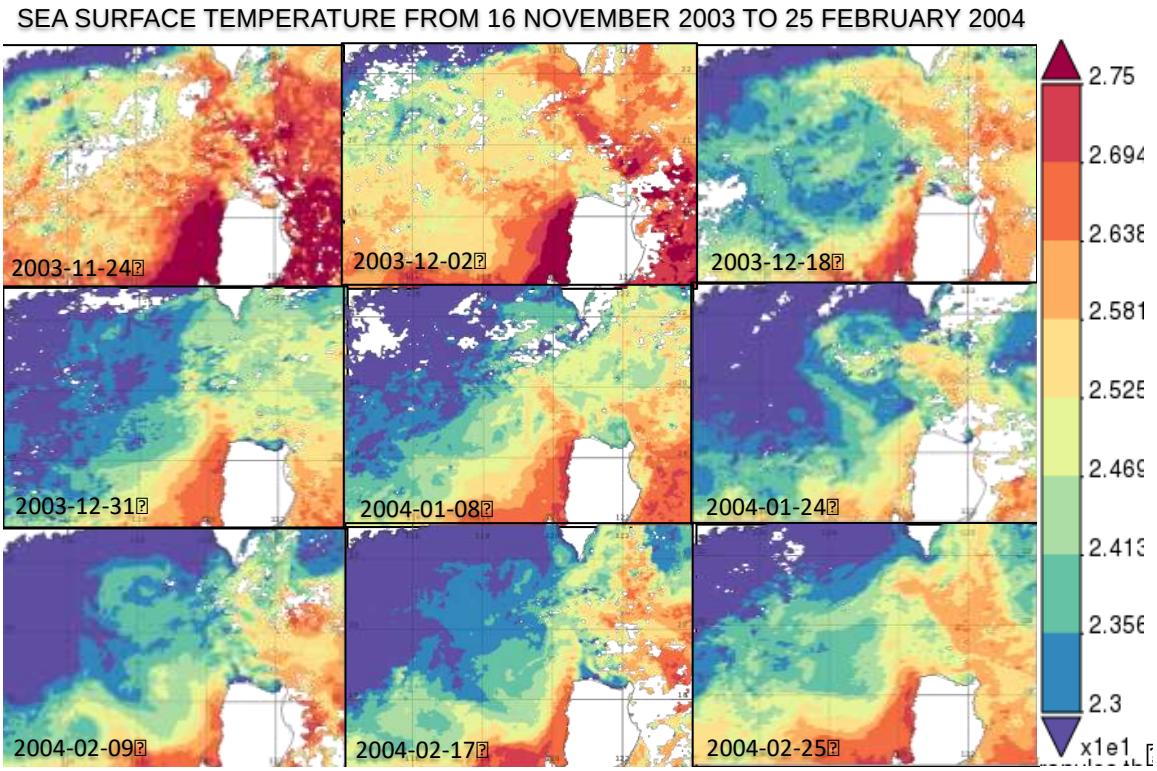

Figure 10: Intrusion of Kuroshio water through the Luzon Strait and eddy formation. Numbers present an 8-day composite of sea surface temperature measurements from November 24, 2003 to February 25, 2004. The images cover the region shown in Figure 1, as insert 3.

The surface temperature of the Luzon Strait becomes more complex because of moving eddies in a westward direction, both in winter and summer, within the depth range of the thermocline (Qu *et al.*, 2000). It is particularly during the winter season that intrusion of eddy formation is clearly detected through the thermal gradient between the Kuroshio and water in the South China Sea, as shown in Figure 10. In November, with the onset of the Northeast monsoon, the South China Sea starts to cool in the northern part, and the warm water around Luzon reduces its temperature as well. In December, bifurcation of the Kuroshio is observed, and intrusion of water from the Kuroshio into the Luzon Strait can be recognized. Although a strong temperature gradient is observed between the intruding Kuroshio water and the Philippine Sea, there is no indication of eddy building until January 24, 2004 when an isolated eddy developed and could be tracked until February 9, 2004, but the eddy lost its thermal

signature towards the end of February. For the time span shown in Figure 10, there were parallel observations made by Jia and Chassignet (2011) of the Kuroshio intrusion that began developing on January 14, 2004 and lasted about 20 days to extend to 118.5°E, where a loop then appeared on February 4, 2004. An anticyclonic eddy formed in the loop and separated from it on February 11, 2004. The anticyclonic eddy had its position at around 21°N, 118.5°E, and was approximately 200 km in longitude and 150 km in latitude and moved at a speed of about 0.3 m s^{-1}. There is general agreement with the position of the eddy and data presented in this study. However, the temperature data in Figure 10 indicate that the formation of a eddy could have formed even earlier on January 24, 2004.

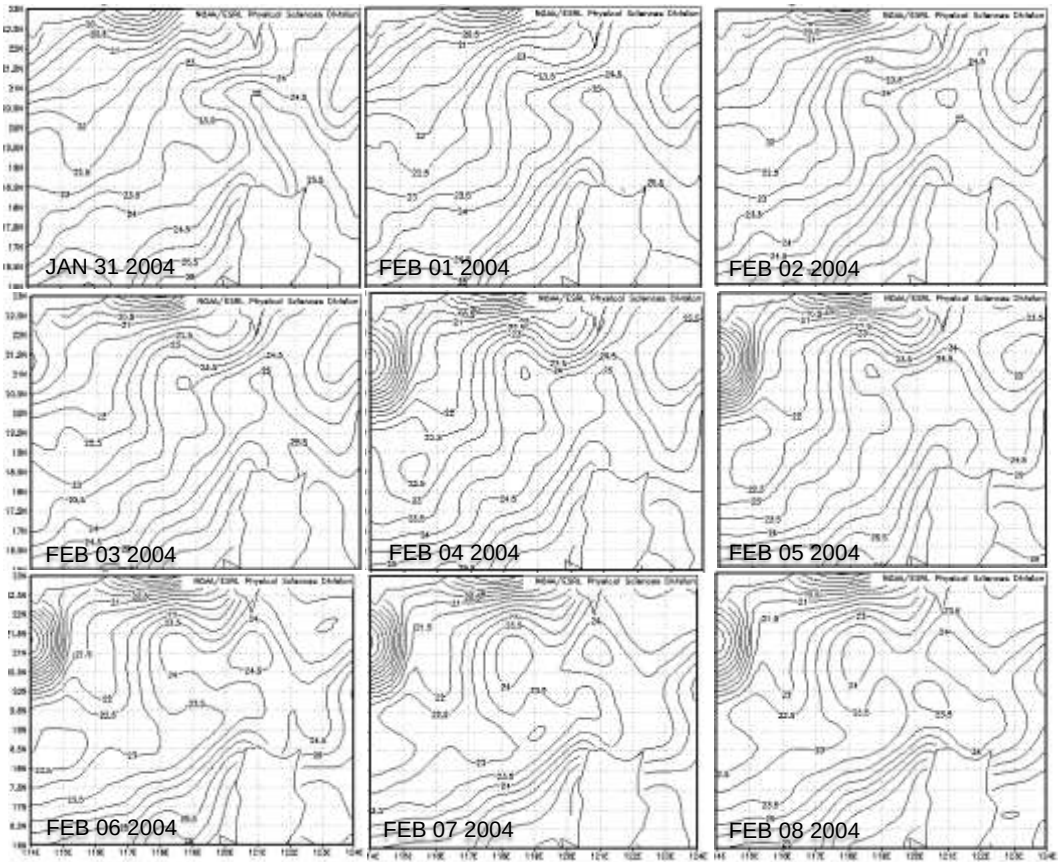

Figure 11: Daily NOAA sea surface temperature.

Additional data of NOAA sea surface temperature support the findings as illustrated in Figure 11 covering the period January 31, 2004 through February 8, 2004, where the deflection of the Kuroshio is shown to enter the Luzon Strait on January 31 and looping becomes visible for the following days. Bifurcation of the Kuroshio and intrusion of its water into the Luzon Strait can be recognized on February 2, and eddy formation and separation from the Kuroshio is visible on February 4 to February 8, and after, the temperature gradients are less pronounced and eddy recognition is reduced.

Salinity data support the observed changes in temperature and chlorophyll related to the influx of Kuroshio water into the Luzon Strait. In Figure 12, salinity data are shown in conjunction with precipitation data that demonstrate the periodic influence of Kuroshio water especially during the winter season. The path of eddies does not seem to be a regular pattern because an anticyclonic warm eddy travelled to the north of Luzon and close to the southwest coast of Taiwan and stayed for over a month

(Zu *et al.*,2013). This has been explained by the impact of local modification of the northeasterly monsoon and associated wind stress that modify the current patterns.

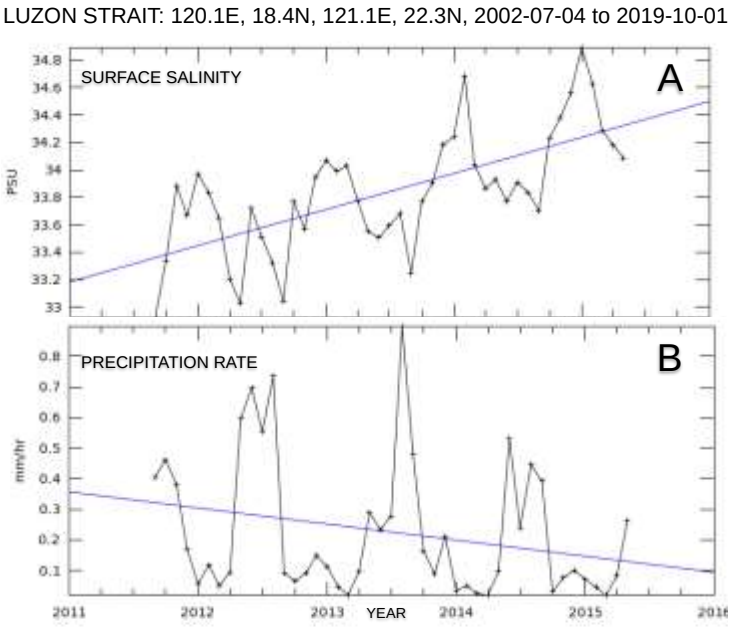

Figure 12: Temporal changes in the Luzon Strait from September 1, 2011 to May 31, 2015. A: Sea surface salinity. B: Precipitation rate. Note that 2015-2016 was a very strong El Niño event. The covered region is shown in Figure 1 with insert 2.

A summary of the averaged salinity is shown in Table 1, according to seasons, and displays the inter-annual change. The yearly maximum of salinity is reached during the winter season while the minimum appears in summer. The surface salinity data show a trend of over three years towards higher values of about 1.3 psu over the observed time, and precipitation rate has a significant decrease. However, both changes cannot be explained by reduced precipitation rates alone, rather large-scale meteorological processes seem to be responsible for the fluctuations.

Table 1: Inter-annual time series of averaged sea surface salinity in the Luzon Strait. The covered region is shown in Figure 1, insert 2.

SEASON	2011	2012	2013	2014	2015
DJF	-	33.81	33.98	34.35	34.68
MAM	-	33.27	33.79	33.94	34.19
JJA	-	33.48	33.60	33.83	-
SON	33.37	33.45	33.63	34.09	-

In conjunction with data shown in Figure 12, temperature and chlorophyll are graphed as Hovmoller latitude-presentation in Figure 13 showing the seasonal cycling in response to monsoonal changes with lower temperatures observed in the northern region of the Luzon Strait close to the southern tip of Taiwan. Chlorophyll shows a different distribution pattern with elevated values along the southern coast

of Taiwan that corresponds well with the cold water of upwelling. In the north, two major events of blooming can be observed of which the first appears at the end of the year with its maximum in January and the second blooming is in June/July but is limited to about 21.5^0N. Around July, minimum chlorophyll is present up to 21.5^0N, as indicated in blue in Figure 14. At 18.5^0N, higher chlorophyll concentrations are found near the latitude where the island group in the Babuyan Channel is located.

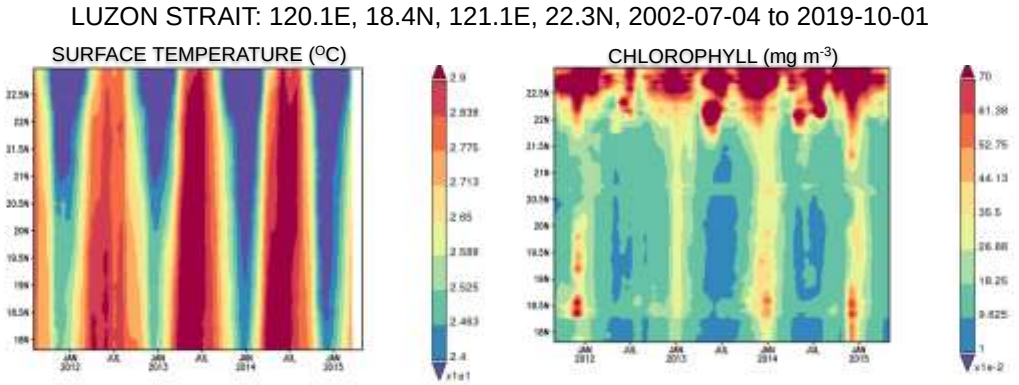

Figure 13: Hovmoller latitude presentation of sea surface temperature and chlorophyll in the Luzon Strait. The covered region is shown in Figure 1 as insert 2.

The distribution of chlorophyll and the temperature field show fluctuations in the inter-annual cycles and intermediate maxima are observed for chlorophyll in particular. This makes averaged data less meaningful for detailed analysis on the relationship between chlorophyll and temperature. For this reason a one-year cycle from December 2017 to December 2018 was selected to compare changes in chlorophyll concentration in relation to the temperature field.

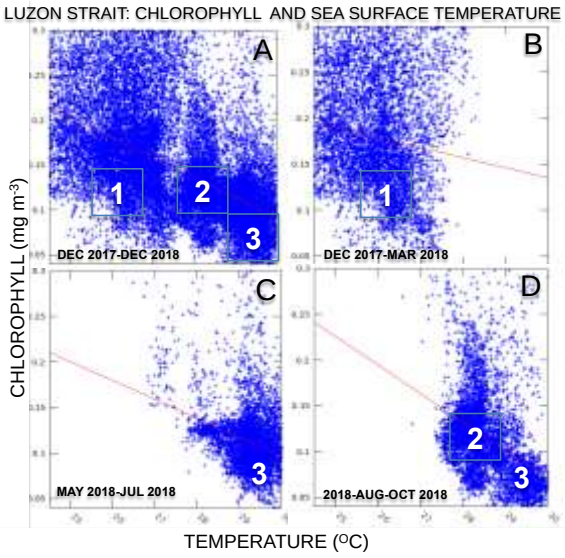

Figure 14: Seasonal change of chlorophyll-temperature clusters in Luzon Strait. A. Data for December 2017 to December 2018; B. December 2017 to March 2018; C. May 201 to July 2018; D. August 2018 to October 2018. The covered region is shown in Figure 1 as insert 2.

The scatter diagram in Figure 14A shows chlorophyll-temperature diagram for the whole year with three clusters that are identified and separated according to their time of advent. The first cluster is identified to appear during the period December 2017 to March 2018 and is shown in Figure 14B with elevated chlorophyll concentration at low temperatures. Figure 14C shows the cluster that is recognized from May 2018 to July 2018 with low chlorophyll concentrations that are associated with elevated temperature. Part of this cluster merged during August to October and is part of two separated clusters.

Concluding remarks

The long-time series of surface parameters used in this communication reveals the hydrographic complexity of the Luzon Strait and neighboring sea at different time and space scales, and are tied to the biological field expressed in terms of chlorophyll, and to the physical environment, expressed in terms of temperature. The temperature, salinity and chlorophyll series show the periodic occurrence of Kuroshio intrusion into the South China Sea water in the form of surface loops and eddies through the Luzon Strait observed during October to January. With the long-term data sets presented in this study, previous findings (for instance, Farris and Wimbush, 1996; Centurioni *et al.,* 2004; Nan *et al.,* 2015) elaborate inter-annual fluctuations that seem to be related to changes in atmospheric circulation. Higher water transport through the Luzon Strait during El Niño years is connected to climate signals from the Pacific into the South China Sea (Jing *et al.,* 2011; Hu and Wang, 2016). In response to the changing wind stress, the Luzon Strait has a lower transport from the Pacific into the South China Sea during La Niña (Qu *et al.,* 2004; Liu *et al.,* 2008, and Nan *et al.,* 2015). Furthermore, the time series revealed seasonal and inter-annual variability of sea surface temperature salinity and chlorophyll distribution that are interpreted to be associated with mesoscale eddies, ocean circulation and upwelling generated by the monsoon winds. The temperature series show details on the formation of bifurcation of the Kuroshio and eddy formation from the Kuroshio water intruding the Strait and there is indication that bifurcation is most probably the primary processes of eddy formation, and that eddy shedding occurred mainly during the period December to March whereas no eddy-shedding event was observed from June to October. This is also in agreement with previous reports on seasonal variation of eddy shedding (Jia and Chassignet, 2001; Nan *et al.,* 2011a; Sun *et al.,* 2018; Yuan *et al.,* 2007; Caruso *et al.,* 2006, Wu *et al.,* 2017). The time frame of eddy detachment and intrusion of eddies into the South China Sea was estimated by Jia and Liu (2004) who found that anticyclonic eddies periodically separate from the Kuroshio intrusion with an average shedding time of 70–90 days, but the data shown in this communication indicate that eddy formation and separation can also happen within a shorter time frame. The salinity measurement showed an increase over a period of close to four years, and it is suggested that this observation can be interpreted as the possible impact of inter-annual cycles.

ACKNOWLEDGEMENT

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