Decreasing trend of kuroshio intrusion and its effect on the chlorophyll-a concentration in the Luzon Strait, South China Sea

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ABSTRACT

Material exchange between oceans and currents is crucial for biogeochemical processes in marginal seas, such as the Kuroshio intrusion in the Luzon Strait, which contributes to nutrient and phytoplankton growth in the adjacent water. Therefore, it is necessary to understand changes in major current systems and their possible effects on marine ecology. In this study, we applied an edge-detection method to satellite-derived sea-surface temperature (SST) images to identify the SST front as the index of Kuroshio intrusion during 1985-2017. Chlorophyll-a (Chl-a) concentrations and geostrophic currents (determined from satellite observations after 1993) were examined by comparing long-term variations related to the Kuroshio front using empirical-mode decomposition analysis. The Kuroshio intrusion into the Luzon Strait gradually decreased after the 1990s, as did the Chl-a concentrations and current speed in the Strait. In contrast, the speed of the Kuroshio Current in the eastern Philippine tended to increase, indicating that the northward Kuroshio Current from the eastern Philippines became stronger, curtailing the westward intrusion of the branch current into the Luzon Strait. The speed of the Kuroshio Current correlated with the bifurcation of the North Equatorial Current (NEC), which is upstream of the Kuroshio Current starting from the southeast Philippines. Therefore, the NEC bifurcation latitude may have shifted more southward, which strengthened the water mass and current speed of the Kuroshio, resulting in decreased westward motion of the Kuroshio through the Luzon Strait. Consequently, the weakening Kuroshio intrusion may have caused a decreasing trend of biogeochemical processes in the South China Sea.

1. Introduction

The Kuroshio is a warm western boundary current in the northwest Pacific Ocean originating from the North Equatorial Current (NEC), which bifurcates to the east of the Philippines and separates into two branch currents, where the northward current mainly contributes to the Kuroshio Current. The Kuroshio flows along the eastern Philippines toward the Luzon Strait, east of Taiwan, and offshore of Japan. A branch current flows northwesternward into the South China Sea (SCS) through the Balintang Channel when the Kuroshio passes through the Luzon Strait (Chern and Wang 1998; Liang et al. 2003; Yuan et al. 2008). The Kuroshio intrusion into the SCS exhibits seasonal variations, where greater westward intrusion occurs during winter than in summer (Shaw 1991; Centurioni, Niiler, and Lee 2004; Liu et al. 2017). The Kuroshio movement can be illustrated by satellite/field observations and modeling simulations that spatial-temporal fluctuations of the intrusion into the SCS has gained attention from oceanographers. For example, the intrusive Kuroshio water can reach further westward (~114°E) during winter, but is confined to the east of 118°E during summer (Liu et al. 2017). In particular, the Kuroshio-intrusion processes and its controlling mechanisms are not only relevant to seasonal monsoons, but also driven by the El Niño-Southern Oscillation climatic event, which occurs once or twice per decade. Yuan et al. (2014) presented evidence indicating that the Kuroshio intrusion into the SCS in winter tends to strengthen during El Niño events, but weaken during La Niña years. The change of wind field can clearly effect on the interannual variability of sea surface temperature (SST) fronts in the basin of SCS in El Niño years (Wang 2017).
et al. 2020). Statistical analysis demonstrated a correlation between Kuroshio intrusion into the SCS and the Pacific Decadal Oscillation (PDO) index (Wu 2013). A review of the Kuroshio intrusion into the SCS revealed a detailed mechanism for the Kuroshio Current, showing that while the PDO and Oceanic Niño Index (ONI) are in the positive phase, the NEC bifurcation latitude shifts northward which enhances the Kuroshio intrusion into SCS (Nan, Xue, and Yu 2015). According to satellite observations and model simulations, the northward shift of the NEC bifurcation latitude weakens Kuroshio transport, thus contributing to the penetration of Pacific waters into the SCS through the Luzon Strait, while these conditions are reversed during La Niña years (Kim et al. 2004; Rong et al. 2007). By studying long-term changes in the Kuroshio Current, Nan et al. (2013) found that the Kuroshio intrusion into the SCS had a weakening trend from the 1990s to the 2010s, based on a combination of satellite images, in situ hydrographic data, and modeling results of water transport.

In addition to the spatial changes of the Kuroshio movement in physical terms, the Kuroshio intrusion exerts crucial effects on the biophysical processes in the SCS. These processes contribute to partial organic carbon flux and fish congregation because the Kuroshio subsurface water is uplifted onto the surface by topographic barriers or air–sea interactions during typhoon events. Deep nutrient-rich water brought to the surface enhances the abundance of phytoplankton that contain biogenic particles, which constitutes the mechanism whereby biophysical processes occur during upwelling or in converging regions of water masses (Li et al. 2018; Chen et al. 2018). The contrasts in water masses can be visualized in satellite images of sea surface temperature (SST) and chlorophyll-a (Chl-a) concentrations because thermal fronts often mark the boundary of upwelling systems, where fronts of Chl-a patches delineate boundaries of high primary production (Chang et al. 2010). Consequently, biophysical coupling is manifested in the oceanic frontal regions and can be easily observed and illustrated by applying an edge-detection method to satellite images (Lee, Chang, and Shimada 2015).

The issue on how the Kuroshio intrudes into the SCS is comprehensively discussed from the view of atmospheric forcing and current/eddies interactions, long-term index to quantify the Kuroshio intrusion strength is still lacking. For example in Nan, Xue, and Yu (2015), they combined several satellite-derived sea surface high data to generate a Kuroshio intrusion index, which can be used to identify the intrusion type in the Luzon Strait. Occurrence probability of different intrusion types and water transport were therefore calculated with time to illustrate potential long-term change of Kuroshio intrusion in an indirect view. As a consequence, this study attempts to investigate long-term change of Kuroshio intrusion strength based on a direct indicator.

Data from many previous studies have clarified the physical mechanism of Kuroshio intrusion associated with climatic factors; however, the long-term changes in Chl-a concentrations in the SCS are not yet understood. These findings prompted us to investigate long-term changes in biophysical processes occurring in the SCS that are due to the weakening trend of Kuroshio intrusion. Therefore, in this study, we employed the empirical-mode decomposition (EMD) approach to define the relationship between the Kuroshio intrusion and Chl-a concentrations by conducting a long-term trend analysis. To observe the intrusion and spatial fluctuations of currents in marginal seas, the SST front (determined by the edge-detection method) has been suggested as a useful indicator in the fields of biogeochemical dynamics and fisheries oceanography (Belkin, Cornillon, and Sherman 2009; Liu et al. 2019; Hsu et al. 2021). Consequently, the SST fronts of the Kuroshio were detected using long-term series satellite-derived images and used as primary indicators to understand the potential influence of the Kuroshio intrusion on the change in Chl-a concentration in the SCS.

2. Materials and methods

2.1 Satellite-derived data, model simulated data, and in-situ Chl-a observations

Figure 1 shows the study area with colored topographical features bounded between 116°E and 130°E in longitude and 8°N to 30°N in latitude, where has ocean currents of China Coastal Current (in winter), South China Sea Warm Current, Luzon Gyre (in winter), North Equatorial Current, Kuroshio, and Kuroshio Branch Current in the Taiwan Strait. Two rectangular regions, i.e. S (120.1°E–121.7°E, 19.6°N–21.2°N) and E (122.2°E–123.2°E, 17.2°N–18.2°N), indicating the satellite and model sampling region that was used to
analyze the Kuroshio intrusion strength (region S) and the upstream region in the eastern Philippines (region E). These two regions were selected for study because Gordon et al. (2014) demonstrated that water transport in those regions are closely related to the fluctuation of nascent Kuroshio and NEC.

A long-term dataset comprising the monthly means SST from 1985 to 2017 was used, which archived using the Operational Sea Surface Temperature and Sea Ice Analysis model with 5 km spatial resolution (https://marine.copernicus.eu). This dataset was generated from satellite and in situ SST observations, combined with Pathfinder Advanced Very High Resolution Radiometer images, and reprocessed using Along Track Scanning Radiometer data and in situ observations from the International Comprehensive Ocean-Atmosphere Data Set. Remote sensing (or model simulated) images are composed of a matrix of pixels, which is the size of the smallest possible feature that can be detected (or calculated). Image pixels are usually gridded in square for a certain area on an image. For the case of SST data we used, each pixel represents an area of 5 km × 5 km on the ground.

Geostrophic current products were generated and distributed by the Copernicus Marine and Environment Monitoring Service (CMEMS), which performs the complete processing and distribution of sea-level anomalies, absolute dynamic topographies, and geostrophic velocities using the Archiving Validation and Interpretation of Satellite Oceanographic (AVISO) database (https://www.aviso.altimetry.fr/en/home.html). The AVISO database combines data from multiple satellites, including ENVISAT, GFO, Jason-1, Jason-2, ERS-1, ERS-2, and TOPEX/Poseidon. The dataset for
the current was consistent with a spatial resolution of 25 km and a temporal scale based on a monthly mean. In this study, geostrophic current data were collected from 1993 to 2017.

The Chl-a concentration reflects the abundances of nutrients or phytoplankton, where a higher phytoplankton population corresponds to a higher pigmentation value in terms of the water color. To investigate the Chl-a patterns and concentration changes relevant to SST front, Chl-a concentrations from Pelagic Interactions Scheme for Carbon and Ecosystem Studies (PISCES) biogeochemical model and Moderate Resolution Imaging Spectroradiometer aboard Aqua satellite (MODIS/Aqua) were used in the variation trend analyses and quantitative comparison, respectively. The satellite-derived Chl-a images from MODIS/Aqua have high spatial resolution of 4 km with daily and monthly mean products enable us to illustrate fine features of Chl-a concentrations associated to current or eddies. The PISCES (Pelagic Interactions Scheme for Carbon and Ecosystem Studies) model provides global configurations in daily and monthly mean Chl-a concentration simulated since January 1993 that enable researchers to discuss long-term changes in marine ecology (Aumont et al. 2015). This model has included the satellite data which were sea surface height altimetry, and wind field. Although satellite remote sensing is a good way to continuously measure Chl-a levels on large and fine spatial features, it has been argued that global algorithms for retrieving sea water variables do not always provide reasonable quality for all areas of the ocean (Pan, Tang, and Weng 2010). Therefore, in this study, we collected in situ observations of Chl-a concentrations from research vessels to compare with satellite-derived Chl-a concentrations before applying long-term trend analysis in the study area. One-liter surface-water samples were collected from 145 stations by R/V Ocean Research I (OR-1) and OR-3 from 2013 to 2016. The spectral absorption of Chl-a was measured using a fluorometric method (Hung et al. 2013). The daytime samples were used only to compare the Chl-a values within one pixel of the images on the same day. The root mean square log error (RMSE) and average difference (bias) were calculated as indicators to determine the accuracy of the satellite data.

### 2.2 Sea surface temperature-based front detection

Oceanic fronts detected in SST satellite imagery were extracted using the edge-detection approach developed by Belkin and O’Reilly (2009). After completing the edge-detection process, the gradient magnitude (GM) of each front candidate pixel was calculated using the following equation:

\[
GM = \sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2}
\]

where \(T\) is the SST and the \(x\) and \(y\) axes are directed eastward and northward, respectively. The GM (°C/km) was calculated using all frontal pixels for each SST image. Thus, we processed the monthly mean SST data as the GM, which was computed for each pixel. The GM map presents frontal patterns and reveals the details of the oceanic frontal systems.

To give a comprehensive view of Kuroshio intrusion related to Chl-a concentration with time change, seasonal composite maps of SST front GM and Chl-a concentrations (see section 3.1) were selected in the year of 2003, 2008, and 2015 that refereeing to the normal condition, La Niña event, and El Niño event, respectively.

### 2.3 The empirical mode decomposition (EMD) method

The EMD method is an adaptive spatiotemporal-analysis method suitable for processing nonstationary and nonlinear series. This method has been frequently examined, updated, and improved to determine the stopping criteria for the sifting process and the separation criteria for the frequency. Rilling et al. (2007) proposed a threshold method to improve the stopping criteria for the sifting process. This study was focused on the EMD method (rather than using an HHT algorithm) to plot the frequency spectrum. However, the EMD method is primarily used to decompose satellite-derived time-series data, which are long-term and continuous in terms of the numbers of components. Furthermore, the intrinsic mode functions (IMFs) and residues (mean trends) represented a long-term trend in the time series. An IMF extracted using a sifting processes with the EMD method was required satisfy the following conditions:

- (condition a) The IMFs must have the same numbers (or differ at most by one) of extrema (the sum of maxima and minima) and zero crossings.
• (condition b) The IMFs must have symmetric envelopes defined by the local maxima and minima. Moreover, the mean values of the two envelopes must be zero.

The IMF decomposition of time-series data obtained using the EMD method is referred to as the sifting process, where the original series data is defined as \( x(t) \), and the process includes the following steps:

(i) Identify all local extrema from the given \( x(t) \) and then connect them with a cubic spline line as an upper envelope; the first step is repeated for the local minima to produce a lower envelope.

(ii) Denote the upper and lower envelope means using \( m_1(t) \), where the difference between the original data \( x(t) \) and \( m_1(t) \) is the first component \( h_1(t) \). After sifting operations based on Equation (2) \( h_1(t) \), an IMF is obtained as follows:

\[
x(t) - m_1(t) = h_1(t)
\]  
(2)

(i) Consider \( h_1(t) \) as the original data, and steps (i) and (ii) are repeated for the sifting process.

\[
h_1(t) - m_{11}(t) = h_{11}(t)
\]  
(3)

The sifting process is repeated \( k \) times:

\[
h_{1(k-1)} - m_{1k} = h_{1k}(t)
\]  
(4)

until \( h_{1k}(t) \) becomes a true IMF that fits the conditions of the IMF (condition a and condition b described above), and it is then designated as follows:

\[
c_1(t) = h_{1k}(t)
\]  
(5)

Finally, the first IMF \( c_1(t) \) is obtained using \( x(t) \).

(i) Subtract \( c_1(t) \) from \( x(t) \), which defines the residue of \( x(t) \) as \( r_1(t) \):

\[
x(t) - c_1(t) = r_1(t)
\]  
(6)

\( r_1(t) \) is considered a new series, and the same sifting process is repeated as described in steps (ii), (iii), and (iii); thus, an increasing number of IMFs can be obtained as follows:

\[
\begin{align*}
r_1(t) - c_2(t) &= r_2(t) \\
& \vdots \\
r_{n-1}(t) - c_n(t) &= r_n(t)
\end{align*}
\]  
(7)

A series of IMFs and final residue \( r_n(t) \) can be obtained as follows:

\[
x(t) = \sum_{i=1}^{n} c_i(t) + r_n(t)
\]  
(8)

Finally, when the residue becomes a monotonic function, no more IMFs can be extracted; thus, the sifting process is stopped. The final residue denotes the long-term trend of the time-series dataset. The EMD method has been widely used in various geophysical studies, including seismology, oceanography, and meteorology, particularly for nonstationary and non-linear time series.

3. Results

3.1 Annual variation of Kuroshio intrusion and Chl-a concentrations

The present findings also revealed similar seasonality in terms of the fluctuations in the main Kuroshio Current from the eastern Philippines to the SCS. Figure 2 shows the seasonal composite features of the geostrophic current superimposed on the SST front GM maps.

Kuroshio intrusion into the SCS through the Luzon Strait was evident, and the SST frontal bands were clear and corresponded to the western boundary of the Kuroshio Current. For example, in the winter of 2003, the intrusion reached south-western Taiwan and moved more westward to reach the coast of mainland China (short white arrow in Figure 2a) where the SST front GM was larger than 2.5°C/km. A leaping path was found in the winter of 2008 (Figure 2b), which has a smaller bend of intrusion into the Luzon Strait, with the majority of the Kuroshio moving northward to the east coast of Taiwan. The strongest Kuroshio intrusion showed a looping path in the winter of 2015 (Figure 2c), when the Kuroshio intruded into the SCS through the middle Luzon Strait with a C shape and then flowed out from the southern tip of Taiwan. In contrast, in summer, SST frontal bands were not obvious in the Luzon Strait because of lower temperature variability in the surrounding warm waters. According to the geostrophic current features, the Kuroshio frequently leaped over the Luzon Strait (Figure 3a) and likely bounded in longitude 121°E, where the looping path (Figure 3b) and leaking path (Figure 3c) occurred occasionally during the 2000s.
and 2010s. The looping path in summer did not accompany Kuroshio outflow through the north Luzon Strait, but flowed northeastward into the Taiwan Strait along the west coast of Taiwan (Figure 3b).

Figure 4 and Figure 5 show seasonal composite maps for the Chl-a concentrations, which were used to determine the Kuroshio intrusion seasonality. In winter of 2003, a higher Chl-a concentration bend (> 0.5 mg/m³) was found in the northern SCS (white arrow in Figure 4a), which showed a northwestwardly intrusion pattern through the Luzon Strait that corresponded to the leaking path. The Chl-a intrusion bend was relatively short in the winter of 2008 (white arrow in Figure 4b), when a high Chl-a jet extended from the coast of mainland China (red arrow). This feature likely revealed that the weak Kuroshio intrusion in the leap path may contribute to lower Chl-a concentrations than the coast of mainland China. Moreover, a circular patch of high Chl-a concentrations was found off the eastern Luzon Strait (black arrow), where mesoscale eddies frequently occur. In the winter of 2015, an intensive Chl-a bend (> 0.8 mg/m³) was found within the loop path (white arrow in Figure 4c) and reached the boundary of 118°E. In summer, Kuroshio intrusion from the Luzon Strait did not contribute to the
phytoplankton bloom for the SCS, where the Chl-a concentration was usually lower than 0.1 mg/m$^3$ within the leaping path (white arrows Figure 5a–5c). However, the Chl-a concentration increased (> 1 mg/m$^3$) in the northern tip of the SCS (red arrows in Figure 5a–5c), which contrasted with the interaction between the northeastwardly current (South China Sea Warm Current) and the topography (Taiwan Bank).

Figure 4. Seasonal mean Chl-a concentration maps derived from PISCES model in winters of (a) 2003, (b) 2008, and (c) 2015. White arrows indicated Chl-a concentrations enhanced by the Kuroshio intrusion from Luzon Strait. Red and black arrows in (b) presented high Chl-a jet extended from Chinese coast and mesoscale eddies off east Luzon Strait, respectively.

Figure 5. Seasonal mean Chl-a concentration maps derived from PISCES model in summers of (a) 2003, (b) 2008, and (c) 2015. Red arrows indicated high Chl-a concentrations enhanced by northeast ward South China Sea Warm Current and the topography of Taiwan Bank.

Figure 6 shows the monthly mean Chl-a concentration in January with high spatial resolution, which demonstrates that Chl-a concentrations in the Luzon Strait were relatively lower in the normal year of 2003 (Figure 6a) and La Niña year of 2008 (Figure 6b), while apparent higher Chl-a concentration occurred in the El Niño year of 2015 (Figure 6c). To confirm the reliability of satellite-derived Chl-a concentrations for qualitative illustration, 146 in situ measurements from six cruises were compared. However, only 28 matching pairs were available for comparison due to cloud coverage. Figure 6(d) shows low Chl-a concentrations (< 0.2 mg/m$^3$) in most areas in the north SCS and high Chl-a values (> 0.5 mg/m$^3$) in the coastal waters and intrusion areas. Although the number of matching pairs was limited, the comparison showed high accuracy with an RMSE of 0.1 and an $r^2$ value of 0.95. Therefore, these statistical results
suggest that satellite-derived Chl-a data enabled analysis of the long-term variability in the Kuroshio region. Although satellite-derived ocean color images provide fine features to investigate ocean dynamics in marginal sea, the cloud affected pixels and short available time period (since January 2003) limited us to generate continuous monthly mean time series data, full coverage of valid pixel, and longer time period data set from model simulations is suitable for long-term trend analysis.

3.2 Long-term change of kuroshio intrusion and Chl-a concentrations

The monthly mean SST data derived from the CMEMS from 1985 to 2017 within the Kuroshio intrusion hot-spot in the SCS (sampling rectangle S in Figure 1) were processed through EMD with a high-frequency component filter, which could define the long-term tendency of the SST. The original SST series (Figure 7a) illustrates a steady seasonal variation, where the highest SST occurred during summer and the lowest SST occurred in winter. The SST residual trends were decomposed by EMD (Figure 7b), which revealed that the SST gradually increased by 0.3°C over the past three decades. In contrast, the SST front GM values, such as the Kuroshio-intrusion index, were lower in summer and higher in winter (Figure 7c). Higher GM values indicated stronger horizontal changes in sea water temperatures at the boundary between the shelf waters and Kuroshio intrusion water. It is therefore evident that Kuroshio intrusion was more obvious in winter than in summer. Moreover, the residue trends of the SST front GM declined over the past three decades (Figure 7d).

Figure 6. Monthly mean Chl-a images derived from MODIS/Aqua satellite in January of (a) 2003, (b) 2008, and (c) 2015. Map of relationship between satellite-derived and in situ measured Chl-a concentrations (d). Red arrows indicated Chl-a patterns in the Luzon Strait.
To clarify the relationship between the Kuroshio intrusion and the Chl-a concentration in the Luzon Strait, a long-term series of Chl-a concentrations from PISCES model (obtained from 1993 to 2018) was also decomposed by EMD. The Chl-a concentration was higher than 0.2 mg/m$^3$ in winter, whereas it was lower than 0.1 mg/m$^3$ in summer (Figure 8a). The comparison of MODIS/Aqua satellite-derived Chl-a concentration showed corresponding variation in both seasonal and annual (red dash line in Figure 8a). We noticed that the Chl-a concentration of PISCES model tended to decrease since 1995. In particular, the mean Chl-a concentration in the Luzon Strait was lower than 0.15 mg/m$^3$ since 2005 (Figure 8b). This decreasing trend in the Chl-a concentration should be related to a limited nutrient supply from the Kuroshio subsurface. We therefore suggest that Kuroshio intrusion has gradually faded in the Luzon Strait since the 2000s.

Figure 7. Original time series (a) and residual trends (b) of the SST (in °C), and the original time series of the sea surface temperature gradient (c, in °C/km) and its residual trend (d) in the Luzon Strait (rectangle S in Figure 1).

Figure 8. Original time series of the Chl-a concentration derived from PISES model and MODIS/Aqua (a) and its residual trends (b) in the Luzon Strait (rectangle S in Figure 1).
Trend changes in both the SST fronts and Chl-a concentrations were further compared with the current field of Kuroshio in the study area to understand the physical process of the current system. As shown in Figure 9, the current speed in sampling region S was usually higher than 0.35 m/s in winter, but it was lower than 0.25 m/s in summer (Figure 9a). The long-term trend of the current in region S revealed a decreasing trend since the 2000s (Figure 9b), which corresponded to the decreasing trend of the SST front GM and Chl-a concentrations. Two perpendicular components of current velocity in zonal (u) and meridional (v) directions were investigated, which illustrated an increasing trend of 0.024 m/s in the U direction (Figure 9c) and a decreasing trend of 0.03 m/s in the V direction. These results indicate a northward movement trend of the Kuroshio in the SCS, which reduced the westward flow transport of the Kuroshio subsurface intruded from the Luzon Strait.

4. Discussion

SST fronts can appropriately reflect the narrow boundaries of different water masses, which can be used as indicators to examine the spatial fluctuations of ocean currents. Therefore, in this study, we defined the SST front of the Kuroshio as an intrusion index for analyzing the strength variations and spatial distributions of frontal bands in the Luzon Strait. The monthly SST frontal maps (Figure 2 and Figure 3) show that the strongest intrusion in the Luzon Strait occurred in winter, whereas the weakest intrusion was observed in summer. The results corresponded appropriately with the pattern of geostrophic currents. Using the integral of the geostrophic vorticity as the Kuroshio-intrusion index in the SCS, Nan et al. (2011) argued that SST and SSH are not good indicators for identifying the Kuroshio pathway from the SCS waters. However, our edge-detection approach showed clear intrusion features from SST GM maps that were
consistent with the determined feature type reported by Nan et al. (2011). Therefore, the SST front GM can be used both to determine the current path and to quantify its strength between currents over time. To investigate the long-term change of the Kuroshio intrusion, the SST front GM time series into the Luzon Strait was decomposed by EMD (Figure 7), which showed a declining trend that should be related to the weakening intrusion of the Kuroshio Current. This resulted in decreasing Chl-a concentrations in the Strait (Figure 8) from 1985 to 2017 because of the limited nutrient supply from the Kuroshio subsurface upwelling during its intrusion. The Kuroshio water initially is warmer and saltier than waters in SCS; however, cold and nutrient-rich subsurface water of Kuroshio upwelled onto the surface because of the shallow topography while Kuroshio intruded into the Luzon Strait from east deep open ocean. Therefore, intense Kuroshio intrusion will contribute cooler SST but higher SST GM and Chl-a concentrations. On the contrary, weakening Kuroshio intrusion will retard exchange between surface and subsurface Kuroshio water (Shao 1991; Wu et al. 2016), which results in the warmer SST and lower temperature gradient change (SST GM), while Chl-a concentrations also decrease regarding to the lower nutrient supply from subsurface water of Kuroshio. The integrated effect from wind stress curl and eddy activity were mainly related to the front generation near Luzon Island, while high correlations for Chl-a concentrations were consistently found in the water west of Luzon Strait (Yu et al. 2019; Wang et al. 2020). Long-term change of Kuroshio front in the Luzon Strait is thus suggested as an important factor in the biogeochemical response from the physical environment.

Kuroshio intrusion features can be classified into three types, as described by Nan et al. (2011): the looping path, the leaking path, and the leaping path. According to a review by Nan, Xue, and Yu (2015), Kuroshio intrusion into the SCS varies seasonally, with peaks in winter and troughs in summer that corresponded with water transport in the Luzon Strait. Nan et al. (2013) analyzed the occurrence probability of intrusion types; both looping and leaking paths are dominant patterns in winter with probabilities of 25% and 69%, respectively. It was also evidenced that the probability of a looping path near the Luzon Strait declined from 1993 to 2010, whereas the leaping path probability increased. Nan et al. (2013) also estimated the water transport of the Kuroshio Current into Luzon Strait using a modeling simulation, which revealed a negative trend of −0.24 sverdups (Sv)/yr that was linked to the weakening Kuroshio intrusion. Regarding the contribution of water exchange from the different Kuroshio intrusion types, the leaping path showed the lowest concentration when the major Kuroshio water flowed northward with a slight curving path into the east Luzon Strait. The increasing occurrence of the leaping path can explain why the long-term trend of SST GM and Chl-a concentrations declined during the study period.

The mechanism long-term trend of weakened Kuroshio intrusion into the Luzon Strait is evident in all result of present EMD analysis, which can be attributed to the global warming. According to Wu et al. (2016), the warming of Pacific warm pool intensified the trade wind and resulted in northerly wind off the Philippines, which drive more Kuroshio upstream water flow northward that induce the southward shift of NEC bifurcation latitude and enhanced the Kuroshio transport off east Luzon Strait. The strengthened easterlies wind enhanced during a negative pacific decadal oscillation (PDO) phase. If stronger trade winds predominate, the Kuroshio will likely be strengthened (England et al. 2014). In other words, a stronger current from the east Philippines indicated lower westward transport into the SCS from the Luzon Strait. In contrast, a weakening of the Kuroshio upstream would help the intrusion, and the westward movement of mesoscale cyclonic eddies from the Pacific Ocean can easily affect the Kuroshio movement (Chang and Oey 2011; Yang et al. 2013; Wang and Oey 2016). However, it has been argued that eddying of the Kuroshio position east of the Philippines has a limited on long-term changes (Nan et al. 2013). Therefore, we suggest that the Kuroshio upstream variation should be a key component that results in changes of intrusion into the Luzon Strait. To validate this possibility, we sampled the long-term change in the Kuroshio Current velocity and performed EMD analysis of the region upstream of the Kuroshio Current (rectangle E in Figure 1). The residue trend of the current in the east Philippines increased with a velocity of 0.03 cm/s since the 2000s (Figure 10a). Moreover, the trend of the u-direction current speed increased linearly from westward to eastward (Figure 10b), whereas the v-direction current
fluctuated without a persistent trend change (Figure 10c). Nan et al. (2013) also presented evidence indicating that Kuroshio transport through the east Philippines (18°N) caused a negative trend of −0.25 Sv/yr from 1993 to 2010. Therefore, we suggest that the upstream Kuroshio caused an increasing trend of eastward flow, resulting in a declining trend of water transport and Chl-a concentrations in the downstream Luzon Strait. This phenomenon can be explained by the planetary vorticity, which accelerates the transition from penetrating into the leaping regime in the downstream waters. In contrast, a weakened inertia of the Kuroshio enables planetary potential vorticity balance that allows the Kuroshio bend to more westward through the Luzon Strait (Sheremet 2001). As a conclusion, Kuroshio intrusion type were likely related to the El Niño Southern Oscillation (ENSO) events while leaping paths occurred in La Niña year (Figure 2b) and looping paths appeared in El Niño year (Figure 2c). For long-term trend, negative PDO phase could resulted in strengthen and offshore ward Kuroshio in east Philippine that weakened the intrusion into the SCS.

Moreover, the upstream Kuroshio Current correlated with the bifurcation of the westward-flowing NEC, which is the source current of the Kuroshio starting from near the southeast Philippines. The NEC bifurcation latitude can be well defined in the region between the water of 12°N–14°N and 127°E–130°E by images showing sea-surface high anomalies, whereas the NEC bifurcation latitude migrated quasi-decadally between 10° and 15°N (Qiu and Chen 2010). It was previously reported that latitudinal changes in the NEC bifurcation have clearly tended southward at 2° latitude during the period from 1993 to 2010 (Qiu and Chen 2012). The southward migration trend was evidenced again until 2013 (Cabrera et al. 2015). Consequently, the current strength of the upstream Kuroshio Current off the east Philippines increased from 1993 to 2014 (Wu et al. 2016), during which time the southward shift trend of the NEC bifurcation latitude was confirmed (Qiu and Chen 2012; Wu, Lin, and Qiu 2019). It is therefore suggested that the decrease in the Kuroshio intrusion trend into the Luzon Strait is attributed to southward NEC bifurcation, which increases the strength of the upstream Kuroshio movement eastward, because the Chl-a concentrations and biogeochemical progress in the northern SCS have decreased over the past two decades. A schematic illustration of the long-term changes in the Kuroshio path and its intrusion into the SCS is provided in Figure 11. Before the 1990s, the

Figure 10. Residual trends in the absolute velocity (a), u component (b), and v (c) component in the in east Philippines (rectangle E in Figure 1).
NEC located in the northernmost direction resulted in the weakest Kuroshio upstream but promoted intrusion into the Luzon Strait and enhanced the Chl-a concentration. In contrast, after the 2010s, the NEC shifted more in the southward direction, which enhanced the Kuroshio main stream and reduced both the intrusion and Chl-a concentration in the Luzon Strait.

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Author contributions
Yi Chang: Conceptualization, methodology, writing, and editing the manuscript. Yun-Chan Tsai: Satellite-derived data analysis. Yung-Yen Shi and Yun-Xuan Lu: Ground truth observations and analysis. James T. Liu: Conceptualization, reviewing, and editing. Tung-Yao Hsu, Jen-Han Yang, and Xing-Han Wu: Validation analysis. Chin-Chang Hung: Advisor, reviewing, and editing.

Data and Codes Availability Statement
The data that support the findings of this study are freely accessible for others to duplicate the analysis. Link of data sources including satellite observations and model analyses are clearly stated in the section of Materials and Methods.

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