Dear Editor and Reviewers

We are very pleased to have your comments concerning our manuscript entitled "Multiple mechanisms for chlorophyll-a concentration variations in coastal upwelling regions: A case study east of Hainan Island in the South China Sea" (egusphere-2022-969). Thank the editor and reviewers for taking time out of your busy schedule to review our paper and provide constructive comments on it. Those comments are all valuable and helpful. We have read and deal with all comments carefully. We have uploaded the file of revised manuscript with all comments highlighted with yellow shading in the text, and point-to-point responses to the reviewers' comments are present following.

Response to Comments of Reviewer 1

[Major Comment 1] The methods of EOF analysis and trend estimation were not presented in Section "Materials and methods".

Response: Thanks for your comment. Empirical orthogonal function (EOF) is widely used in climate research to identify dominant patterns of variability and to reduce the dimensionality of climate data. In my opinion, it is a general method. Therefore, the description is omitted in the previous manuscript. Based on your comment, a brief description has been added as Section 2.5.

2.5. Empirical orthogonal function

Empirical orthogonal function (EOF) is a useful tool and widely applied to reduce the dimensionality of climate data (North et al., 1982). EOF analysis is used to determine the dominant patterns of Chl-a in the study area. The Chl-a data is prepared as an anomaly in the form of matrix, X. Decomposition is applied by B·E = X. EOF modes (i.e., E, spatial patterns) and their corresponding principal components (i.e., B, temporal coefficients) could be obtained by decomposition of the anomaly matrix. The EOF patterns and the principal components are independent.

Reference

North, G.R., Bell, T.L., Cahalan, R.F., Moeng, F.J., 1982. Sampling Errors in the Estimation of Empirical Orthogonal Functions. Monthly Weather Review 110, 699-706.

[Major Comment 2] Why did the authors use two wind datasets? The results related to the surface wind are merged from the two datasets? If so, it should be mentioned in the text.

Response: Thanks very much for this useful comment. The data used in this manuscript is mainly remote sensing data. Sea surface wind data observed by satellite is the first choice. However, the lifetime of satellite is limited, about several years. Therefore, I used the monthly product obtained from multiple scatterometers, i.e., ASCAT and QuikSCAT. The rationality of analysis from the combined data should be discussed. However, it is not the purpose of this manuscript. Therefore, I used sea surface wind data from ERA5 with your comment. The description of the data and correlated analysis are corrected.

Data description

The sea surface wind (SSW) at 10 m above the sea surface, with a spatial resolution of 0.25°, were obtained from the Copernicus Marine Service (CMEMS). The wind data is a sub set from the fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis of the global climate covering the period from January 1950 to present. The data from 2002 to 2020 used in this study were a monthly product

The wind stress is determined as

$$\tau = \rho_a C_D U|U|$$

where ρ_a, C_D, and U are air density, drag coefficient and sea surface wind. $\rho_a = 1.29$ kg m^{-3}. $C_D = (0.75+0.067U) \times 10^{-3}$ (Garratt, 1977). Moreover, wind stress curl is obtained by $\nabla \times \tau$.

Figure by using data

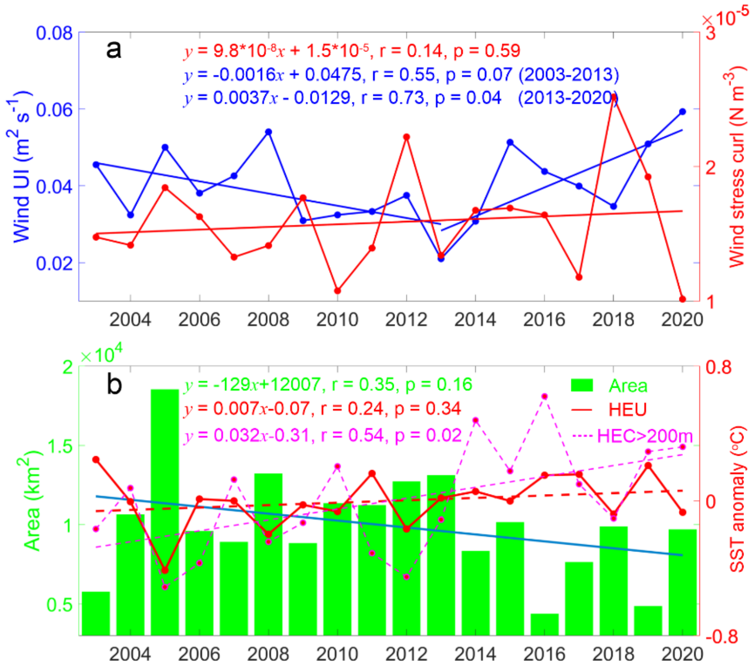


Figure 2. Time series of Upwelling index (UI) and upwelling characteristics. (a) Time series of mean sea surface wind UI and wind stress curl in HEC region. Blue dotted curve denotes the mean UI during June-August; the red dotted curve is mean wind stress curl during June-August; and blue and red curves are the trends of the UI and wind stress curl, respectively. (b) Time series of upwelling area and SST. Green bar denotes the area of UEH region. Red and magenta dotted curve denote mean SST of UEH region and slope region (depth>200 m) in HEC, respectively. Blue, red and magenta curves are the trends of the upwelling area, mean SST in UEH and slope area, respectively.

Reference

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J-N. (2018): ERA5 hourly data on single levels from 1959 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). (Accessed on < 15-Dec-2022 >), 10.24381/cds.adbb2d47.

Garratt, J.R., 1977. Review of Drag Coefficients over Oceans and Continents. Monthly Weather Review, 105, 915–929.

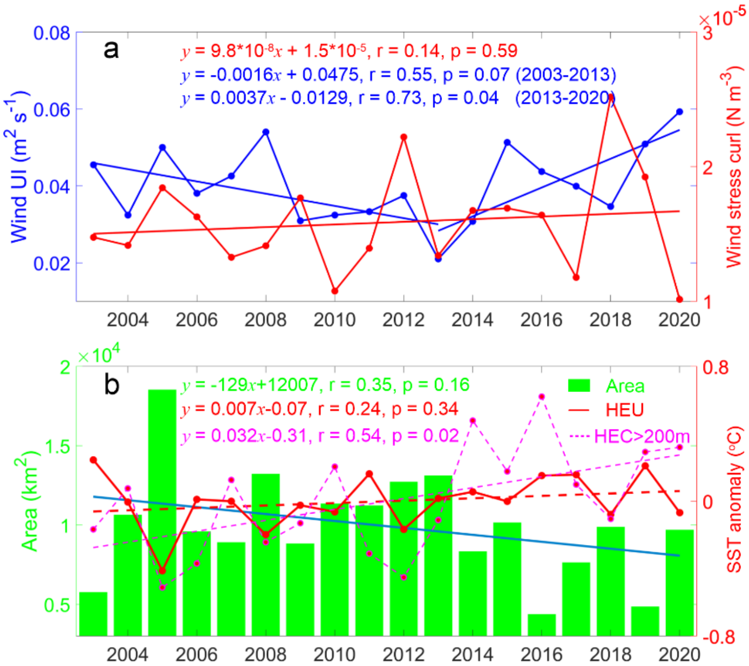
[Major Comment 3] Linear trends of wind upwelling index (UI), wind stress curl, SST and upwelling areas were estimated without assessing statistical significance of the trends. The trends of SST, wind stress curl and upwelling areas might be insignificant in statistics because the r coefficients are small. Also note that the decreasing trend of UI from 2003-2020 was not presented in Fig. 2a.

Response: Thanks for your useful comment.

(1) We have added the *p* value into Figure 2 to indicate statistical significance of the trends. Because the period of data is only 18 years, it is a little too short to demonstrate the significance of the trend. Therefore, *p* value and *r* are not so statistically significant owing to the limitation of data. However, the trend is not the main result for this manuscript. We have mentioned this point in the manuscript.

(2) This time we use sea surface wind data from ERA5, which shows an increasing trend, from 0.45 to 0.55 $m^2 s^{-1}$. The wind stress curl shows an increasing trend, too. The information extracted from wind data indicates that the upwelling is enhancing during 2003-2020. However, the mean SST of UEH (core of upwelling) increased gradually from 2003 to 2020 as shown in Figure 2b. The increasing SST indicates that upwelling is weaking.

It seems that the trends of wind and SST are contradictory. We checked the mean SST of background (>200 m in HEC, magenta curve in Figure 2b). It shows that the SST of background increases much faster than that in UEH. Therefore, we conclude that the upwelling is enhanced by the stronger wind stress and curl, even though the SST of background increases much faster. We have added the trend of SST for background into Figure 2, and update the wind data in Figure 2a.



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[Major Comment 4] Line 223-230: "Comparing the time series of Chl-a concentration shown in Figure 3 to the time series of upwelling characteristics shown in Figure 2, one can see that low UI values coincide with high Chl-a concentration in the UEH, and vice versa…". For the sake of visual comparison, the time series of Chl-a concentration and UI should be presented in the same figure. On the other hand, to gain a convincing result the out-of-phase relationship between the two-time series should also be quantified.

Response: Thanks for your useful comment. We have added the UI curve into Figure 3. As we can see, the peaks of Chl-a in summer (red curve) corresponded to valley of UI, especially before 2014. In 2018, there were minima for both of UI and Chl-a. However, the maximum of wind stress curl existed in 2018, which means the strongest wind stress curl was the leading factor for the upwelling process. The strongest wind stress curl generated a strong upwelling, and the Chl-a concentration is minimum in that year.

The relationship between UI, wind stress curl and Chl-a were very different in 2015, an unusual ENSO event. It looks like that the strong eastern-Pacific (EP) type caused this unusual high Chl-a concentration. Jing et al. (2011) had pointed out the analogous high Chl-a concentration in this study area in 1998. The correlation coefficient between wind UI and Chl-a concentration during 2003-2012 is -0.3, which shows a negative relationship. Because the limitation of data, the coefficient is a little small.

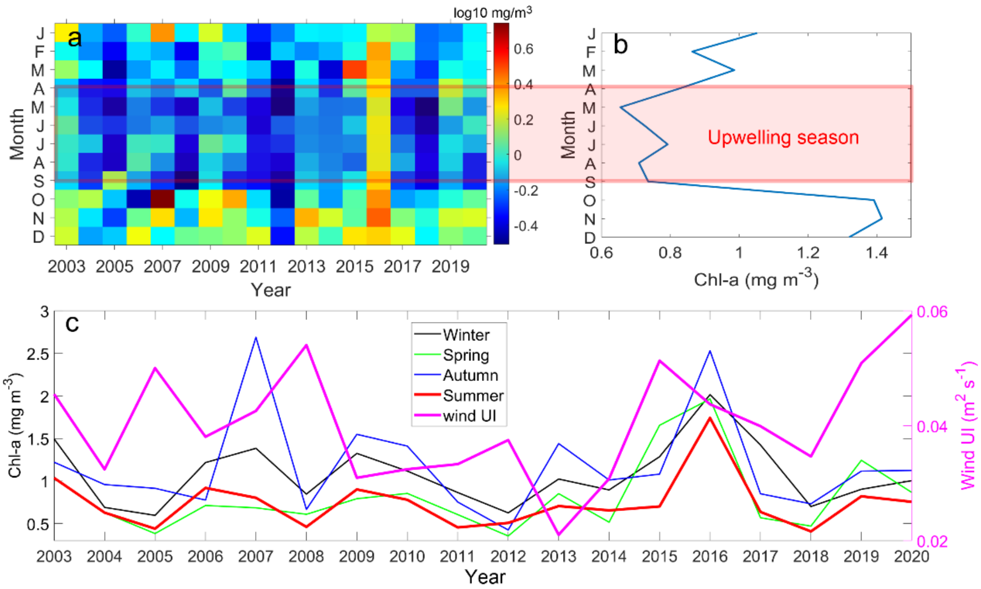


Figure 3. Time series of (a) the spatial mean of the Chl-a concentration in the upwelling area, (b) the monthly climatological mean, and (c) the seasonal mean of Chl-a and wind UI.

Reference:

Jing, Z., Qi, Y., and Du, Y., 2011. Upwelling in the continental shelf of northern South China Sea associated with 1997–1998 El Niño, Journal of Geophysical Research, 116, C02033.

[Major Comment 5] Line 470-490. "In the upwelling season, i.e., summer, the wind stress was smaller during El Nino events (Table 2) than during La Nina events (Figure 2a)...". I am confused. Previous studies (e.g. Wang et al (2001), Fang et al (2006), Huynh et al (2020)) showed that an anomalous anticyclone (cyclone) develops over the western North Pacific during El Nino (La Nina) years and the summer southwesterly surface wind in the northwestern South China Sea can be enhanced after the El Nino peak. In Fig 2a, one can observe that the UI increased in 2005, 2010, and 2019, which correspond with the 2004-2005, 2009-2010 and 2018-2019 El Nino events. Therefore, the statement that the wind stress was smaller in the upwelling season during El Nino events might be incorrect. Did the authors discuss the relationships between Chl-a/wind stress and ENSO during the developing phase of ENSO, i.e. before ENSO peaks?

Response: Thanks very much for your comment.

(1) Yes, an anomalous anticyclone (cyclone) develops over the western North Pacific during El Nino (La Nina) years. However, the temporal period of anticyclone or cyclone is much shorter than one month. I think they are in different scales. Therefore, it is not paradoxical.

(2) The relationship between sea surface wind and El Nino in the northwestern South China Sea is a little complicate. Firstly, Hong and Zhang (2021) showed that the annual mean wind in different area in the northwestern South China Sea is different (Figure 5 with red legend) by using sea surface wind data of ERA5. The speed of sea surface wind was almost flat in station C (near HEC in this study) during 1981-1992. However, peaks and valleys could be seen clearly in Stations A, B and D during 1981-1992. Secondly, Yu et al. (2020) showed that the interannual variability indicates low levels of Chl-a southeast of Vietnam during El Niño years because of the weakened southwest monsoon. Huynh et al. (2020) also found that the western North Pacific anticyclone (cyclone) anomalously develops (Figures. 10b, e, c, f and 18b–d), leading to a weaker (stronger)-than-normal surface wind in the SCS in El Nino (La Nina) years. **These previous studies conclude that the weaking sea surface wind appears in El Nino years.**

There are some exceptions, i.e., 1997-1998 and 2015-2016. Fang et al. (2006) showed that the first time coefficient functions (TCFs) lags the Nino3.4 SST by 3 months during 1997-1998 event. In this study, the wind stress and curl were both strong during 2015-2016.

Moreover, La Nina event appears after El Nino event. The large time lag between Nino Index and sea surface wind could also confuse us. Therefore, I did not calculate the time lag in this study.

I think it depends on the type of El Nino. Maybe the eastern-Pacific (EP) type causes the strong wind during El Nino events in this study area. I have added the discussion into the manuscript. And, the helpful reference has added into the manuscript.

(3) I have added a figure to show the relationships between Chl-a, along-shelf wind and Nino Index.

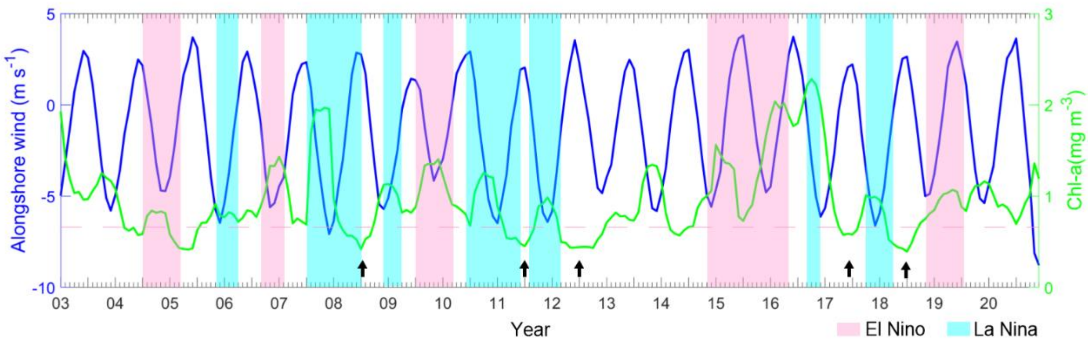
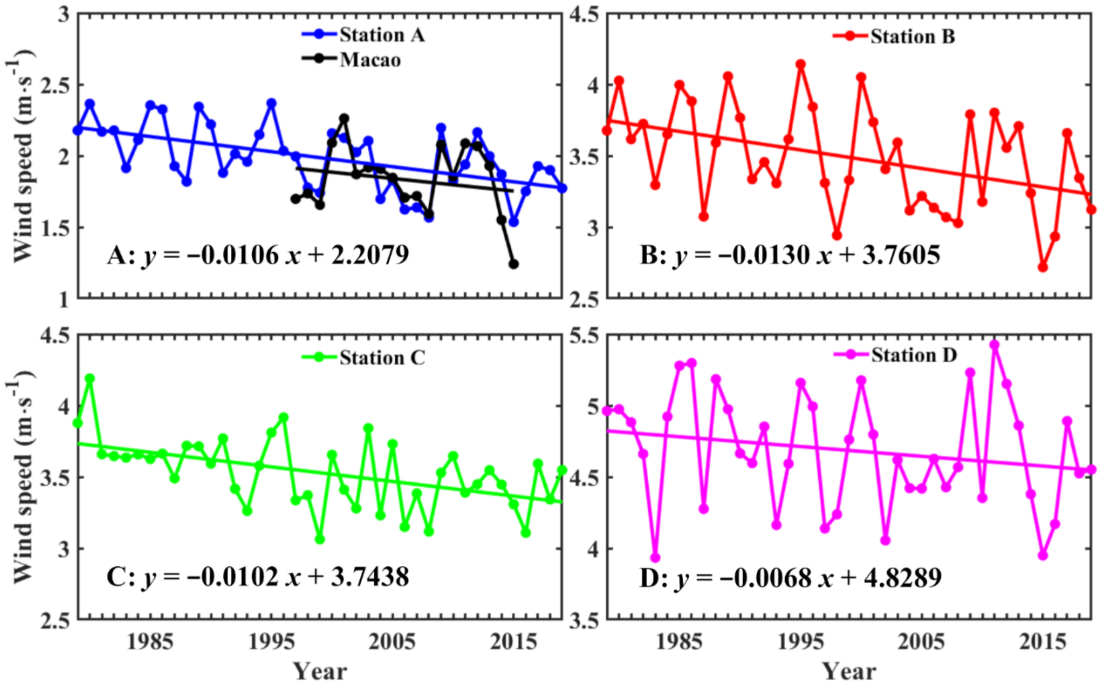
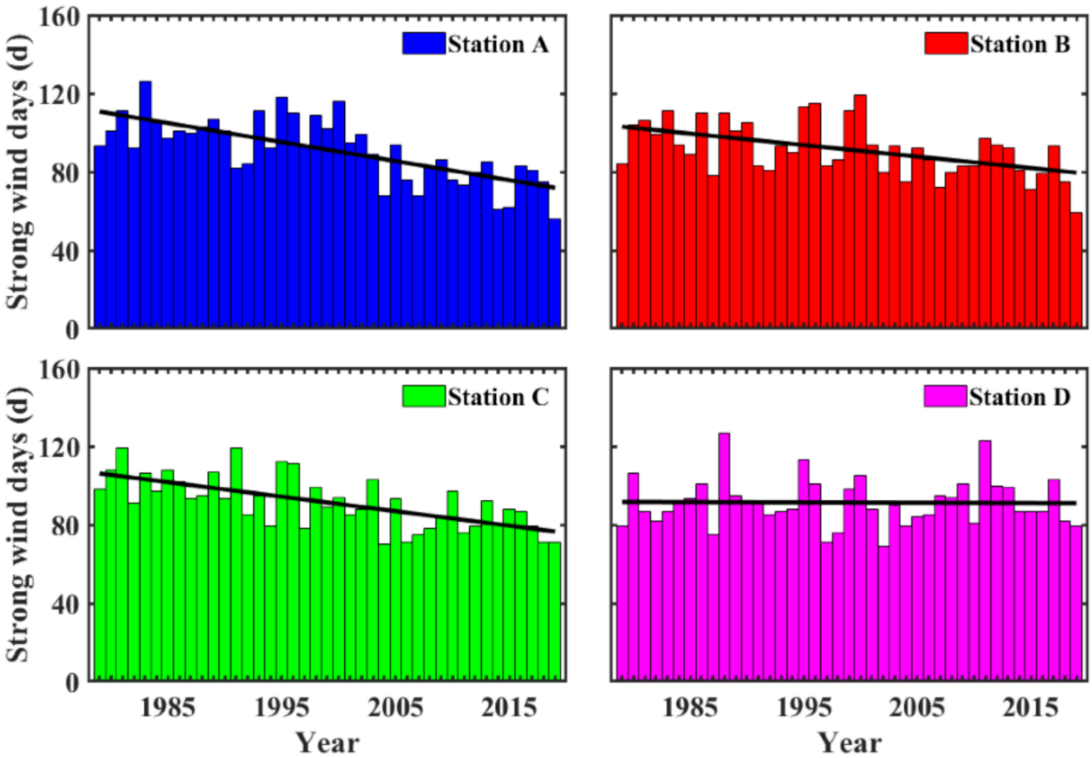


Figure. Time series of Chl-a (green curve) and along-shelf wind (blue curve). Stripes point out the El Nino (magenta) and La Nina (blue) events. Black arrows point out the minima value of Chl-a concentration. Magenta dashed line indicate the high Chl-a concentration during El Nino events.



(a)



(b)

Figure 5. Trends of annual mean wind speed (a) and strong wind days (b) at station A, B, C and D, respectively, from 1979 to 2019. The annual mean wind speed and corresponding trend obtained from ERA5 data at station A were compared with the data obtained from the adjacent Macau Airport (from 1997 to 2015). Stations A and B are in the Pearl River Estuary. Station C is in Yuexi (near

HEC in this study). Station D is in Yuedong. *Cited from Hong and Zhang (2021).*

References

Hong B, Zhang J., 2021. Long-Term Trends of Sea Surface Wind in the Northern South China Sea under the Background of Climate Change. Journal of Marine Science and Engineering. 9(7):752. https://doi.org/10.3390/jmse9070752

Huynh, HN.T., Alvera-Azcárate, A. Beckers, JM. Analysis of surface chlorophyll a associated with sea surface temperature and surface wind in the South China Sea. Ocean Dynamics 70, 139–161 (2020). https://doi.org/10.1007/s10236-019-01308-9

Yu, Y., Y. Wang, L. Cao, F. Chai, 2020. The ocean-atmosphere interaction over a summer upwelling system in the South China Sea. Journal of Marine Systems, 208, 103360.

[Major Comment 6] Line 496-499."The Chl-a concentration in summer was mainly regulated by upwelling processes (Jing et al., 2011), with a negative correlation (Figures 2–3). Therefore, the increased precipitation and weaker upwelling processes could have induced the increased Chl-a concentration in the HEC (upward arrow in Figure 12)." Why does the summer upwelling have a negative correlation with the Chl-a concentration in the HEC?

Response: The upwelling in HEC is control by alongshore wind and wind stress curl (Hu and Wang, 2016). Strong (weak) southwesterly wind and positive curl would induce strong (weak) upwelling. From Figure 2-3, one can see that minimum (2005, 2008, 2012, 2015 and 2018) Chl-a concentration appears with maximum wind UI or wind stress curl (strong wind stress curl in 2018) during upwelling season (red curve for Chl-a and magenta curve for wind UI). The strong (weak) upwelling exists with low (high) Chl-a concentration. Therefore, the summer upwelling has a negative correlation with the Chl-a concentration in the HEC.

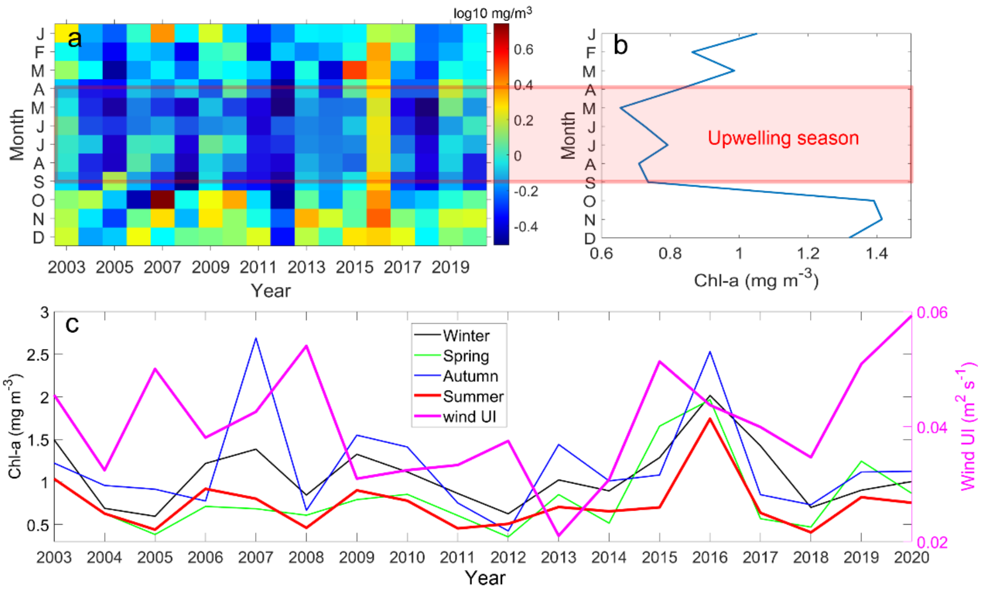


Figure 3. Time series of (a) the spatial mean of the Chl-a concentration in the upwelling area, (b) the monthly climatological mean, and (c) the seasonal mean of Chl-a and UI.

Reference:

Hu JY, XH Wang, 2016. Progress on upwelling studies in the China seas. Reviews of Geophysics, 54(3):653-673.

[Major Comment 7] Line 533-536. "There was a positive correlation between the Chl-a anomalies and the La Nina events…". The quantitative correlation between Chl-a and ENSO should be estimated.

Response: Thanks very much for your comment. Because La Nina event appears after El Nino event, therefore, a large time lag between Nino Index and sea surface wind or Chl-a concentration could confuse their relationships. I have added figure to show the relationships between Chl-a and along-shelf wind.

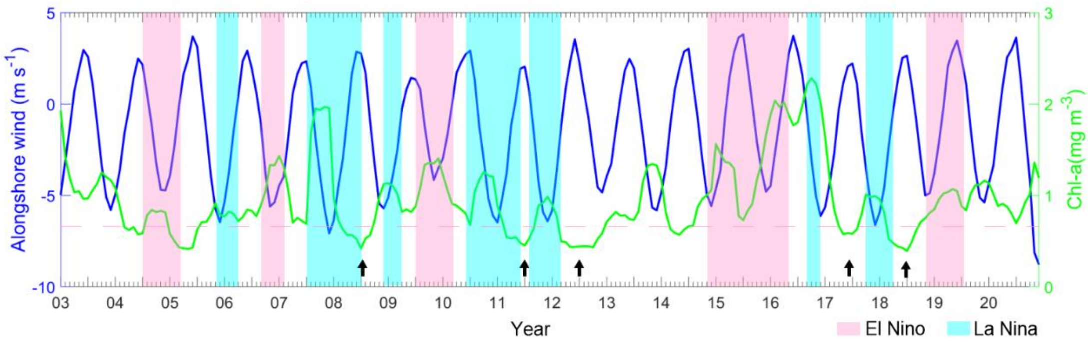
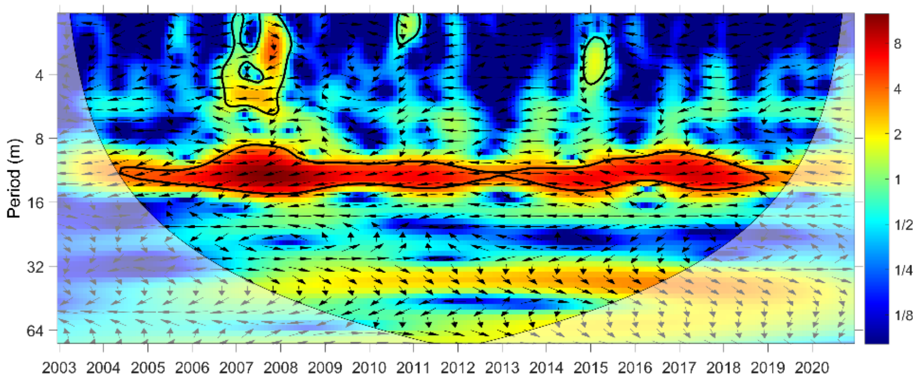


Figure. Time series of Chl-a (green curve) and along-shelf wind (blue curve). Stripes point out the El Nino (magenta) and La Nina (blue) events. Black arrows point out the minima value of Chl-a concentration. Magenta dashed line indicate the high Chl-a concentration during El Nino events.

Moreover, as an attached drawing for this response, cross wavelet analysis is used to indicate the relationship between wind and Chl-a concentration. The main period band is 1 year. For most of time, Chl-a lags wind about 3 months. During 2015-2016, the time lag is about 6 months.



Attached Figure. Cross wavelet analysis between along-shelf wind and Chl-a concentration. The thick line is the 5% significance level against red noise and the core of influence is shown as the thin line. The arrows show the relative phase relationship between two time series with in-phase (anti-phase, leading and laging) pointing right (left, down and up).

[Minor Comment 1] Line 182-189. The caption does not totally correspond to Fig. 2.

Response: Thanks very much for your comment. I have revised the caption as follows.

“Figure 2. Time series of Upwelling index (UI) and upwelling characteristics. (a) Time series of mean sea surface wind UI and wind stress curl in HEC region. Blue dotted curve denotes the mean UI during June-August; the red dotted curve is mean wind stress curl during June-August; and blue and red curves are the trends of the UI and wind stress curl, respectively. (b) Time series of upwelling area and SST. Green bar denotes the area of UEH region. Red and magenta dotted curve denote mean SST of UEH region and slope region (depth>200 m) in HEC, respectively. Blue, red and magenta curves are the trends of the upwelling area, mean SST in UEH and slope area, respectively.”

[Minor Comment 2] Line 215. Change “climatologic” to “climatological”

Response: Thanks very much for your comment. I have changed the word “climatologic” into “climatological”.

[Minor Comment 3] Line 244-246. “... (d) euphotic depth and TSS in the study area…” should be “...(d)euphotic depth, TSS and Chl-a concentration in the study area…”

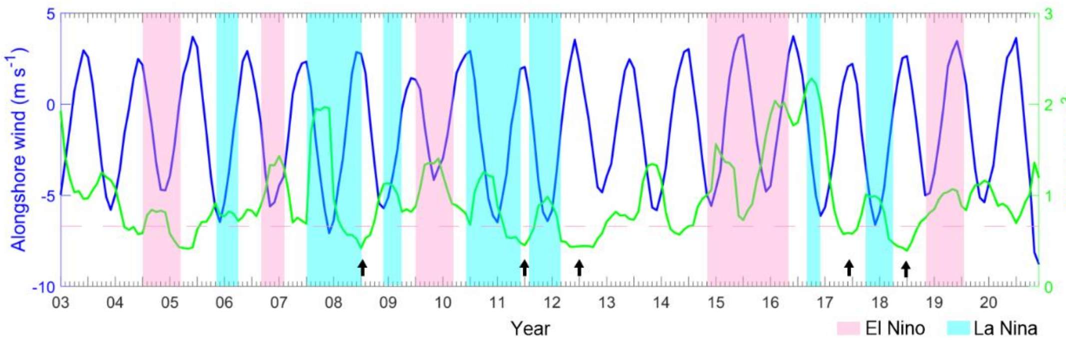
Response: Thanks very much for your comment. I missed the word “Chl-a”. I have revised the caption as the suggestion.

[Minor Comment 4] Line 227-228. “Moreover, one can see that the Chl-a concentration is unexpectedly low in the upwelling season, as shown in Figures 2a-b” should be “... in Fig. 3”

Response: Thanks very much for your comment. I have corrected it.

[Minor Comment 5] Line 484-485. An El Nino (La Nina) often takes place between two calendar years. However, most of the El Ninos listed in Table 1 are single year events, for example the 2015 El Nino which actually occurred from October 2014 to April 2016 (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php). Please correct the data in Table 1.

Response: Thanks very much for your comment. I have revised the Table 1. I have added figure to show the relationships between Chl-a and along-shelf wind, which is more clearly than Table 1.



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