Interactive comment on: “Impact of the Kuroshio intrusion on the nutrient inventory in the upper northern South China Sea: Insights from an isopycnal mixing model” by Du et al.

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Response to Anonymous Referee #1

This manuscript reported observation of nutrients in the NSCS and analyzed seasonal variation of nutrient inventory and the influence of Kuroshio intrusion on it. In general, this manuscript is well organized and written. The analysis is well designed and the results are interested. I hope following comments will be helpful for their revision.

[Response] We appreciate the positive comments from the reviewer.

1. Please give a full description on the concept of “nutrient inventory” and on why it (or its seasonal variation) is important to us.

[Response] We defined “nutrient inventory” in our revised MS and have added more rationales on its seasonal variation. Nutrient inventory is the depth integrated nutrient concentration in a given reservoir of the oceanic water body, reflective of the nutrient level that ultimately determines the primary productivity. This is particularly true for the oligotrophic regimes such as the basin area of the South China Sea (SCS), the surface part, or euphotic zone of which is deficit in nutrients and thus any changes in nutrients therein would result in changes in primary productivity of the ecosystem. In this study, we mainly focus on the upper 100 m of the northern SCS, roughly the euphotic depth which directly links with the primary productivity.

2. As described in section 3.3, the development of surface mixed layer is apparent in the NSCS. Since diapycnal processes are important to the development of surface mixed layer, it is therefore necessary to address why the development of mixed layer has no relation to the discussion in section 4.1 where only diapycnal mixing at 100m depth is given.

[Response] We appreciate that the reviewer pointed out this critical issue. In our original text in section 4.1, we took the 100 m depth as an example to demonstrate how the isopycnal fluxes dominated over the diapycnal fluxes by showing that the horizontal flux are at least three orders of magnitude larger than the vertical flux across the 100 m boundary. In responding to the reviewer’s comment, we also drew comparisons in between across the 20 m and 50 m depths (Table 1), which again showed the dominance of the horizontal fluxes. We have briefly stated in our revised MS that the predominance of isopycnal over diapycnal mixing stands throughout the upper 100 m water column.

Table 1. Vertical vs. horizontal N+N fluxes at the depths of 20 m, 50 m and 100 m in the NSCS.

Layer	Vertical			Horizontal			Ratio
	K_V ($m^2\ s^{-1}$)	dc/dz (mmol m^{-4})	F_V (mmol $m^{-2}\ d^{-1}$)	K_H ($m^2\ s^{-1}$)	dc/dx (mmol m^{-4})	F_H (mmol $m^{-2}\ d^{-1}$)	F_H/F_V
20 m	2.0×10^{-2}	~0	0	500	6.7×10^{-9}	3.3×10^{-6}	--
50 m	1.0×10^{-6}	0.1	1.0×10^{-7}	500	6.7×10^{-7}	3.3×10^{-4}	3300
100 m	1.0×10^{-5}	0.1	1.0×10^{-6}	500	1.3×10^{-5}	6.7×10^{-3}	6700

3. As causes of seasonal variation in nutrient inventory in the surface 100m water column, Kuroshio intrusion and biochemical processes are addressed in the manuscript. I am wondering how the circulation inside the SCS, which can change its direction (P6942, L13-14), affects the seasonal variation of nutrient inventory in the NSCS. It is better to add some sentences on this point.

[Responses] The reviewer is perfectly right that the seasonality of the Kuroshio intrusion into the SCS is not only controlled by the Kuroshio mainstream transport but also by the circulation inside the SCS, which certainly impacts on the nutrient inventory in the NSCS. By using an isopycnal mixing model, this study was able to constrain the seasonal change in nutrient inventory that appear to be largely driven by the Kuroshio intrusion. Note that our model was based on the mixing of endmembers between the SCS and the Kuroshio water masses, and hence the seasonal change in water circulation within the SCS realm has been in theory considered by looking at the bulk fractional contribution of the Kuroshio water mass. Note however that our current model was not able to distinguish in a quantitative way the impact between the Kuroshio and the SCS water masses because any water masses in the upper SCS are ultimately influenced by the Kuroshio at a relatively longer time scale. Nevertheless, because of the large gradient in nutrient concentrations between the Kuroshio and SCS water masses, the most important drivers causing the nutrient seasonality in the surface SCS should be the Kuroshio intrusion. We have stated in our revised MS the above reasoning. We have also explicitly stated in the revised MS that our estimation of the seasonal variation in nutrient inventory based on water property observed among discrete cruises might have uncertainties because of the different spatial coverage among cruises. However, by using Ca^{2+} ion as a conservative tracer, the uncertainties of our model prediction would be better than 10%.

The second concern is on the seasonal variation in the depth of isopycnal layer. The authors chose 100 m depth as lower limit for integration of nutrient inventory and used isopycnal mixing model to understand the seasonal variation of calculated nutrient inventory. If the isopycnal layer at 100 m depth changes with season, this effect must be included as a cause of seasonal variation in nutrient inventory.

[Response] Yes, reviewer is perfectly correct that the isopycnal layer at 100 m depth does change with seasons. The change of the isopycnal layer, either upward or downward would however not impact our model prediction, either the fractional contribution of the Kuroshio water or the model predicted nutrient concentration. This is because the change in isopycnal layers may only affect the location (depth) of a given water body while both the potential temperature and salinity of the water body would be invariable as being reflected by the constant potential density as shown in the T/S diagram.

However, the change in the isopycnal layer dose alter the nutrient inventory in a given water column, say in the upper 100 m water column. The overall positive correlation between the density and nutrient concentration observed in the upper ocean suggests that any lift of the isopycnal layer would induce increase in nutrient inventory in the upper water column. As a matter of fact, this is exactly the reason why we observed much scattered relationship between the station-integrated Kuroshio water fraction and the nutrient inventory as shown in Fig. 9B. Such impact can also be seen at the seasonal time scale reflected in the different slopes in Fig 9B.

The drivers causing the changes in isopycnal layers can be beyond the Kuroshio intrusion. For example, both the mesoscale eddy and the basin scale Ekman convergence/divergence may induce such variations in isopycnal layers. The impact of the mesoscale eddy on isopycnal layer/nutrient inventory could be significant in the northeast SCS during winter, when we see a low nutrient inventory center that may not only reflect the Kuroshio intrusion but also a warm eddy. During our spring cruise, the high nutrient inventory center in the centre of the NSCS (corresponding to the isopycnal layer uplift) should be attributable to the basin scale convergence. We are aware that both mesoscale eddies and basin scale convergence/divergence may have induced the scattered relationship and different slopes between the observed nutrient inventory and the station-integrated Kuroshio water fraction as shown in Fig. 9B in our MS.

We have substantially expanded the discussion related to the variation in isopycnal layers relative to our defined lower limit of 100 m for the estimate of the nutrient inventory. Moreover, in the revised section 4.3, we further calculated the proportional contribution of the Kuroshio intrusion from the variation of the nutrient inventory, the residual of which should be attributable to the biological effect and/or other physical processes such as mesoscale eddy and basin scale Ekman convergence/divergence.

4. Is it possible for the authors to change “Kuroshio intrusion” to “Kuroshio surface intrusion” in their title? Their analysis is actually limited to surface layer (0-100m). It is also necessary to realize the intrusion depth of Kuroshio water when using the term “Kuroshio intrusion” inside the manuscript.

[Response] Since the influence of Kuroshio Current can be down to 400 m (Fang et al., 2009) while the present study is focused on its impact on the 100 m water column of the SCS basin, we would like to keep the constraint of “surface” in the title. .

5. P6943, L7: please mention depths of water sampling.

[Response] Information added as suggested.

6. P6944, L7-8: I guess this comparison is at the same density. If so, please clarify this point.

[Response] Yes, and the text has been amended.

7. Fig.3: the texts inside the black background for land are hard to recognize. The same thing is also true for other similar figures.

[Response] Figures 3, 5, 8 are amended as suggested.

8. P6945, L5: why wind-driven upwelling produced such local high nutrient concentration?

[Response] The CTD measured sea surface temperature (SST) during the fall cruise is shown below (Fig. 1). The area with high N+N concentrations corresponded to the low SST region (red box, Fig. 1), which led us to infer that the wind driven upwelling and/or vertical mixing potentially induced such local high N+N concentrations. Indeed and as being shown in Fig. 1, the low SST appeared in region II, when the wind speeds were overall higher than that in the regions I and III (Fig. 2) based on the NOAA blending multiple-satellite observations data. Moreover, the wind speeds when we cruised through the shelf break region was overall higher than those when we sampled in the basin area.

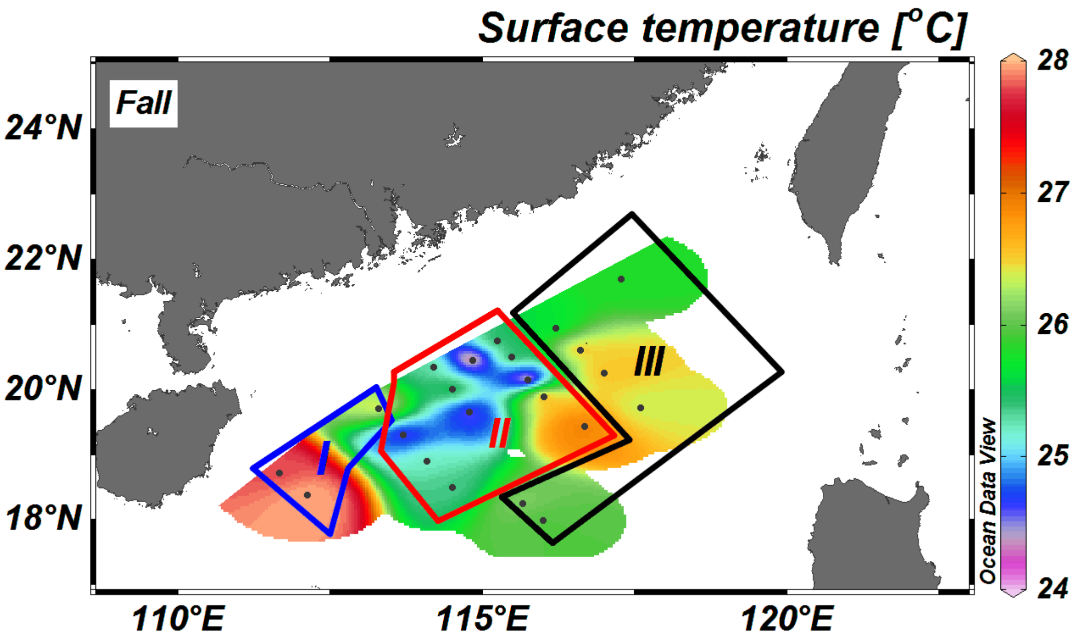

Figure 1. Sea surface temperature during the fall cruise in October, 2010. Different color boxes represent the different sampling periods (I, the blue box was sampled on October 26- November 1; II, the red box was sampled on November 7-18; III, the dark box was cruised through on November 19-23.

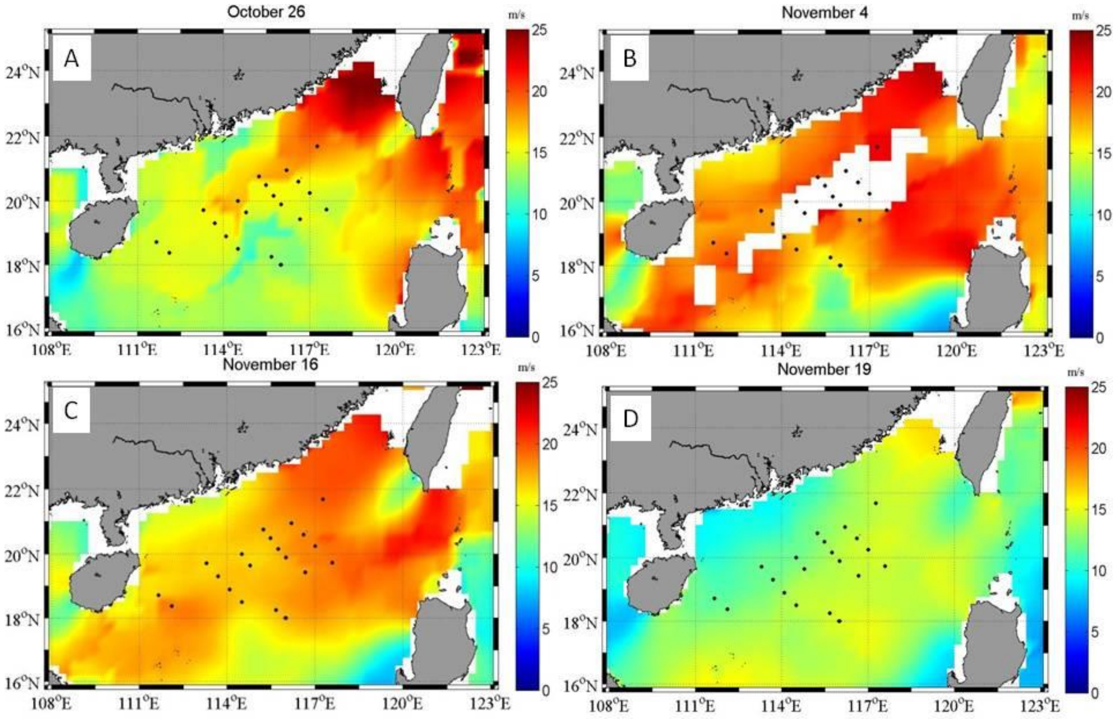

Figure 2. Three-day averaged wind field in the northern SCS during October, 2010. (A) October 26, 2010; (B) November 4, 2010; (C) November 16, 2010; (D) November 16, 2010. A corresponded to the region I, B and C corresponded to the region II, and D corresponded to the region III in Fig. 1. The dark dots represented the sampling stations in the cruise. The wind speeds data from the blending of multiple-satellite observations was downloaded from NOAA National climate data

centre, http://www.ncdc.noaa.gov/oa/rsad/air-sea/seawinds.html#data.

9. Section 3.3: following Fig. 3, it is natural to expect vertical profile of N+N in Fig.4. Please mention why the authors use SRP, not N+N, in Fig. 4b.

[Response] We added illustrations as suggested. The reason that we used SRP was simply that there were not enough nanomolar level N+N data collected in the upper layer during the four cruises.

10. Fig. 4: it is not easy to understand why vertical profile of nutrient does not follow that of temperature. The water temperature is homogenous inside the surface mixed layer, but the nutrient concentration is not. For example, the surface mixed layer reaches _70 m but the concentration of SRP is much higher at 50 m than at 25 m. Why?

[Response] We believed that the reviewer is questioning the decoupling between the nutricline and thermocline, or between the top of the nutricline (TND) and the mixed layer depth (MLD). As a matter of fact, prior studies have already observed that the TND was generally deeper than the MLD in winter at the SEATS station (Tseng et al., 2005; Tseng et al., 2007). Such a decoupling may be a result of the combination of the physical dynamics and biological alteration.

1) It can be attributable to the uneven consumption rate of nutrients by biological metabolism vs. water depth within the mixed layer depth because of the light intensity changes.

2) It can also be related to the definition of the MLD. Here we defined the MLD when the temperature gradient ΔT is smaller than 0.8 ^{o}C (Kara et al., 2000). This definition of MLD might not be sensitive enough at times to catch for example weak stratification that would diminish the mixing within the upper layer.

3) It should also be pointed out that the coarse sampling resolution of our discrete nutrient samples also made it difficult to precisely estimate the depth of TND.
We have expanded in our revised MS the possible reasons that could cause the decoupling between the TMD and TND.

11. Fig.4: why the mixed layer vanishes in spring but develops in summer? This is opposite to general case. Usually, heat flux increases from spring to summer.

[Response] This comment is related to #10. The T-S diagram based on the data collected in spring showed that the SCS water was much closer to the Kuroshio endmember (Fig. 3), suggesting that the water mass from the Kuroshio intrusion (with higher temperature than the SCS) may have influenced the mixed layer in spring. We contend that this is also one of the merits of our paper by using the isopycnal mixing model to address the 3-D dynamics of the upper ocean since the evolution of the upper ocean thermocline structure in the NSCS is not solely determined by the 1-D mixing-restratification process. Note that previous studies conducted at the SEATS station neither showed a distinct decrease of the mixed layer depth from spring to summer (Tseng et al., 2005; Tseng et al., 2007).

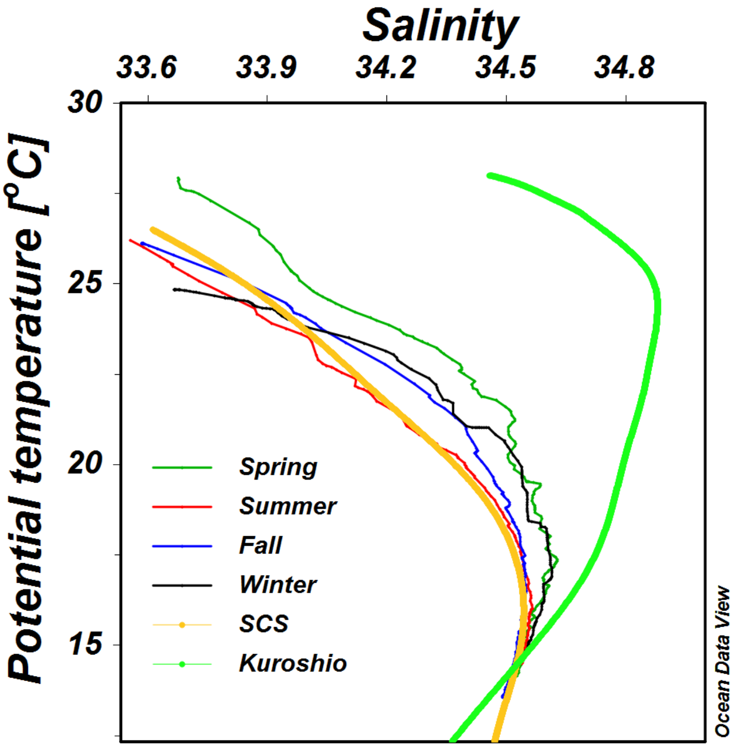

Figure 3. T-S diagram at the SEATS station.

12. P6948, L11: what is evidence for the “lower limit”? This value is possible, but is not so small.

[Response] We have deleted the sentence.

13. P6949, L2-3: the authors may check whether they can obtain the same mixing ratio from water temperature and salinity. Maybe they can add one figure to show Rk from water temperature versus that from salinity.

[Response] The comparison is shown in Fig. 4A. The mixing ratios derived from the two methods are almost identical at temperature < 26.5 ^{o}C (Fig. 4B). Large discrepancies appeared when temperature > 26.5 ^{o}C. These are due to the non-conservative nature of the temperature in the upper layer, which is significantly influenced by the surface heat flux. We have explained this in the revised MS.

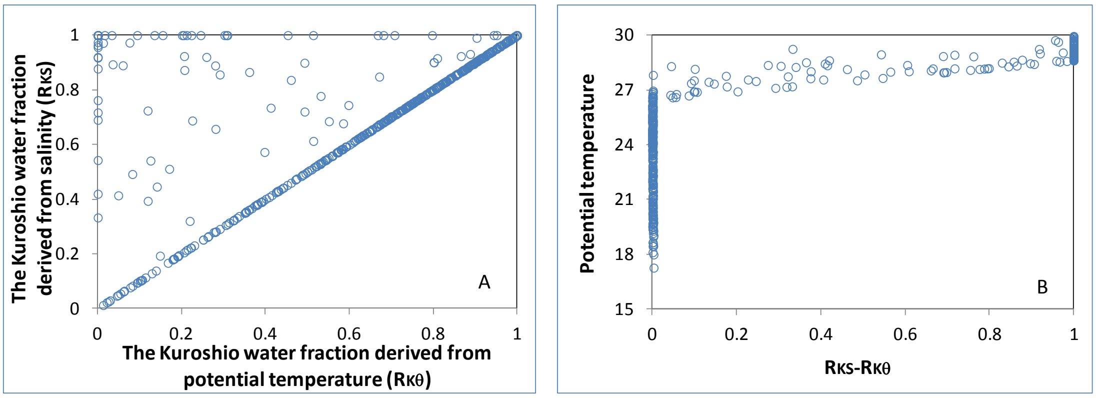

Figure 4. (A) The Kuroshio water fraction derived from the potential temperature versus that from salinity. (B) The ratio derived from salinity subtracts that derived from the potential temperature plots versus the potential temperature.

14. P6949, L2-3: since the surface mixed layer is at order of 50 m, it is not reasonable to apply isopycnal mixing model to the upper 60 m. Please add some sentences to address this point.

[Response] We are not 100% sure about this comment from the reviewer. Essentially, we adopted a simple isopycnal mixing approach to quantify the proportion of the Kuroshio water in the SCS. Provided that the along-isopycnal intrusion is dominant in water mass transformation, the isopycnal mixing model works well throughout the upper 100 m water column. Our Ca^{2+} data was further able to well validate the model prediction.

15. Fig.6: As I compare Fig. 6 with Fig. 2, it is likely that some data in Fig. 2 (e.g., data with salinity > 34.8) are beyond the range between the Kuroshio and SCS water. It is therefore better to add the lines for two end members of Kuroshio water and SCS water in Fig.2 and to state the relation of two end members with the deleted data.

[Response] Thanks for reviewer’s suggestion. The data shown in Fig. 6 only included those collected within the region shown by the blue box in Fig. 1 (main text). The Luzon and E4 sections were excluded due that they were not included in our subject zone. We have now added the data from the Luzon and E4 sections into Fig. 6 in our revised manuscript. Discussion in this aspect has been expanded in the revised MS.

16. Fig. 6b: it is better to reduce range of color bar. The data between two end member lines is smaller than 20.

[Response] Amended as suggested.

17. P6952, L19: If it is really an “exchange”, why the fraction of Kuroshio water decreases? “exchange” occurs in two ways in which the Kuroshio water must enter the SCS.

[Response] The fraction of the Kuroshio water in the SCS that our model derived is a result of the combination of Kuroshio intrusion and the water residence time. As such, we estimated the mean residence time of the water mass which is defined by the volume (our objective zone) divided by the total inflow/outflow rate: τ=total volume / summing of inflow rate (Kuroshio intrusion + input from the shelf water + input from the southern SCS water)), our initial estimation of the inflow rate in our original MS only considered the Kuroshio intrusion, which is obviously subject to large uncertainties. Also, we believe that the term "exchange" could be misleading. As such, we have eliminated the estimation of the residence time in the revised MS.

18. P6952, L21: please mention how this estimation (4.1 years) was done. "24%" is not throughout one year.

[Response] Please see our response to reviewer's comment #17. We have eliminated this part in the revised MS.

19. P6952, L1-10: it is better for the authors to add some sentences to address the causes why the fraction of Kuroshio water is low in winter than in spring and why the nutrient fraction of Kuroshio is generally lower than the water fraction in Fig. 8. I also do not understand the spatial pattern of water fraction of Kuroshio water in spring. It is natural to expect a reduction in the fraction of Kuroshio water with a distance from the Luzon Strait. However, this is not the case in spring when a high fraction was identified in the area close to the northern shelf of SCS. Why?

[Response] That the nutrient fraction of Kuroshio is lower than the water fraction is simply because the nutrient concentration in the Kuroshio is much lower than that in the SCS. The patchy rather than homogeneous distribution of the Kuroshio water in the SCS proper might be partly due to the combination of the interior SCS circulation and the Kuroshio intrusion. On the other hand, it should be noted that the estimated Kuroshio water fraction based on the isopycnal mixing model is not necessarily/directly related to instantaneous intruding processes because any formation of a water mass containing fractions of the Kuroshio water may have taken a much longer time than the seasonal time scale. We have added explanations of the seasonality of the Kuroshio water fractions in the SCS as well as the patchy distribution of the Kuroshio water fraction.

20. P6954, L27: please define the difference. I guess it is "predicted concentration – measured one". If the authors can change it to "measured concentration – predicted one", then a negative difference means biological consumption. This way is similar to the figure of nutrient concentration versus salinity in the estuary.

[Response] Amended as suggested.

21. P6957, L10-15: I like this note. But, why the authors observed higher nutrients concentration in the SCS water than in the Kuroshio water. Please add one or more sentences to clarify causes.

[Response] The main causes are the basin-wide upwelling and stronger mixing which supply much faster high nutrients from the depth as compared to the Kuroshio outside the SCS. This fact has been well documented in the literature (e.g., Gong et al., 1992; Chen et al., 2001).

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