First of all, thank for all the comments of the referees. Replies to the other referees have been published by one of our co-authors as short comments except reply to the anonymous referee. Here we want to make some supplements about several questions first.

C. W. Hughes (referee) 27 May 2014

2) The authors make a good case for a northward Ekman flux accounting for much of the integrated flow in the mixed layer. A good question would be, how does that flow return to the south? Is it in boundary currents or throughout the interior?

Reply: Seen from the velocity field at the bottom of the January mixed layer (Fig 1a), the southward return flow is mainly by strong western boundary currents. The meridional velocity distribution along the 17.25° N section in January (Fig 1b) also shows that southward flow is mainly confined to west boundary current east of 112° E rather than throughout the interior region.

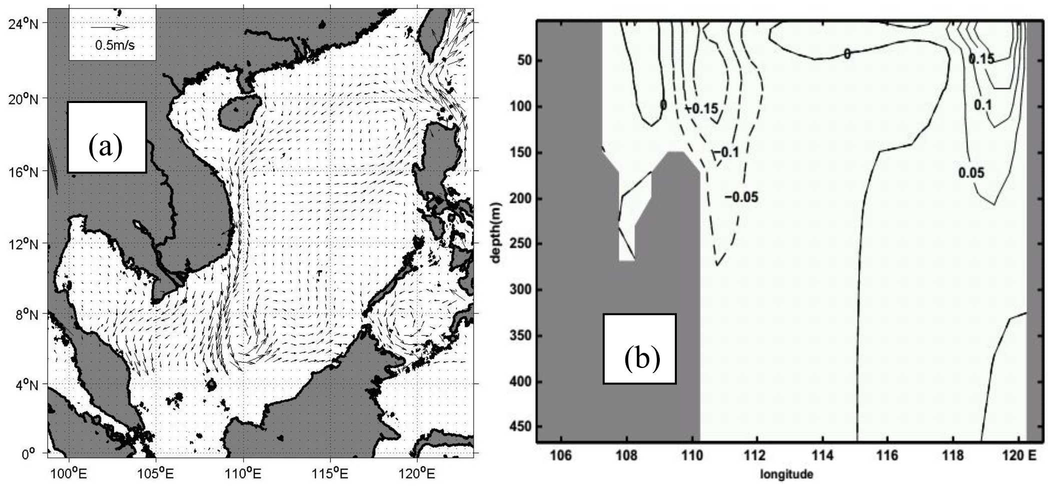

Fig 1. (a) Geostrophic velocity field at the bottom of January mixed layer; (b) meridional velocities along the 17.25° N section in January (m/s, positive values refer to northward).

3) The calculation of subduction rate (section 4.2.2) moves from the MOC in zcoordinates, to the water mass formation associated with flow through the mixed-layer base (which is not at constant z). However, the formulation in terms of a linear vorticity balance is dubious in the presence of bottom friction and nonlinear *vorticity, and there is no need for such an idealised formulation when the full model fields are available -simply calculate the flow through the chosen surface. Incidentally, the v in (3) is supposed to represent the geostrophic velocity only, not any v associated with the Ekman layer. No attempt is made to account for the fact that the MOC in z-coordinates is not directly relevant to this quantity. I also find it strange that subduction into the interior is considered, but entrainment back into the mixed layer (negative subduction) is set to zero.*

Reply: We calculated the subduction rate instead of directly calculating vertical water transportation across a certain surface using the model vertical velocity data, because we think the subduction process can explain the formation mechanism of the downwelling branch of the meridional overturning circulation. We want to know what drive the meridional overturning circulation to form rather than just the water volume budget. The subduction rate refers to the water volume detraining from the mixed layer into the thermocline irreversibly in the winter. It should always be nonnegative because it is defined only for the effectively detrained water (Qiu et al., 1995). A negative rate of subduction does not mean that water in the thermocline is pumped up into the mixed layer above, because the entrainment process occurs in the season when the mixed layer deepens rapidly, which is in contrary to the formation season of subduction when mixed layer shallows rapidly. The negative value just implies that no effectively detrained trajectories exist. So we change all the negative values into zero.

We admit that we made a mistake by using the velocity data directly, so we re-calculated the subduction rate using the geostrophic velocity data obtained from absolute dynamic height calculated from the SODA temperature, salinity and sea surface height data. The result is shown in Fig 2. The subduction rate pattern obtained by using the geostrophic velocity is similar to that in our paper (Fig 7c) with two significant subduction zones existing in the SCS: off the south coast of mainland China and off the Vietnam coast. The specific values of subduction rate have changed. The subduction rate at each latitude is shown in Fig 3. The annual mean subduction rate in the northern SCS is about 1.1 Sv (17° N~20° N) and is about 3.9 Sv off the Vietnam coast (8° N~15° N).

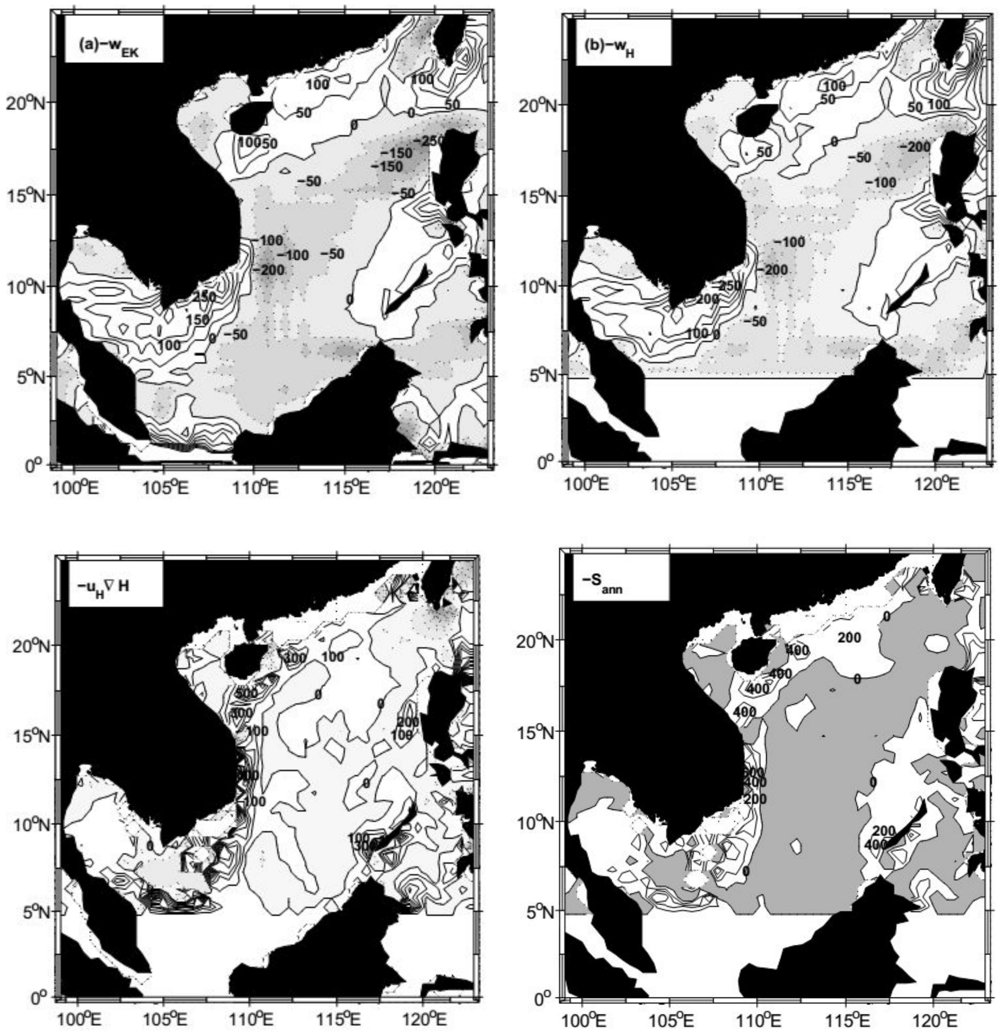

Fig 2. (a) Annual-mean Ekman pumping; (b) annual vertical velocity, $-w_H$ into the main thermocline; (c) lateral flux, $-u_H \cdot \nabla H$ into the main thermocline; (d) annual subduction rate S_{ann} (m/yr) into the main thermocline.

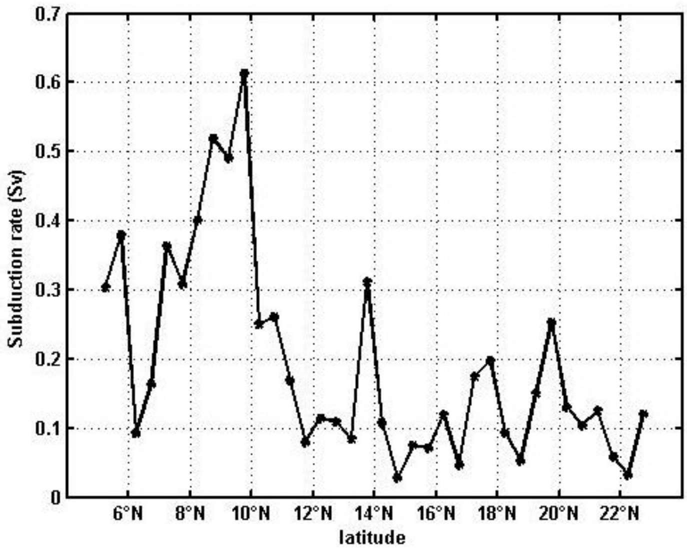

Fig 3. Annual mean subducted water volume at each latitude

Below is a reply to the anonymous referee (13 June 2014).

This manuscript confused me. There are several different components to the work and I had difficulty with each part. I recommend that the authors submit a new manuscript "discussing the... driving mechanisms... in different seasons" (as they indicate in the last sentence that this will be their next study) and include the results from this manuscript in the new manuscript as averages over the seasonal (or monthly) analyses.

Reply: Thank you for your comment. We mainly discuss the structure and formation mechanisms of the shallow meridional overturning circulation of the SCS on the annual mean scale. Seen from the meridional overturning streamfunctions (Fig 1a in our paper), water are transported northward in the mixed layer, downwell in the northern SCS, flowing back southward in the thermocline layer, and upwell at around 10 ° N. After we have made clear the structure of the meridional overturning circulation, we want to find out its formation mechanism. We study on the seasonal wind fields of the SCS first and found that the physical processes (including subduction and upwelling) related to January and July wind fields may have significant effect on the meridional overturning circulation, because wind is weak in the other seasons when wind direction change. So we mainly discuss subduction process in winter in the northern SCS and summer upwelling off the Vietnam coast. We think it is the winter subduction causes water to detrain from mixed layer into and then keep flowing in the thermocline layer, and it is the summer upwelling off the Vietnam coast that causes water to upwell from below the mixed layer to go up into the mixed layer, thus the meridional overturning circulation forms. We have to admit that physical processes in the other seasons may have effect on the meridional overturning circulation but the effect must be less significant than in January and July.

We've carried out a few studies on the structures of seasonal meridional overturning circulation and we found that structures of meridional overturning circulation are different in different seasons (Fig 4). For example, the meridional overturning circulation in July exists and lasts in a deeper depth than in January. The water at about 100 m flows southward in January while flows northward in July. So when we say discussing the driving mechanisms in different seasons, we mean that we plan to find out what cause upwelling and downwelling in summer since winter subduction distinct in this season, and what cause upwelling and downwelling in winter separately.

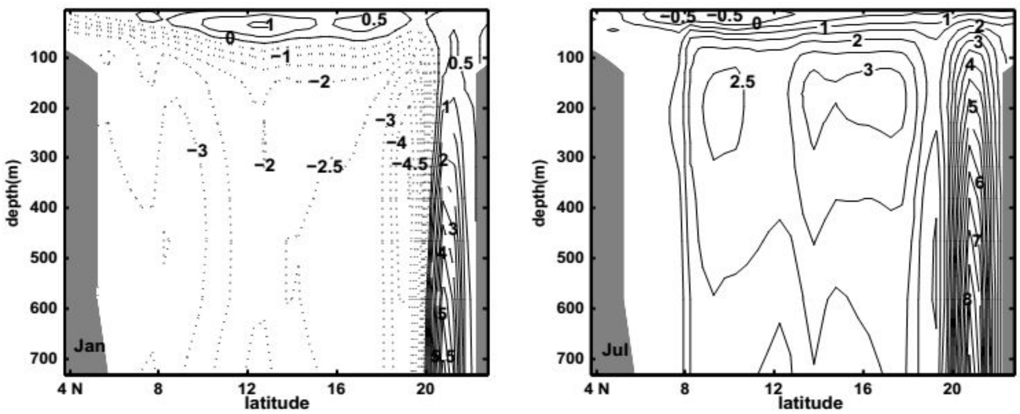

Fig 4. Meridional overturning circulation in January (left) and July (right)

The manuscript is an analysis of the annual mean circulation in the South China Sea where the seasonal variations associated with the monsoons may be very large. It is primarily an analysis of SODA model data. To my eye, the comparison in circulation between SODA and OFES models (in Figure 1) is not very good, raising questions *about the reliability of SODA. The circulation on which the authors focus is an "interior" pattern from 8N to 18N but most of the action in the model circulations is north of 18N.*

Reply: Other referees also mentioned this problem. We admit that using the OFES data to confirm the SODA data is inappropriate here. Indeed, the values of meridional streamfunction obtained from SODA and OFES are different. But SODA data assimilate many observational data while OFES data are just model output results. And the OFES data are used only for validation of the existence of the shallow meridional overturning circulation in the SCS. And Fig. 1b in our paper dose show a meridional overturning circulation pattern limited to a shallower depth compared to what obtained form the SODA data. And as mentioned in the second paragraph of section 3 (line 5, page 1195), some previous studies can prove that SODA data have been widely used in the study of the SCS and meridional overturning circulation in the Indian Ocean. In the assimilation of SODA, it is continuously corrected by contemporaneous observations with corrections estimated every 10 days (Carton et al., 2007), which makes it more credible. And the study of Liu (2008) also used the SODA data. So we believe that the meridional overturning structure of the SCS obtained from the SODA data is credible. And OFES data are not used in the other sections of our paper except for section 3.

We've noticed that significant vertical water movement exist north of 18° N, but we mainly focus on the meridional flow in the SCS, so we studied the meridional overturning circulation between 8° N and 18° N.

The shallow annual mean circulation turns out to be primarily associated with annual mean Ekman transport and is quite small, though the monthly variations are likely to be large. It was not clear to me whether the authors use the same wind stress climatology for Ekman transport calculations as SODA uses to drive the model circulation.

Reply: Thank you for the wind question. The wind used to drive the SODA model circulation is ECMWF ERA-40 daily wind, and the NCEP/NCAR long term monthly means reanalysis wind data is used in our paper. NCEP wind is widely used, and we believe it can produce credible results. But your question remind us to calculate Ekman transport etc. using ECMWF data for consistency. SODA also have wind stress data itself. The seasonal and annual-mean wind stress fields from SODA wind stress data are shown in Fig 5 and Fig 6 separately. They have similar patterns as the wind fields obtained from NCEP wind data which are shown in our paper (Fig 2 and Fig 3). We re-calculate the Ekman transport, subduction rate and upwelling using the SODA wind stress data. The annual mean Ekman transport at each latitude is shown in Fig 7. The annual-mean Ekman transport across 18° N is about 1.2 Sv (0.9 Sv when using the NCEP wind data). The annual mean subduction rate in the northern SCS is about 1.1 Sv (17° N~20° N) and is about 3.9 Sv off the Vietnam coast (8° N~15° N). The average summer upwelling off the Vietnam coast is 6.2 Sv (discussed in details in the following questions)

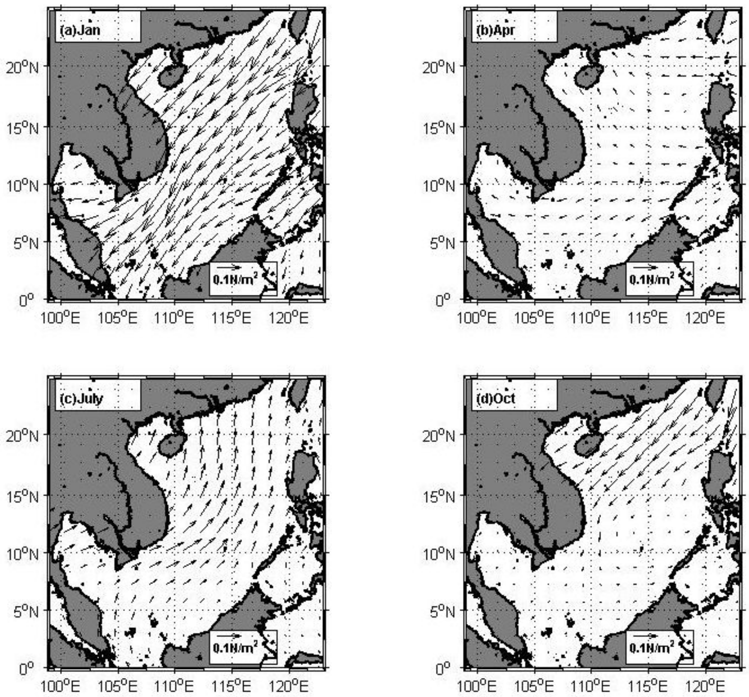

Fig 5. Monsoon wind fields from the SODA wind stress data for (a) January, (b) April, (c) July and (d) October

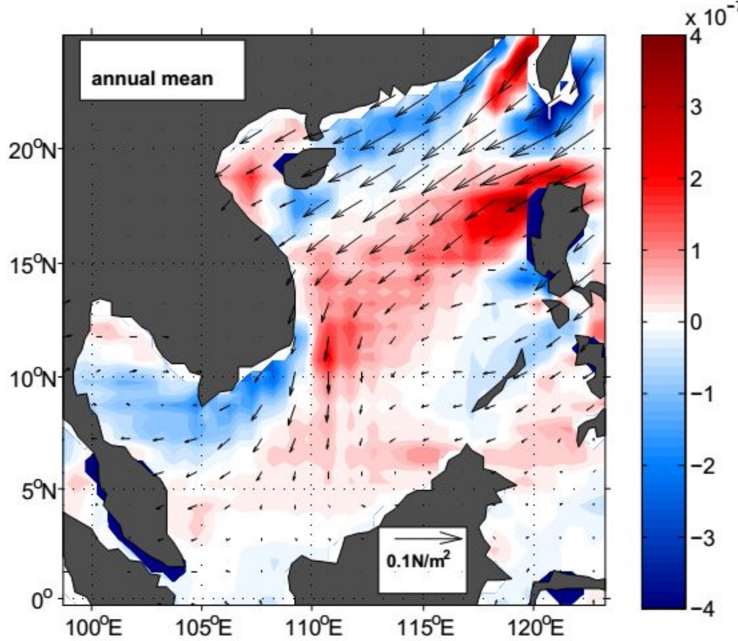

Fig 6. Annual-mean wind stress (arrows) and wind-curl (contours) from SODA wind stress data. The contour interval for wind curl is $0.2\times10^{-7}\,Nm^{-3}$.

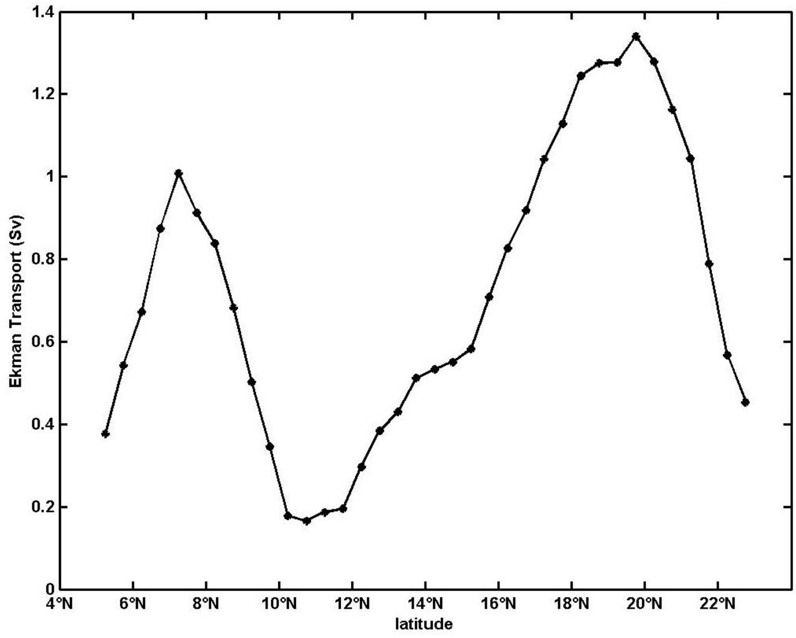

Fig 7. Annual-mean meridional Ekman transport at each latitude calculated from $\frac{-\tau^{x}(0)}{f\rho}$ using the SODA wind stress data

The subduction rate is estimated using annual mean vertical velocity and annual mean horizontal velocity times annual mean slope of the mixed layer depth. I thought the point of Stommel's "Ekman demon" papers was that the subduction primarily happened in late winter so the late winter structure was core to the vertical transfer. Since the equations are nonlinear, should the authors be doing monthly (or daily) subduction calculations and then time averaging the time series of subduction analyses to produce an annual mean?

Reply: It is true that subduction mainly occurs in late winter. We used the annual mean vertical velocity at the bottom of the winter mixed layer and winter horizontal velocity times winter slope of the mixed layer depth rather than annual mean horizontal velocity times annual mean slope of the mixed layer depth. We calculate the annual mean subduction rate according to Marshall's equation put forward in 1993.

The annual subduction S_{ann} into the permanent thermocline is identified with the annual volume flux across the winter mix-layer depth. The first term in equation (2) is vertical velocity at the bottom of the winter mixed layer, which is related to the Ekman pumping using linear vorticity balance. The second term in equation (2) is lateral transfer of fluid out of (into) the winter mixed layer. Both the two terms are relative to the winter mixed layer and winter structure is indeed core to the vertical transfer. We don't need to do monthly or daily subduction calculation first, because this equation takes the subduction process into account and subduction dose not occur every month. It is based on the winter mixed layer properties and can provide a good approximation to the annual mass flux from the mixed layer to the permanent pycnocline.

Toward the end of the manuscript, upwelling (Section 4.3) is discussed on a monthly basis which led me to conclude that the shallow circulation and subduction would also be much better presented in terms of monthly variability. The comparison with the Indian Ocean subduction (Section 5) seemed out of place in this manuscript on the *shallow overturning in the South China Sea.*

Reply: As we have mentioned above, the reason why we discuss the summer upwelling off the Vietnam coast is because we want to investigate what causes the upwelling branch of the meridional overturning circulation on the annual mean scale since there is strong winter subduction off the Vietnam coast. As have been pointed by many studies, coastal wind stress and increase in southwestly winds can pump the cold water from beneath the mixed layer to the surface along the south Vietnam coast. Fig 8 show the temperature, salinity and potential density along 109.25° E meridional section off the Vietnam coast. There is an obvious upwelling zone between about 10° N and 15° N. The upwelling zone can be identified by waters about 2 ℃ colder than its environment (Fig 8a) and salinity 36.8 front separating southern from northern waters (Fig 8b). Fig 8c shows that water of $\sigma_\theta < 22kgm^{-3}$ is in exchange with the surface near the front while away from the upwelling zone the mixed-layer density is below $21kgm^{-3}$. So we speculate that the upwelling branch of the meridional overturning circulation is mainly caused by summer upwelling off the Vietnam coast. We calculate the summer upwelling rate in July using NCEP wind data in our paper, but we re-calculate the average upwelling for June-August using SODA wind stress data (Fig 9) for accuracy. Assuming for the high estimate that all the Ekman pumping water will be upwelled into the mixed layer and becomes permanently transformed, yields an upwelling transport of 6.2 Sv (8-15° N). But the winter subduction there is about 3.9 Sv. The two values yield a net upwelling about 2.3 Sv off the Vietnam coast. This can account for the upwelling branch there. The net upwelling off the Vietnam coast seems to be unbalanced with the Ekman transport and subduction rate in the northern SCS. We have explained in our paper, it is because this is a high estimate assuming all the Ekman pumping water will be upwelled into the mixed layer and flow northward thereafter.

We have realized that some problems arise in the comparison part with the Indian Ocean shallow meridional overturning circulation. This part is added after the paper has been finished, so it seems to be a little disconnected with the other parts. In face, shallow meridional overturning circulations in the SCS and in the Indian Ocean have similar patterns and characteristics. They are all balances of Ekman transport, subduction and upwelling essentially. So we added this part.

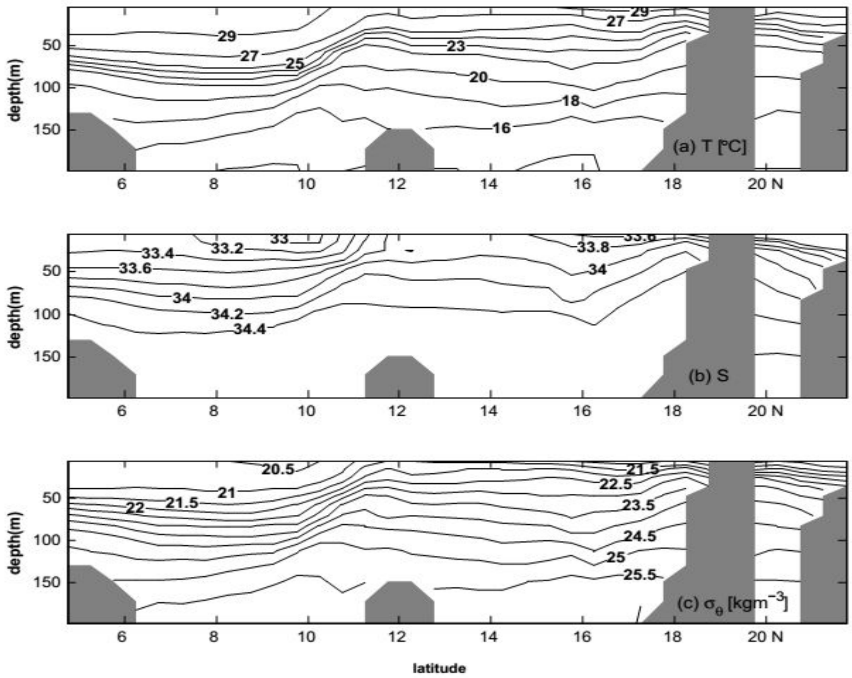

Fig 8. 109.25° E meridional section along Vietnam coast (a) temperature, (b) salinity, (c) potential density

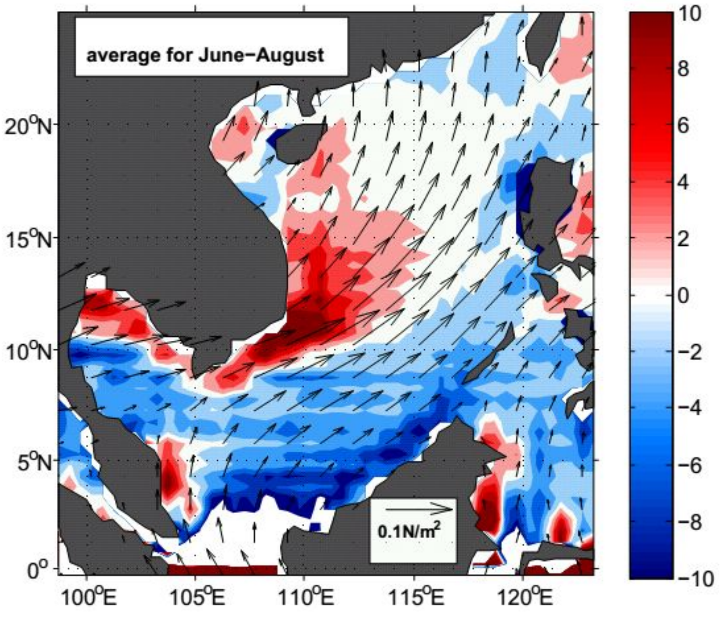

Fig 9. SODA wind stress vectors averaged for June-August (vectors) and Ekman pumping velocity (upward positive in 10^{-6}m/s).

In conclusion, I think the authors need to map out exactly what the topic of this manuscript is. The last sentence says "there may be different driving mechanisms when discussing them in different seasons. We will discuss this in a further study." For me this "further study" would represent a better way forward for discussing the meridional overturning circulation of the South China Sea, possibly including an annual average of the seasonal (or monthly) circulations to properly address the topics presented here in this manuscript.

Reply: Thank you for your suggestion. As we have explained above, we plan to discuss the seasonal driving mechanisms because we found that seasonal meridional overturning circulation have significantly different structures. In this paper, we mainly want to explain what cause the northward surface flow, the downwelling in the northern SCS, and the upwelling off the Vietnam coast on the annual mean scale. But your suggestion is good, if we look into the seasonal meridional overturning circulation in details, we will make our study on the meridional overturning circulation of the SCS an integral one.