Response to reviewer for manuscript "Long-term eddy modulation inhibited the meridional asymmetry of halocline in the Beaufort Gyre" by Lu et al.

The author comment is presented in the following sequence: (1) itemized comments from the reviewer in black, (2) author's response in blue, (3) quotations from the revised paper in indented *blue italic*.

Anonymous reviewer #1:

This paper explores the relationship between the varying eddy field and the changes in the shape and depth of the Beaufort Gyre halocline in the past two decades. The authors used in-situ observations, altimetry, and reanalysis data, to describe the changes in the halocline structure, with an emphasis on the meridional asymmetry. They then examined eddy activities, from both individual eddies and kinetic energy perspectives, and connect them to halocline structure via available potential energy. The study found that eddies played an important role in redistributing fresh water and thus adjusted the halocline structure through analysis of eddy fluxes. Despite the paper's intriguing ideas, the writing is unclear, making it very difficult to follow. The overall flow needs improvements. Therefore, I cannot recommend this paper to be published in its current form.

Thanks to the reviewer for recognising the value of our work and constructive comments. We genuinely appreciate the time and effort you have dedicated to thoroughly reviewing our work. We agree the thorough suggestions to improve our manuscript. The overall flow has been carefully polished to clarify our scientific results. We have also made more detailed explanations in our responses and revised our manuscript.

Minor points:

Line 132: Could the authors explain how eq (3) relates to this sentence?

Thanks for pointing it out. The author apologizes for the wrong text provided. The Eq. (3) is corrected to Eq. (2).

Line 146: This is not the right place to insert citation.

Thanks for pointing it out. We corrected it.

> *(Line 149-154)*
>
> *…… ψ^* is represented as*
>
> $$\psi^* = \frac{\overline{V'S'}}{S_Z} = -\frac{\overline{w'S'}}{S_y} \quad (5)$$

where $\overline{V'S'}$ is the average meridional eddy salt flux and $\overline{S_Z}$ is the average vertical salt gradient (Manucharyan et al., 2016; Manucharyan and Spall, 2016; Manucharyan and Isachsen, 2019; Marshall and Radko, 2003).

Line 205-206: Mooring C ends before 2008. How can we make a conclusion about the shape in the northeast and northwest in recent years?

Sure, we are also aware of the limit of mooring observations but the results still show that the time series of halocline depth and thickness from MMP in the northwest (mooring B) and northeast (mooring C) are well overlapped before 2008. We also supplement the results from CTD (dot), which is better for better understanding the difference between northern and southern sites over the whole period. The evolutions of halocline at the southwestern (mooring A) and southeastern (mooring D) sites are similar. Likewise, The evolutions of halocline at northern sites are also similar. Compared with MMP results, the mean relative errors of CTD on halocline depth (thickness) are 2.0% (3.4%), 4.4% (7.0%), and 1.0% (3.0%) for moorings A, B, and D, respectively. Figure 2 is modified shown below.

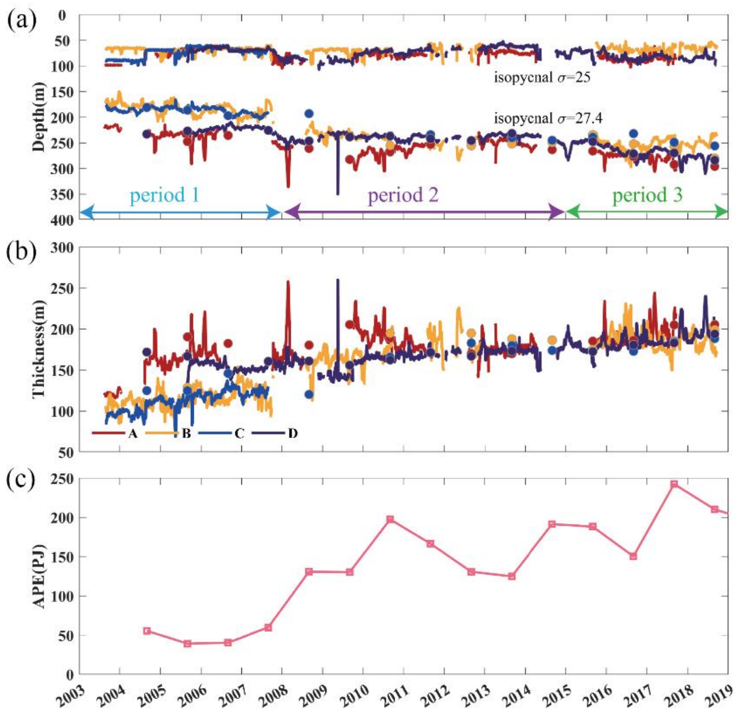

Figure 3: APE at a single point is not meaningful. It represents the slope of the halocline in a region, not a single point. The reference density in the APE equation is related to some mean density across the field. Authors should make it clear.

Thanks for the advice. The Eq. (3) is corrected to estimate the APE in the BG area. Figure 2 in our revised paper is also modified that is shown in the previous item.

(Line 147-150)

The calculation of APE here is following Eq. (3):

$$APE = PE - PE_{ref} = \iiint_{z_{ref}}^{surface} g[\rho(z) - 1027.4]zdz\, dA \qquad (3)$$

where z_{ref} represent the depth of the halocline lower boundary, A is the gyre area (Armitage et al. 2020; Polyakov et al., 2018; Bertosio et al., 2022).

Figure 6: The lengths of data available are determined the days of open ocean. Will different data lengths impact the results?

The altimetry observations are available in summer and fall when there is nearly no sea ice covered in the area we interest. EKE is strongest in summer/fall and weakest in winter (Wang et al., 2020; Manucharyan and Thompson, 2022). Using altimetry, we can well reap the long-term variability of major EKE.

Figure 6: The plot is from satellite data, so I assume it indicates surface EKE. How is it related to the previous paragraphs in which subsurface EKE are discussed?

We are trying to discuss EKE at the surface and subsurface together to better clarify the EKE variability in the upper layer. The order of figures was changed in this section for better understanding. Original Figure 6 was changed to Figure 7. Figure 7 shows the evolution of EKE pattern. After 2008, EKE was strengthened along southwestern slope than before, agreeing with more active halocline eddy activity in the BG region from moored observations.

Line 306: This statement made based on observations from two points. Other factors could be responsible. For example, eddies were generated near the mooring site; or the eddies simply did not pass by the mooring.

Thanks for pointing it out. This statement was modified. There are main two factors emphasised, including the eddy distribution and eddy transportation.

Figure 10: How is the probability estimated?

The estimation of probability was added. And related expressions were added as follow:

(Line 381)

We compare the probability analysis results of EKE and geostrophic velocities averaged in the AL region based on the satellite altimetry in three periods (Fig. 10), which is estimated by statistical frequency of the area mean time series in every period.

Line 399: Eady timescale is not interpreted previously.

Meaning and calculation of Eady timescale are interpreted in section 2.2. It estimates the oceanic baroclinic instability.

Major point:

The authors described both surface and subsurface EKE. There could be asymmetry in the surface sea level and subsurface halocline. How does the surface EKE relate to the subsurface halocline shape?

Thanks for suggestions. We try to clarify the relationship between eddy activity and halocline changes which are related to Beaufort gyre variation, and we have revised the explanation in sections 4 and 5.

Based on the previous works, the surface eddy activities responding to the extra wind energy input are linked to gyre stability (Armitage et al, 2020), meanwhile the subsurface EKE from baroclinic instability and APE release are also linked to gyre stability (Manucharyan and Spall, 2016; Manucharyan et al., 2016). Since the two processes both modulate halocline variability in the BG, eddy activities at the surface and subsurface are needed to discuss together to explain their impact on oceanic stratification in the upper layer. The surface EKE can hinder the development of mean kinetic energy (MKE) and slow down the increasing rate of mean currents, which promoted the BG stabilisation (section 5.1). From this perspective, eddy activity can weaken the gradient of surface sea level to inhibit surface geostrophic currents, but it is not the main point of the study. What we are concerned about is that surface and subsurface eddy activities jointly influenced oceanic stratification by inhibiting surface mean flows and promoting APE release above the halocline layer related to BG stabilisation. When mean kinetic energy and potential energy are more stable in the final period (after 2014) than before, eddy modulation leads to freshwater redistribution in the upper layer through enhanced eddy lateral fluxes, which inhibited the meridional asymmetry of halocline changes (section 5.2). It is shown that freshwater distribution has an impact on the variability of halocline thickness and strength (Bertosio et al., 2022). Therefore, we concluded that eddy fluxes, generating low-salinity water transportations in the upper layer (Fig. 11b), resulted in a smaller difference in halocline depth between north and south of BG.

To show how the writing could be improved, I will provide some wording issues in the first 50 lines. Please note that this list is not exhaustive, but rather serves as a guide for improving the paper’s overall clarity.

Thanks for the guideline. We checked the whole manuscript again for better clarification.

Line 10: Please specify the “varying eddies”. Number, shape, velocity?

Thanks for pointing it out, we have specified.

Line 16: This long sentence is confusing. Maybe it would be clearer if breaking into several shorter sentence.

Thanks, this long sentence was divided into several segments.

> *(Line 16)*
>
> *In the meantime, eddy activities in the upper layer from the southern margin of BG to the abyssal plain have been enhanced. Moreover, eddy-induced low-salinity water transportations have been continuously increasing towards the central basin as halocline structures on either side of the basin reach a nearly identical and stable regime.*

Line 16: The second "Eddy" should not start with capital letter.

Thanks for pointing it out, it was corrected.

Line 30: This sentence is not grammatically correct.

Thanks for pointing it out. This sentence was reorganised.

> *(Line 29)*
>
> *Meanwhile, increased active ocean–atmosphere interactions and mesoscale processes in the Canada Basin (CB) due to the emergence of broader open areas have attracted increasing attention.*

Line 37: It should be "paid attention" instead of "payed attention"

Thanks for pointing it out, it was corrected.

Line 39: "The increase of isopycnal slope with depth" is a new piece of information and it should be introduced before directly describing the mechanism.

Thanks for this recommendation. "The increase of isopycnal slope with depth" explained the interior increased PWW thickness. This paragraph was reorganised.

> *(Line 43-47)*
>
> *Pacific Winter Water (PWW), which lies above the eastern Arctic origin lower halocline water, is recognized as a component of the western Arctic halocline (Shimada et al., 2005). Observations indicated that PWW layer generally deepened during 2004–2018 while isopycnal layer thickness increased (Kenigson et al., 2021). Likewise, there was an isopycnal deepening by 70 m during 2004–2011 (Zhong et al., 2018), suggesting a spin-up of the gyre. The isopycnals are increasing with depth, which can be attributed to the eddy-induced stream function, explaining the interior increased PWW thickness (Kenigson et al., 2021).*

Line 42: “Likewise” used here is confusing. The previous and this sentence do not have characteristics in common.

Thanks for pointing it out, it was corrected. These sentences are modified for more coherence.

Line 43: Should be “identified as”.

Thanks for pointing it out, it was corrected.

Line 46: high resolution eddy-resolving?

Thanks for pointing it out, it was corrected.

Line 47: “etc” should not be used.

Thanks for pointing it out, it was corrected.

Line 48: “focused on” instead of “focus”.

Thanks for pointing it out, it was corrected.

Line 48: “Moreover” is not correctly used here. The following sentence changes the topic.

Thanks for pointing it out. The following sentence is the same topic on the vertical distribution of eddy activity. This sentence was rephrased for more coherence.

Line 50: “even they may extend”?

This sentence has been rephrased.

> *(Line 52)*
> *Eddies are mainly concentrated in the subsurface (30-300 m) even though they can extend to thousands of metres in depth (Zhao et al., 2014; Zhao and Timmermans, 2015)……*

Reference:

Armitage, T., Manucharyan, G. E., Petty, A. A., Kwok, R., and Thompson, A. F.: Enhanced eddy activity in the Beaufort Gyre in response to sea ice loss. Nat. Commun., 11, 1-8. https://doi.org/10.1038/s41467-020-14449-z, 2020.

Bertosio, C., Provost, C., Athanase, M., Sennéchael, N., Garric, G., Lellouche, J. M., Bricaud, C., Kim, J. H., Cho, K. H., and Park, T.: Changes in freshwater distribution and pathways in the Arctic Ocean since 2007 in the mercator ocean global operational system. J. Geophys. Res. Oceans, 127, e2021JC017701. https://doi.org/10.1029/2021JC017701, 2022.

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Beaufort Gyre constrained by mesoscale eddies. Geophys. Res. Lett., 43, 273-282. https://doi.org/10.1002/2015GL065957, 2016.Manucharyan, G. E., Spall, M. A., and Thompson, A. F.: A theory of the wind-driven Beaufort Gyre variability. J. Phys. Oceanogr., 46, 3263-3278. https://doi.org/10.1175/JPO-D-16-0091.1, 2016.

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Wang, Q., Koldunov, N. V., Danilov, S., Sidorenko, D., Wekerle, C., Scholz, P., Bashmachnikov, I. L., and Jung, T.: Eddy kinetic energy in the Arctic Ocean from a global simulation with a 1 - km Arctic. Geophys. Res. Lett., 47, e2020GL088550. https://doi.org/10.1029/2020GL088550, 2020.