Authors point-to-point responds Referee Comment #1 to egusphere-2025-2665

Please find the author's responses in black below the reviewer's comments in blue. The italicized text within quotation marks indicates the proposed revisions in the revised manuscript.

1. L11: change "Arctic sea ocean-sea ice system" to "Arctic ocean-sea ice system"

Thanks, the phrase has been changed on P1, L11.

2. L14: please clarify what "multi-scale" refers to.

Thank you for requesting clarification. The term "multi-scale" in our context primarily refers to temporal scales, encompassing a broad range from seasonal to interannual-decadal variability. We have revised the abstract (P1, L14-15): "... *a simulation framework capable of resolving processes from seasonal to decadal timescales*"

3. L23-24: "These systematic biases may be attributed to three principal sources ...... in key gateways". This speculation should be supported by some evidences in the main text.

Regarding the statement in the original abstract ("These systematic biases may be attributed to three principal sources: inadequate representation of eddy dynamics, limitations in mixing parameterizations, and insufficient resolution of cross-scale interactions in key gateways (e.g., Fram Strait)."), we provide the following detailed clarifications and context, which have been incorporated into the relevant sections of the revised manuscript. However, it is important to note that, due to computational constraints, the attribution of these biases primarily relied on insights from the existing literature. Acknowledging that these attributions remain suggestive rather than proven, we have removed the specific claim regarding the three sources from the abstract.

(1) "inadequate representation of eddy dynamics"

1) E3SMv2-MPAS failed to capture the observed significant decadal freshening signal in the upper ocean of the Amerasian Basin during the 2000s–2010s (Fig. 13 in the revised manuscript). We have added supporting evidence and references at the relevant location (P23, L502-510):

   "*The simulated salinity biases may be related to the use of an inappropriately high and constant isopycnal diffusion coefficient (κ=300 m²/s) in the GM parameterization. This high diffusion coefficient likely results in excessively strong along-isopycnal mixing, which oversmooths horizontal salinity gradient fronts formed by freshwater accumulation (e.g., from melting ice and increased* *runoff). During the 1970s, when background freshwater signals were relatively weak, the effect of strong diffusion was less pronounced. However, under the strongly increased freshwater input in the 2000s–2010 (Polyakov et al., 2013; Wang et al., 2019), the persistently high κ value continuously and excessively diffused the simulated upper-layer low-salinity anomalies, hindering their realistic accumulation and maintenance in the basin upper layer. As a result, the model significantly underestimates the magnitude of decadal freshening observed in the region.*"

2) The model did not reproduce the observed seasonal variation of the Atlantic Water, characterized by a warmer and thicker in winter compared to summer (Fig. 12). Corroborating discussion has been added in the text (P21, L468-474):

   "*This discrepancy may be attributed to the GM parameterization scheme, which models mesoscale eddy effects on heat and salt redistribution through bolus advection and Redi diffusion. In general, the Arctic winter features greater mixed layer depth and weaker stratification due to brine rejection during sea ice formation and wind-driven stirring (Peralta-Ferriz and Woodgate, 2015). These processes promote eddy penetration, increasing the efficiency of vertical heat transport. In contrast, strengthened stratification in summer restricts the vertical scale of eddies and reduces heat transfer. However, the GM scheme employs a fixed diffusion coefficient, which prevents it from capturing the seasonal variability modulated by stratification changes.*"

(2) "limitations in mixing parameterizations"

1) Co-located biases in SST, SSS, and SIC in the Barents and Greenland Seas. Supporting discussion has been added (P17-18, L404-413):

   "*In the Greenland and Barents Seas, systematic underestimation of SST and SSS (Figs. 8c and 9c) coincides with overestimation of SIC (Figs. 3 and 4). These regions are situated within the marginal ice zone, where strong surface wind stress facilitates the transfer of energy to deeper ocean layers through the excitation of near-inertial oscillations and associated turbulent mixing processes (D'Asaro, 1985). This discrepancy may be attributed to the model's potential overestimation of this downward energy transfer. Similarly, Zhu et al. (2022) reported that in the equatorial Pacific cold tongue region, the KPP scheme overestimates downward turbulent heat flux, leading to a cold bias in both upper-ocean and sea surface temperatures. A primary reason for these biases lies in the scheme's reliance on a single Richardson number (Ri) relationship for parameterization. Although this approach captures instability conditions in stratified shear flows, it is insufficient to uniquely determine turbulent states and* *mixing intensities (Zhu et al., 2022), thus limiting its performance in complex dynamic environments.*"

2) Misplaced warming layer in the Eurasian Basin: Observational data indicate warming occurred primarily in the upper~500m on decadal scales, whereas the model simulated the warming predominantly in the 200–1000m layer. Relevant evidence is now discussed in the manuscript (P23, L489-497):

   "*These discrepancies may be partly attributed to biases in the representation of vertical processes. As indicated by sensitivity experiments such as those of Liang & Losch (2018), enhanced vertical mixing could promote upward heat transport from AW, potentially causing cooling at intermediate depths (200–900 m). Our model uses a relatively low background diffusivity (1.0×10^{-5} m²/s), which remains constant across time periods despite evidence that Arctic amplification and Atlantification in the 2000s–2010s (Polyakov et al., 2017, 2025; Rantanen et al., 2022; Richards et al., 2022; Shu et al., 2022) may have strengthened vertical mixing compared to the 1970s. The model's failure to represent this temporal increase in mixing efficiency might have limited upward heat transfer, confining warming mainly to intermediate and deeper layers—consistent with the underestimation of shallow warming and exaggerated deep response seen in our simulations.*"

(3) "insufficient resolution of cross-scale interactions in key gateways (e.g., Fram Strait)"

We acknowledge that the original phrasing might have been ambiguous. Our intended meaning was that shortcomings in both vertical mixing and mesoscale eddy parameterizations could potentially be mitigated by increased resolution, particularly in narrow yet critical gateway regions like Fram Strait.

To address this more thoroughly, we have added a new section in the Discussion (Section 5.2: Sources of Systematic Biases and Trade-offs Between Resolution and Parameterizations; P37, L775-798):

"*Analyses in Section 3 not only discussed the simulation biases of E3SMv2-MPAS but also traced their potential origins. For most biases, the primary causes can be attributed to inadequacies in physical parameterizations. First, the inadequate representation of eddy dynamics is a key source. For instance, the underestimation of freshening in the Amerasian Basin may result from the use of a fixed eddy diffusivity (κ=300 m²/s in the Arctic), which oversmooths salinity fronts. Similarly, the model's failure to capture the seasonal variability of the Atlantic Water layer likely stems from the invariant κ in the GM scheme, which cannot respond to the seasonal cycle of sea ice retreat and associated changes in stratification. Second, limitations in vertical mixing parameterizations act as another key source. The coordinated biases in SST, SSS, and SIC in the Greenland and*

Barents Seas, for example, may arise from the inherent limitations of the KPP scheme's single Ri-based approach in defining turbulent states and mixing intensities within complex dynamic environments. Additionally, the misrepresentation of the warming layer in the Eurasian Basin could be linked to inappropriate background diffusion coefficients within the KPP framework.

Increasing model resolution presents an effective pathway to reduce reliance on empirical parameterizations by more directly resolving key physical processes, such as mesoscale eddies. Enhanced resolution can, to some extent, mitigate the inaccuracies of existing schemes. For instance, studies have shown that higher resolution improves the simulation of the Atlantic Water layer's temperature, thickness, spatial distribution, and its decadal warming trends (Wang et al., 2024). However, the small Rossby radius of deformation (often ≤3 km) in the Arctic (Veneziani et al., 2022) implies that even with computationally feasible resolution increases, critical processes (e.g. mesoscale eddies, vertical mixing, and ice-ocean interactions) may remain under-resolved (Chassignet et al., 2020; Wang et al., 2018). Therefore, the development of more advanced physical parameterizations remains imperative. It is noteworthy that resolution increases have proven effective in improving the simulation of volume, heat, and freshwater transports through critical gateways such as the Fram Strait and Davis Strait (Wang et al., 2024). The Fram Strait, in particular, serves as a pivotal channel for Atlantic heat influx into the Arctic Ocean (Herbaut et al., 2022; Pnyushkov et al., 2021). In conclusion, we propose that a cost-effective strategy involves targetedly increasing resolution in key gateway regions while concurrently refining parameterizations for mesoscale eddies and vertical mixing."

4. L27: change "components" to "area"

We thank you for this suggestion. The change has been made accordingly (P1, L26).

5. L37-38: "Liang and Losch, 2018; Tian et al., 2022" are based on regional ice-ocean model, not climate model.

Thank you for correctly pointing this out. The cited references "Duarte et al., 2020; Hinrichs et al., 2021; Liang and Losch, 2018a; Tian et al., 2022; Wassmann et al., 2015" were indeed based on regional models. We have updated them to more appropriate citations: "Dörr et al., 2021; Hinrichs et al., 2021; Rieke et al., 2023; Shu et al., 2022". (P2, L36)

6. L48: change "and" to "to"

Corrected as suggested (P2, L46).

7. L53: change “seafloor regions” to “seafloor”

Corrected as suggested (P2, L51).

8. L60: change “shifts” to “shift”

Corrected as suggested (P2, L58).

9. L79: change “temporal” to “spatial” ?

We sincerely thank you for catching this error. You are correct; “temporal” should be “spatial”. This has been corrected (P3, L77).

10. L95: change “FESOM’s” to “FESOM”

This has been corrected in the revised manuscript (P3, L93).

11. L96: delete “then”

This word has been deleted (P3, L94).

12. L130-132: “The North Atlantic sector ...... in the Gulf Stream extension region”. Please rephrase this sentence.

The sentence has been rephrased for clarity: “*... the North Atlantic sector is strategically refined, transitioning from 20 km to 10 km earlier than the Pacific to guarantee at least 15 km resolution in the Gulf Stream extension region (~40°N; Veneziani et al., 2022) ...*” (P5, L131-132)

13. L134: “subpolar North Pacific sector adjacent to the Arctic Ocean”?

Thank you for identifying this careless error in our description. The sentence has been corrected to: “*... the North Pacific sector maintains computational efficiency while achieving approximately 10 km resolution in its subpolar region adjacent to the Arctic Ocean (north of 50°N).*” (P5, L133-134)

14. L139: how long is the sea ice dynamic step? The same to ocean dynamic step?

We apologize for the imprecise original description. The sea ice dynamic time step is 15 minutes. The manuscript has been revised to state this clearly (P5, L139-140): “*For sea ice, we employ a 15-minute dynamic time step and a 30-minute thermodynamic time step (a 2:1 ratio).*”

15. L157: rapidly

We thank you for this correction. In response to the feedback received from other reviewers, we have determined that the original phrasing containing this term was imprecise. Consequently, the sentence has been removed from the revised manuscript.

16. ***L159-161: “The simulation periods ...... period consistency checks (1995–2020)”. If I understand correctly, you derive the simulation of 1995-2020 using JRA55 forcing during 1995-2020 but initialized at the latest model state of 1980. It is seldom to see such design of model simulation. As the intermediate years only span 15 years, I suggest the authors conduct a continuously simulation from 1960 to 2020.

We greatly appreciate your deep insight into our simulation design. Your understanding is perfectly accurate: to initiate the 1995–2020 JRA55-forced simulation, we used the model state from the end of 1981 (generated by a prior 1958–1981 JRA55-forced simulation) as the initial conditions, without performing any model integration for the period 1982–1994.

We fully share your concern regarding continuity. However, a continuous and complete simulation from 1958 to 2020 was computationally prohibitive under our resource constraints. Given these limitations, we prioritized ensuring a simulation for our core analysis period (1995–2020), which benefits from the richest observational data.

From a physical mechanism perspective, the potential impact of this initialization approach for the 1995–2020 simulation is likely confined to the very beginning of our analysis period. The core focus of our study—the surface and upper ocean, along with sea ice—exhibits much shorter adjustment timescales compared to the deep ocean and is predominantly governed by the contemporaneous atmospheric forcing. Thus, disequilibrium introduced by the initial conditions (the state from the end of 1981) would be rapidly overwritten and adjusted by the realistic, synchronous atmospheric forcing applied from 1995 onward. This approach is physically justified and analogous to the common practice in ocean modeling of initializing with climatological mean states (e.g., PHC), which similarly relies on atmospheric forcing to constrain the model’s interannual variability. (This reasoning is also presented in the manuscript: P7, L191-195.)

The model output initialized from the 1981 state also demonstrates physically consistent behavior during the 1995–2020 period, further supporting the validity of this approach. The temporal evolution of key diagnostic variables—including sea surface temperature (Fig. 8d) and sea ice-related variables (Fig. 7)—shows that the simulation quickly aligns with the observed/reanalysis trajectory after 1995, with no persistent systematic bias. Spatial distributions of these variables are also in good agreement with evaluation datasets (Figs. 3–5, 8a–c), and the long-term trends from 1995 to 2020 closely match those in the references (Fig. 7). These results, which will be discussed in detail in the following sections, indicate that the initialization from 1981 did not adversely affect the simulation of central climate features during the study period. (This reasoning is also presented in the manuscript: P7, L198-204.)

Furthermore, we have explicitly acknowledged the limitation of this simulation design in the Discussion section (Section 5.3: Limitations of the Experimental Design), and have committed to performing a full continuous simulation from 1958 to 2020 in future work when computational resources allow:

"*Due to computational resource constraints, this study adopted a two-phase simulation strategy with non-consecutive time periods: first, the model was integrated from 1958 to 1981, and the final state of this period was used as the initial condition to directly start the simulation for the 1995–2020 period. Although this approach effectively reduced computational costs, and both previous studies and our model diagnostics indicate that key upper-ocean and sea ice variables had reached a quasi-equilibrium state by 1981, skipping the continuous integration of the 1982–1994 period may introduce certain limitations. For instance, the simulation of some medium- to long-term fluctuations or memory-dependent processes might be affected. Should computational resources allow in the future, we will perform a continuous simulation from 1958 to 2020 to more accurately reproduce the evolution of the climate system.*" (P37-38, L800-807)

17. ***Section 2.1: there is no detailed information of sea ice model provided here. Please specify sea ice thermodynamics and dynamics in this configuration. As section 3.1 relates to sea ice validation, sea ice model description is necessary.

We thank you for this helpful comment. We have now added a detailed description of the sea ice thermodynamics and dynamics configurations used in MPAS-Seaice in Section 2.1 (P5-6, L148-155). An excerpt is provided below:

"*MPAS-Seaice builds upon the core numerical and physical framework of the Los Alamos Sea Ice Model (CICE). The dynamics are governed by the elastic-viscous-plastic (EVP) rheology, with the internal ice stress divergence operator adapted for MPAS's unstructured polygonal mesh (Turner et al., 2022). Sea ice and tracer transport are handled by an incremental remapping scheme (Lipscomb and Ringler, 2005), adapted for polygonal cells. The thermodynamics and vertical column physics remain consistent with CICE (Turner et al., 2022). The configuration includes the "mushy layer" thermodynamics for vertical heat transfer, the delta-Eddington shortwave radiation scheme, a level-ice melt pond parameterization, ice thickness distribution mechanics, and transport in thickness space (Petersen et al., 2019).*"

18. L197: EN.4.2.2 dataset

Thank you for spotting this typo. This error has been corrected (P9, L243).

19. L244: from Figure 3a, "systematic winter overestimation" is caused partly by positive sea ice bias in the southern Greenland Sea and south extension of sea ice cover in the Barents Sea, suggesting upper ocean temperature bias in these regions. "moderate summer underestimation" may be related to inaccurate ice-albedo feedback and melt pond dynamics.

We appreciate this insightful comment. Our original text only described the biases observed in the time series without discussing their potential sources.

As you rightly pointed, the "systematic winter overestimation" is partly caused by the positive sea ice bias in the southern Greenland Sea and the southward extension of sea ice cover in the Barents Sea (Fig. 3 in the revised manuscript). Following your suggestion regarding potential upper ocean temperature bias, we have added an analysis of winter SST spatial biases (Fig. S3), which indeed reveals significant cold biases in precisely these regions.

According to the interannual time series from 1995 to 2020, E3SMv2-MPAS overestimates the summer minima (Fig. 7a). Combined with the spatial maps of summer SIC (Fig. 4), the overestimation is primarily located in the Greenland Sea, Barents Sea, East Siberian-Laptev Seas, and Beaufort Sea. We further analyzed summer albedo (Fig. S4) and found that the model simulates higher albedo in these specific regions, leading to reduced absorbed shortwave radiation and consequently an overestimation of sea ice.

We have incorporated this discussion on the potential sources of the seasonal SIC biases into the revised manuscript (P15, L350-355): "*Consistent with NSIDC, simulated SIC and SIE exhibit certain seasonal biases. The systematic winter overestimation, attributable to positive SIC biases in the southern Greenland Sea and southward-expanded ice cover in the Barents Sea (Fig. 3e), coinciding with pronounced cold SST biases in these regions (Fig. S3). During summer, E3SMv2-MPAS overestimates the seasonal minimum (Fig. 7a–b), particularly in the Greenland Sea, Barents Sea, East Siberian-Laptev Seas, and Beaufort Sea (Fig. 4e). These regions also exhibit elevated surface albedo values (Fig. S4), reducing absorbed shortwave radiation and contributing to the sea ice overestimation.*"

20. L249: "overestimated seasonal variability amplitudes" relates to sea ice thermodynamics, as no sea ice thermodynamics information is provided, it is hard to judge its causality.

The phrase "overestimated seasonal variability amplitudes" was originally a description for the 1960–1980 period, which might still be within the model's spin-up phase and lacks robust observational data for detailed attribution. Consequently, we have removed this statement from the revised manuscript. Our analysis of bias sources now focuses primarily on the well-observed 1995–2020 period, as described in response to your previous comment.

21. ***L258-269, 279-281: The modeled SIT has large biases in the Beaufort Gyre region, suggesting potential upper ocean thermal biases in the Beaufort Gyre. The author could check whether the ocean-ice heat flux over the Beaufort Gyre region is reasonable.

Thank you for this excellent suggestion.

Given the scarcity of direct ocean-ice heat flux measurements in the Arctic, we analyzed the 0-100m ocean heat content (OHC) instead. A comparison with the IAP observational dataset reveals a general underestimation of OHC in the Beaufort Gyre region, which could contribute to the overestimation of SIT there.

We have included this supporting analyzes in the revised manuscript (P13, L323-328):

"*The model overestimates SSH in the Beaufort Sea, suggesting an erroneously enhanced ice convergence. Additionally, the simulated OHC in the 0–100 m layer is underestimated in this region (Fig. 6d–f), which may further contribute to the positive SIT bias. Thus, the persistent 0.5–1 m positive bias in the Beaufort Sea is hypothesized to originate from an overestimated intensity of the Beaufort Gyre and associated upper-ocean thermal biases in E3SMv2-MPAS, which then may impede the realistic export of sea ice through the north of Canadian Archipelago and east of Greenland.*"

Additionally, following your suggestion, we examined the ocean-ice heat flux in the Beaufort Gyre region (shown in the Fig. 1 below). A broad comparison with Figure 2 from Zhong et al. (2022) suggests the overall magnitude is reasonable, though it might suffer from a systematic low bias consistent with the OHC analysis.

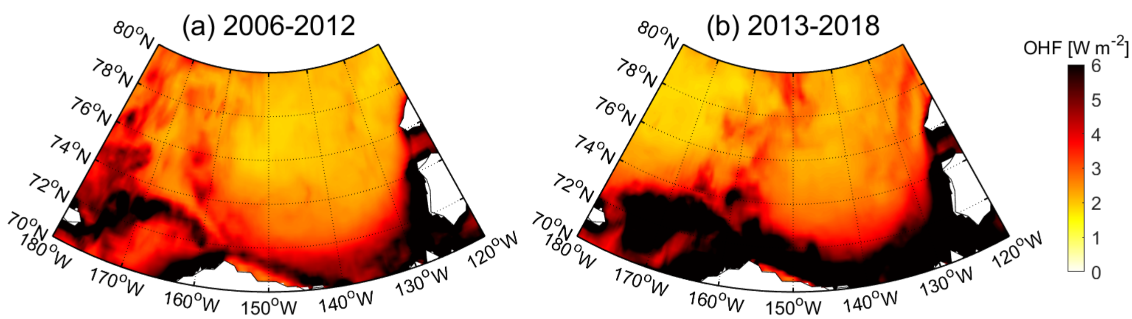

Figure 1. Gridded average ocean-ice heat flux during (a) 2006–2012 and (b) 2013–2018.

Reference:

Zhong, W., Cole, S. T., Zhang, J., Lei, R., and Steele, M.: Increasing Winter Ocean-to-Ice Heat Flux in the Beaufort Gyre Region, Arctic Ocean Over 2006–2018, Geophysical Research Letters, 49, e2021GL096216, https://doi.org/10.1029/2021GL096216, 2022.

22. Figure 4d: given the known biases of the PIOMAS SIT, I suggest the author additionally validate the modeled sea ice volume against that derived from the CS2SMOS SIT from 2012.

We are grateful for this suggestion. We have replaced the comparison with ICESat by validating the modeled SIT against the CS2SMOS SIT product for winter (December-February) over the period 2011-2019. This new analysis confirms that E3SMv2-MPAS systematically overestimates SIT in the Canadian Archipelago and Greenland coastal regions. The corresponding text has been updated (P12-13, L311-318):

"*Considering PIOMAS's known limitations in overestimating thin ice while underestimating thick ice (Laxon et al., 2013; Schweiger et al., 2011), additional validation using CS2SMOS data (Ricker et al., 2017) is conducted (Fig. S1). Consistent with previous findings, PIOMAS exhibits underestimation in regions with thicker sea ice, such as north of the Canadian Archipelago and east of Greenland (Fig. S1e). Similarly, E3SMv2-MPAS shows pronounced positive biases relative to CS2SMOS in areas including the northern Canadian Archipelago, the southern Canadian Basin, and the Beaufort Sea (Fig. S1d), aligning with the bias pattern identified in comparisons with PIOMAS (Fig. 5c), thereby corroborating the spatial reliability of PIOMAS-indicated biases.*"

23. L347: Please specify the define of AW layer thickness.

Thank you for your comment. However, since the spin-up duration of E3SMv2-MPAS is considerably shorter than that of fully-coupled CMIP6 models, a direct comparison between the two would not be scientifically equitable. Therefore, the analysis section containing this sentence has been removed from the revised manuscript.

24. L347-349: This sentence needs to be rephrased as "Amerasian Basin" is not in Figure 8.

Thanks for pointing this out. The mentioned sentence has been removed in the new version.

25. L362-363: "E3SMv2-MPAS maintains systematic temperature overestimation (~0.5C average)". This statement is not appropriate for the other three regions.

We agree that this statement was not accurate or rigorous enough. It has been revised to (P19, L439-440): "*~1℃ in the western Eurasian Basin, ~0.3 ℃ in the Chukchi Sea and the Beaufort Sea …*"

26. L364-365: systematic salinity underestimation only occurs in western and eastern Eurasian Basin.

Thank you. This sentence has been removed along with the deleted CMIP6 comparison section.

27. L390: ~ 0.5 C at 800 m ?

We apologize for this careless error. You are correct; it has been changed to "*the same depth*" for accuracy (P35, L748).

28. L417: I understand from section 2 that both the E3SMv1 and E3SMv2 use the same KPP. Why the vertical mixing scheme in E3SMv2 is refined?

We thank you for your careful reading. Similar to CMIP6, E3SMv2-MPAS was run with one cycle of JRA55 forcing, whereas E3SMv1 was run with three full cycles. This difference in experimental setup makes a direct comparison between the two models inappropriate. Accordingly, the comparison with E3SMv1, including the discussion of the KPP scheme, has been removed from the revised manuscript. We apologize for any inaccuracy in our original wording.

29. Figure 11: please clarify this figure is conducted over the whole Arctic Basin or Eurasian Basin or Amerasian Basin?

We apologize for not specifying the region. The figure represents a pan-Arctic Basin average. This clarification has been added to the figure caption: "*Figure 11. For the Arctic Basin, …*". (P20, L447)

30. ***L466-467, 469-470: "likely modulated by differential ocean-ice feedbacks and cross-basin transport dynamics", "indicating limitations in AW transport pathways and heat redistribution", such speculations are too arbitrary, it's better to avoid using such speculations.

Thanks for this feedback. We agree that these speculations were too arbitrary without stronger direct evidence. Consequently, the phrases "likely modulated by differential ocean-ice feedbacks and cross-basin transport dynamics" and "indicating limitations in AW transport pathways and heat redistribution" have been removed from the revised manuscript.

31. L488-490: see the previous comment.

As noted above, the related text has been deleted.

32. L519: delete “the” before “Fram Strait”. “Similar negative deviations (-0.5 C)”

The sentence containing "the Fram Strait" pertained to the attribution of model biases and was not sufficiently rigorous; it has therefore been removed from the revised manuscript. The phrasing “Similar negative deviations (-0.5 °C)” has been corrected (P30, L649).

33. L527-530: This conclusion can not derived from the observations STRICTLY.

You are absolutely right. We have erred on the side of caution and removed this sentence.

34. L582: a detailed description of the thermal linkage framework between the upper and intermediate ocean layers is needed here.

We sincerely thank you for this insightful comment. We agree that a more precise description of the methodology is necessary. The core of this framework is the analysis of spatiotemporal correlation (both instantaneous and lagged) between temperature at 5 m and 400 m depths.

We have revised the manuscript accordingly to provide a clearer and more detailed description. The specific changes can be found in P32, L698-700: “*A diagnostic framework based on spatiotemporal correlation analysis is established to quantify the thermal linkage between the upper (10 m) and intermediate (AW core layer, 400 m) ocean layers.*”