Authors responses to editor's comments

Characteristics of ocean mesoscale eddies in the Canadian Basin from a high resolution pan-Arctic model

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In the following, all page numbers refer to the revised manuscript.

General comments

Editor: I was waiting for the second referee to post (and an informal referee to comment) before I posted, and thankfully they corroborate what I was going to say already. I also think the paper can be published eventually, but quite a bit of elaboration and appropriate literature review will be required, and would recommend the authors to do replies and make revisions in due course.

Authors: We appreciate the meaningful effort at summarizing the reviewers' points and adding constructive suggestions for improvement of the paper. We have substantially modified the manuscript, in particular by rewriting the introduction and restructuring the results section. We have also provided a detailed justification of the ability of our model to resolve a large portion of the mesoscale eddy spectrum and added more discussion on the limitations of the method. Below, we provide point by point responses to the general comments provided by the editor.

Editor: To be blunt about this, my big issue with a lot of the eddy detection papers is "so what?", and to me this paper falls into that category. The polarity, eccentricities, depth extent, numbers etc by themselves are to me rather meaningless if they are not linked up explicitly to the appropriate physical mechanisms and/or possible consequences. A few of these might be:

- biases in polarity may be related to deviation from geostrophic theory
- vortices have a tendency to circularise, so highly eccentric vortices may indicate forcing mechanisms at play disrupting their shape
- deep/intermediate/shallow extent of the eddies may be related to the generation mechanism of the eddies
- numbers may indicate changes in the generation or dissipation mechanism (e.g. ice-ocean drag)

At the moment some of the eddy metrics are presented and it is as if the reader is supposed to just know why these are important (I am not personally convinced they are to be honest). Anyhow, the fix is probably reasonably "easy" to do in principle: motivate the science and relationship with the metrics to be presented in a more comprehensive fashion in the introduction section (and may be recap accordingly in the conclusion), adding (probably quite a few) references of the literature as appropriate.

Set up the scene on why the metrics to be discussed are going to be relevant, then go into detail as much as the authors would like.

Authors: To address your "so what?" concern, we have worked on reframing and restructuring the paper. Mainly:

- The introduction has been rewritten to link the metrics with the physical mechanisms. In particular, we examine the eddy location, number and radius in relation to their generation mechanisms and the eddy duration in relation to the dissipation mechanisms. We use these metrics in the paper to (1) document the spatial and seasonal characteristics of mesoscale eddies in the Canada Basin and (2) investigate the evolution of the number of eddies over the past decades in link with the sea ice decline and circulation intensification.
- The results section has been restructured to align with the two main goals stated above.
- The discussion and conclusion section has been modified to better discuss the use of these metrics and the interpretation of some results in link to the limitation of the model. Biases in eddy polarity are discussed in this section, as well as eddy temperature anomalies and possible impact on heat transport.

We believe that these major changes provide a more compelling story in better adequation with our approach and goals.

Editor: Note that the referees point out that there are some details that are not entirely sufficient at present (e.g. statistical significance), so do have a look at those and address those accordingly.
Authors: We now provide more details about the implemented methods following the recommendations by the reviewers. For example, we added an explanation on how the reported % increases and decreases are calculated on lines 473-474 (addressing the reviewer's concerns about statistical significance) and modified the wording associated with the SSH-gradient calculation in the caption of Fig. 10 so that the methodology is clearer.

Editor: Eddy detection per vertical level, as noted by the referees also. This overblows the amount of eddies there actually are, and the vertical coherence and structure of the eddies are one of the most important aspects associated with geostrophic eddies partly because these probably relate to the generation mechanism and/or background turbulence characteristics (e.g. Eady-modes are deep while Charney-Green modes are more vertically confined; QG theory suggests inverse cascades and barotropisation but maybe there are things present in the system that does not allow that to proceed fully). This really should be fixed, or failing it being fixed completely in this article, some samples of cases showing vertical coherency should probably be shown somewhere to at least demonstrate it is doable. I am making the assumption that there are cases with vertical coherency because that's what theory would suggest; it would be more surprising if there wasn't (although I would then be inclined to think the choice of method has deficiencies instead).

Authors: We acknowledge that the detection of eddies per depth level prevents a precise count of the total number of eddies in the basin and an in-depth investigation of the mechanisms linked to the generation and evolution of these eddies, especially processes at the time scale of one individual eddy's life (e.g. barotropisation). That being said, when reporting the number of eddies in the basin, we have been careful to account for this limitation. Yet, reading the reviews has made us realize that our wording may have been misleading so we now have adapted it following the suggestion of the reviewers by reporting the number of eddies per layer instead of averaged per model depth level.

Our 2D approach of detecting eddies is due to the limitation in computational resources (tracking eddies in 3D is extremely expensive; see e.g. Crews et al. [2018], Le Vu et al. [2018], Nencioli et al. [2010]) and by the fact that reconstructing the vertical extent of detected eddies is far from being trivial, so that there is a higher confidence in 2D detection and tracking than in a similar exercise in full 3D. While the incomplete detection keeps us away from an in-depth investigation of the vertical structure of eddies and of its underlying mechanisms, it allows us to encompass a large domain where robust statistics can be provided at every depth level.

Within this framework, we can still obtain an idea of the vertical structure by looking at a few specific objects. This does not form any statistical characterisation of the vertical extent, but as mentionned by the editor, should give confidence in the performance of the detection and tracking. This can be done, for instance, by looking at the vertical structure of kinetic energy at virtual moorings, in relation to the eddies passing by these moorings that our algorithm has detected (Fig. 5). These moorings show surface intensified eddies, eddies spanning the pycnocline and eddies spanning the whole AW layer, which agree well with previous observations and idealized model-based vertical structures [Carpenter and Timmermans, 2012, Zhao and Timmermans, 2015, Meneghello et al., 2021].

The definition of the three layers used in the manuscript thus overall arises from *(i)* the mean stratification of the basin, *(ii)* the examination of the variation of eddy metrics across the vertical (Fig. 4) and *(iii)* examining a few eddies vertical extent (Fig. 5). The latter has now also been included at the beginning of the result section of the revised manuscript so as to provide some insights into the vertical structures of detected eddies; and to give confidence in the layer-averaged description of the eddy statistics :

Lines 329-332 : We observe some vertical coherency when looking at a few structures individually, in particular for structures spanning the pycnocline between 70-250 m, or surface *intensified eddies, or eddies spanning the whole water column below 200 m (Fig. 5). This vertical structure is similar to vertical structure obtained from observations [Carpenter and Timmermans, 2012, Zhao and Timmermans, 2015] or predicted from baroclinic instability estimate [Meneghello et al., 2021] in the CB.*

Editor: 1/12 degree is probably not completely sufficient to resolve eddies in the Arctic region and the eddies that are actually detected here might have been mis-represented / mangled already. If the authors go with "high res models are expensive and we have this model handy so we will do it on this as a first try" then sure, but the authors go with "this is a precursor to compare with observations", then a natural question that arises would be whether a comparison is even meaningful at all. The latter stance to me is a problematic one to take with the present dataset; the former stance is at least slightly more defensible.

Authors: We are well aware of the limitations of the 1/12 degree resolution. The choice of the model was motivated by the goal of the paper to investigate the evolution of the number of eddies over the last decades that have seen the most drastic changes in the sea ice state and circulation. The relatively long period of integration of the model not only allows for this investigation but also for a longer period of equilibration of the solution than that performed with fully eddy-resolving models. While the model only resolves the larger scales of the mesoscale spectrum, this part has been shown to contain most of the kinetic energy [65% of the EKE is contained in scales larger than 20km, Liu et al., 2024].

The revised manuscript contains the following additions and modifications to clearly state the limitations of the model in terms of resolution of mesoscale eddies and to motivate the choice of resolution :

- *Lines 147-153 (Method) : This relatively fine horizontal grid size allows for an explicit resolution of most of the mesoscale spectrum within the deep basins where the first Rossby radius of deformation R_o is $\approx 10 - 15$ km, but not over the continental slope and shelf where $R_o < 7$ km [Nurser and Bacon, 2013, see also Fig. S1]. Higher resolution simulations of the Arctic Ocean ($\approx$ 1 km) have shown that the EKE spectrum peaks around 50 km [Li et al., 2024] and that more than 80% (resp. 65%) of the EKE is contained in scales larger than 10 km [resp. 20 km; Liu et al., 2024]. Therefore, we argue that 1/12° is a resolution fine enough to represent most of the mesoscale features in the Beaufort Gyre and along its margins (but not over the shelves), while it runs at a cost that allows for decadal integration.*
- Supplementary materials : A figure (S1) showing the ratio of the first Rossby radius of deformation Ro to the model grid spacing dx is shown (as required by one of the reviewers). It shows that the BG area is resolved with $Ro/dx = 3$ and the Makarov

Basin with $Ro/dx = 2.5$. It also shows that the shelves are resolved with $Ro/dx \leq 1$.

- Discussion : It is now clearly acknowledged that any direct and quantitative comparison with observations is limited by the model resolution that is not high enough to resolve the very small eddies detected by e.g. ITPs (down to 3 km).
  Lines 608-611 : Yet, a proper and detailed comparison with observations would require using a model at higher-resolution given that most features identified with moorings, ITPs or satellite fall between the meso- and the submeso-scales. Such a comparison would also benefit from an adequate model subsampling, through an Observing System Simulation Experiments, to take into account the observations sampling biases.

Editor: Detection methods based on Okubo-Weiss. I have my opinions on Okubo-Weiss as well as Eulerian methodologies but the thing that is sticking out the most is a lack of discussion with other eddy detection methodologies (as raised also by the referees). By all means make a choice, but that choice needs to be evaluated against other known methodologies, and that's not really done here at the moment.
Authors: The justification of why OW was chosen now appears in the method section.
Lines 232-241 : As we aim to detect any vortex-like features that may develop in the Canadian Basin, including those which are not materially coherent, we choose a Eulerian over a Lagrangian approach for detection. The OW-method is based on velocities (u, v) and thus preferable over SSH-based methods for detection in sea ice-covered areas where SSH-based detections are known to miss objects that do not have a surface expression. Additionally, the OW-method has the advantage to be computationally efficient and thus seems well-suited for a detection run for 26 years at each model level between the surface and 1200 m. A comparison of our OW-based detection with those from Nencioli et al. [2010, u, v - based] and Chelton et al. [2011, SSH-based] was performed by Rieck et al. [2025, see their Fig. S3]. They show that the OW-based method detects higher numbers of eddies compared to the other methods, mostly due to its capability to detect weak eddies, i.e. eddies with small rotational velocities and SSH anomaly. This detection bias towards weak eddies is commented in the discussion section.

Editor: Comparison with observations: There was some suggestion the work forms a precursor to comparison with observations, but then do the current results tell us more about where we should observe, what kind of temporal / horizontal / vertical resolution would be need, and whether that provides a logistical constraint on what is observable and what is not?
Authors: Our study provides a continuous and complete eddy census of the Canada Basin over 26 years. Doing so, it confirms at the scale of the basin some of the results based on punctual observations, such as the abundance of eddies all along the continental slope and the

presence of large relatively long-lived eddies within the halocline and at depth in the central basin. Yet, a proper and detailed comparison with observations would require using a model at higher-resolution given that most features identified with moorings and ITPs fall between the meso- and the submeso-scales. Such a comparison would also benefit from an adequate model subsampling, through for e.g. an OSSE, to take into account the observations sampling biases. As mentioned in response to previous comments, we have rewritten the introduction and part of the conclusion and discussion to clarify the goals and implications of the paper. In particular we have removed the following sentences:

- *Introduction : This census aims to facilitate the comparison with observations [...]*
- *Conclusion and discussion: By providing a thorough characterization of eddy properties in the Canada Basin, this model-based eddy census can inform the analyses and interpretation of eddy censuses based on observations and help quantify some of the biases associated to in-situ deployments.*

Editor: I would suggest the authors consider justifying this work in another way, because I think that stance is hindering rather than helping the paper by raising more questions that lead to not very convincing answers...

Authors: The introduction now emphasizes the documentation of the spatio-temporal characteristics of eddies in the Canada Basin and their evolution over the past decades.

Minor comments

Editor: We generally don't like or accept phrases like "The eddy dataset is available upon request" on line 526. If the raw dataset is large then please say so, but minimally the expectation is that a subset of the raw data or the processed data be made available. The review process can continue but is subject to that aforementioned point about data availability be addressed accordingly.

Authors: Unfortunately, the raw dataset is too large (over 50GB) to be stored on public data storage. We now provide on Zenodo a subset of the raw dataset with eddy detection and tracking output for 4 depths (30 m, 70 m, 150 m and 500 m) discussed in the paper.

References

L. Crews, A. Sundfjord, J. Albretsen, and T. Hattermann. Mesoscale Eddy Activity and Transport in the Atlantic Water Inflow Region North of Svalbard. *Journal of Geophysical Research: Oceans*, 123(1):201–215, 2018. ISSN 2169-9291. doi: 10.1002/2017JC013198. URL `https://onlinelibrary.wiley.com/doi/abs/10.1002/2017JC013198`. _eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2017JC013198.

Briac Le Vu, Alexandre Stegner, and Thomas Arsouze. Angular Momentum Eddy Detection and Tracking Algorithm (AMEDA) and Its Application to Coastal Eddy Formation. *Journal of Atmospheric and Oceanic Technology*, 35(4):739–762, April 2018. ISSN 0739-0572, 1520-0426. doi: 10.1175/JTECH-D-17-0010.1. URL `https://journals.ametsoc.org/view/journals/atot/35/4/jtech-d-17-0010.1.xml`.

Francesco Nencioli, Changming Dong, Tommy Dickey, Libe Washburn, and James C. McWilliams. A Vector Geometry–Based Eddy Detection Algorithm and Its Application to a High-Resolution Numerical Model Product and High-Frequency Radar Surface Velocities in the Southern California Bight. *Journal of Atmospheric and Oceanic Technology*, 27 (3):564–579, March 2010. ISSN 1520-0426, 0739-0572. doi: 10.1175/2009JTECHO725.1. URL `http://journals.ametsoc.org/doi/10.1175/2009JTECHO725.1`.

J. R. Carpenter and M.-L. Timmermans. Deep mesoscale eddies in the Canada Basin, Arctic Ocean. *Geophysical Research Letters*, 39(20):2012GL053025, October 2012. ISSN 0094-8276, 1944-8007. doi: 10.1029/2012GL053025. URL `https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2012GL053025`.

Mengnan Zhao and Mary Louise Timmermans. Vertical scales and dynamics of eddies in the Arctic Ocean's Canada Basin. *Journal of Geophysical Research: Oceans*, 120(12):8195–8209, December 2015. ISSN 21699291. doi: 10.1002/2015JC011251. Publisher: Blackwell Publishing Ltd.

Gianluca Meneghello, John Marshall, Camille Lique, L Erik Isachsen, Edward Doddridge, Jean-Michel Campin, Heather Regan, and Claude Talandier. Genesis and Decay of Mesoscale Baroclinic Eddies in the Seasonally Ice-Covered Interior Arctic Ocean. *JOURNAL OF PHYSICAL OCEANOGRAPHY*, 51, 2021.

Caili Liu, Qiang Wang, Sergey Danilov, Nikolay Koldunov, Vasco Müller, Xinyue Li, Dmitry Sidorenko, and Shaoqing Zhang. Spatial Scales of Kinetic Energy in the Arctic Ocean. *Journal of Geophysical Research: Oceans*, 129(3):e2023JC020013, March 2024. ISSN 2169-9275, 2169-9291. doi: 10.1029/2023JC020013. URL https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2023JC020013.

A. J. G. Nurser and S. Bacon. Arctic Ocean Rossby radius Eddy length scales and the Rossby radius in the Arctic Ocean Arctic Ocean Rossby radius. *Ocean Sci. Discuss*, 10:1807–1831, 2013. ISSN 1807-1831. doi: 10.5194/osd-10-1807-2013. URL www.ocean-sci-discuss.net/10/1807/2013/.

Xinyue Li, Qiang Wang, Sergey Danilov, Nikolay Koldunov, Caili Liu, Vasco Müller, Dmitry Sidorenko, and Thomas Jung. Eddy activity in the Arctic Ocean projected to surge in a warming world. *Nature Climate Change*, 14(2):156–162, February 2024. ISSN 1758-6798. doi: 10.1038/s41558-023-01908-w. URL https://www.nature.com/articles/s41558-023-01908-w. Publisher: Nature Publishing Group.

Dudley B. Chelton, Michael G. Schlax, and Roger M. Samelson. Global observations of nonlinear mesoscale eddies. *Progress in Oceanography*, 91(2):167–216, October 2011. ISSN 00796611. doi: 10.1016/j.pocean.2011.01.002. URL https://linkinghub.elsevier.com/retrieve/pii/S0079661111000036.

Jan K. Rieck, Carolina O. Dufour, Louis-Philippe Nadeau, and Andrew F. Thompson. Heat Transport toward Sea Ice by Transient Processes and Coherent Mesoscale Eddies in an Idealized Southern Ocean. *Journal of Physical Oceanography*, 55(4):377–396, April 2025. ISSN 0022-3670, 1520-0485. doi: 10.1175/JPO-D-24-0073.1. URL https://journals.ametsoc.org/view/journals/phoc/55/4/JPO-D-24-0073.1.xml.