Authors responses to reviewer #2 comments

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

Noémie Planat, Carolina O. Dufour, Camille Lique, Jan K. Rieck, Claude Talandier, L. Bruno Tremblay

Manuscript Reference Number: 2025-3527

Date: November 25th, 2025

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

General comments

Reviewer: This manuscript documents the characteristics of mesoscale eddies in the Canadian Basin simulated by a 1/12th deg regional model of the Arctic. While the work has the potential to be a useful contribution, the manuscript in its current form is largely descriptive, and the results presented are not particularly compelling. It is not entirely clear what new physical insights are gained from this study and also what the important implications of the results are.

Authors: We thank the reviewer for their detailed review of the manuscript and insightful suggestions. To address the major concerns of the reviewer on the presentation of the results and on the insights and implications of the study, we have largely modified the structure of the introduction and that of part of the results to better clarify the focus and outcome of the study. We have also rewritten part of the discussion. We believe that these modifications have significantly improved the manuscript. Below, we address all the concerns raised by the reviewer and indicate the changes made to the manuscript.

Reviewer: Importantly, since the study is entirely model based, it is essential to demonstrate that the model simulates the eddy field in the Canadian Basin well by comparing with available observations. At present, the evaluation is very limited: only one figure (Figure 2) shows model-simulated EKE compared with mooring-based estimates at two depths, and the model-data comparison is addressed in a single sentence, which simply states that the agreement is good. This level of validation is insufficient. A more extensive and quantitative comparison with available observations is needed for the simulated eddy field. Without this, readers cannot be confident in the reliability of the subsequent analysis of eddy characteristics from the model output. In fact, Figure 2 shows that there are considerable discrepancies between the simulated and observed EKE.

Authors: We agree with the reviewer that validating the eddy field is key to give confidence in the results of the study. In the revised manuscript, the discussion on the comparison between the mooring-based estimates of EKE (von Appen et al. 2022 dataset) and our model EKE has been extended to better highlight the differences and similarities (see updated text below). We also have extended the evaluation of the mesoscale eddy field of the model by comparing our kinetic energy to Fig. A1 from Meneghello et al. 2021 using a virtual mooring. This figure shows that the vertical levels of energy are similar to the one derived from mooring observations, with sub-surface intensified structures between 30-200 m, and deeper (although weaker) structures between 400-2000 m.

Lines 201-212 : Climatologies of EKE computed relative to monthly means show larger values along the shelf break and along topographic features such as Northwind Ridge, both at *the surface (not shown) and within the pycnocline (Fig. 2a). In contrast, the deep basin is more quiescent, with EKE one to two orders of magnitude lower than on the shelves (Fig. 2a,b). The shelf-deep basin contrast in EKE magnitude is a typical feature of the mooring-based estimates [von Appen et al., 2022]. Yet, the intensity of EKE is about one order of magnitude smaller in our model than that derived from observations [von Appen et al., 2022], as documented previously in Regan et al. [2020]. The MKE, which captures the location of the main currents, is of similar order of magnitude as in observations [von Appen et al., 2022] , with discrepancies being partly attributed to the difference in the exact locations of the main currents between models and observations (Fig. S5). Finally, the vertical structure of the total kinetic energy is similar to that derived from the Beaufort Gyre Exploration Project Moorings [compare Fig. S6 with for instance Fig. A1 from Meneghello et al., 2020] with sub-surface intensified structures between 30-200 m, and deeper (although weaker) structures between 400-2000 m, as evidenced in observations by Carpenter and Timmermans [2012].*

Reviewer: The model stratification differs from climatology (Figure 1). What is the corresponding radius of deformation in the model? Can your model properly resolve it?

Authors: In the revised manuscript, we have added a figure in the appendix (Fig. S1), showing the ratio of the first Rossby radius of deformation Ro to the model grid spacing dx (as also requested by the other reviewer). This figure 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 $Ro/dx \leq 1$. We have added a discussion on the ability of the model to resolve the eddy field in the method section :

Lines 147-153 : 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 (≈ 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.

Reviewer: There are several other eddy detection methods, e.g., contours of SSH anomaly. Could briefly discuss why you choose a method based on the OW parameter and what the advantage of this method is over other existing eddy detection methods.

Authors: We have followed the reviewer's suggestion and have added some discussion on the eddy detection method to 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.

Reviewer: It would be of interest to many readers to see the spatial distribution of EKE in the three layers, as this would bring together information on eddy number and intensity.
Authors: We show in the main manuscript the EKE at 70 and 500 m because these are depths with available observation-based estimates of EKE (Fig. 2). The EKE at 30 m, 70 m, and 150 m is visible on Fig. I, where strong similarities are distinguishable between all layers.

Reviewer: All the trends reported need to be tested for statistical significance.
Authors: We report the decadal change in the number of eddies by comparing the first 5 years with the last 5 years of the simulation, hence no trend is computed. It now appears more clearly at the beginning of Sect. 3.2 :
Lines 473-474 : % changes are computed using averages over the first and last 5 years of the simulation)

Reviewer: The strong reduction in eddy number along the southern edge of the BG is attributed to the stabilizing effect of the continental slope. However, the slope (as indicated by the grey contours) appears to lie south of this region of low eddy number? In addition, why would the stabilizing effect of the slope result in stronger eddy intensity there?
Authors: As suggested by the reviewer, the stabilisation effect of the slope likely occurs close to the slope itself. Offshore, we compute gradients of background potential vorticity ($\partial_{lon} PV$, see Fig. II, or see also Fig. 9 from Meneghello et al. [2021]). The area with decreased eddy density is located where $\partial_{lon} PV$ is minimum, associated to the isopycnal tilting of the gyre.

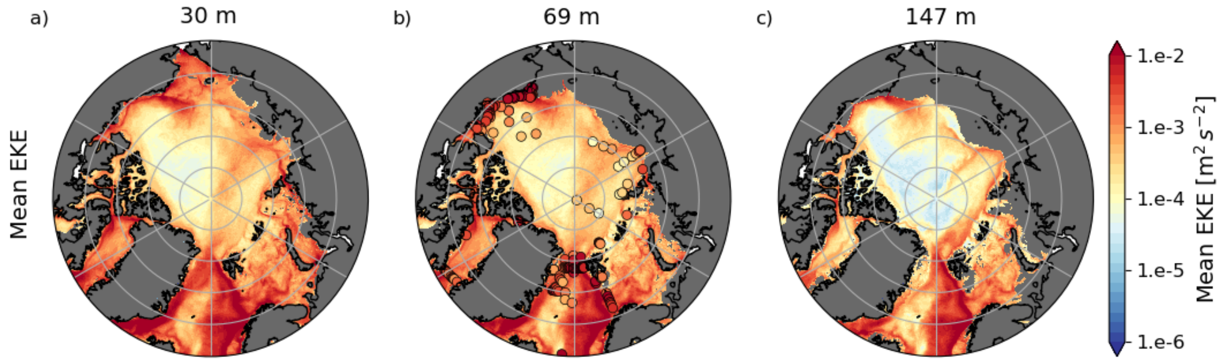

Figure I: Eddy Kinetic Energy (EKE) computed from velocity anomalies with respect to the monthly means in CREG12 and averaged over the 26 years of simulation (a) at 30 m, (b) at 69 m and (c) at 147 m. uper-imposed are mooring-based estimates of EKE fromvon Appen et al. [2022], computed with fourth-order Butterworth filter 2-day to 30-day cutoffs. The reader is referred to von Appen et al. (2022) for exact calculation method.

This indicate diminished baroclinic instabilities and thus likely explain the low eddy density. It now reads in the text :
Lines 428-434 : We suggest that the inner part of this local reduction in eddy generation is linked to a stabilizing effect of the continental slope. The growth of instabilities is known to be hampered over regions where the ratio of the continental slope to the isopycnal slopes is greater than 1 [Manucharyan and Isachsen, 2019], as is the case for the slope of the CB in the model [not shown, see also Regan et al., 2020]. However, this reduction occurs up to 250 km away from the shelfbreak. There, we observed diminished background PV gradients [not shown, see Fig. 9 from Meneghello et al., 2021] associated to diminished baroclinic instabilities, which offer an alternative explanation for the extended area with diminished eddy density.

Minor comments

Reviewer: Line 154. "from R=10 km to 2*pi*R=60 km". Is there a typo here?
Authors: There is no typo here, we adopted the definition of e.g. Tulloch et al. [2011]. However, no vortices are detected with larger radii anyway.

Reviewer: Line 270. Explain why there is a dominance of anticyclones at the very surface within the Canada basin and cyclones within the Chukchi shelf break area in winter?

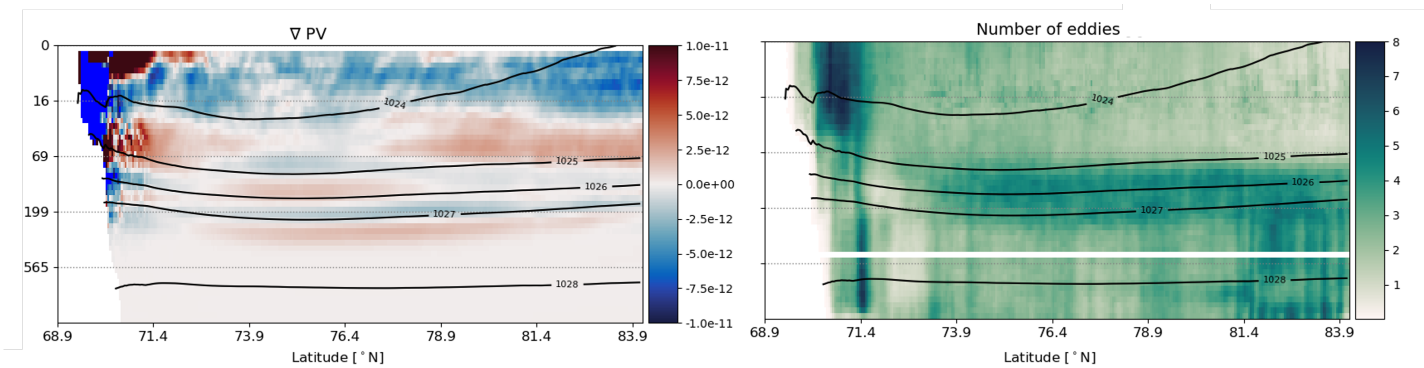

Figure II: (a) Gradient of background potential vorticity computed with respect to the longitudinal direction $\partial_{lon} PV$ along a latitudinal section (see Fig. 1). Plain blue indicate values smaller that $-1 \cdot 10^{-11}$. (b) Number of eddies detected along that section, with 50 km wide longitudinal width.

Authors: We don't have a clear explanation of hypothesis for this feature. We have removed this sentence from the main manuscript.

Reviewer: Line 280. Explain what the theoretical mean turnaround time is and how it is calculated.

Authors: In the revised manuscript, we have added a definition of the turnaround time :
Lines 282-283 : [...] their turnaround time scale, defined as the time it takes for a water parcel to do a full revolution, $\tau = 2\pi/|\Omega|$ [i.e. an approximation of the expression suggested by Smith and Vallis, 2001, that is $\tau = 2\pi/\zeta_{rms}$, where ζ_{rms} is the root-mean-square vorticity.].

Reviewer: Line 298. How is "generation rate" defined?

Authors: Generation rate is used equivalently to eddy density, as it is computed at generation. To avoid any confusion, it does not appear anymore in the text.

Reviewer: Line 329. ... in our domain...

Authors: Done.

Reviewer: Line 335-337. This sentence is not clear, as the expansion of the ice-free area also contributes to increased energy input to the ocean.

Authors: It now reads :
Line 505-509: In the MIZ and open ocean, the increase in eddy generation is mainly a step increase in 2008 with reduced (shut down) interannual variability in the MIZ (Open Ocean) in the following years. This enhancement in the density of the eddy population presumably

results from the additional energy penetrating into the ocean in the recent state of the BG, in light with the current and future projections of Li et al. [2024]. In the open ocean, this accumulation of energy could be attributed to the acceleration of the BG from atmospheric forcings [Giles, 2012], and in the MIZ to a combination of less compacted ice [Martin et al., 2016] or to the thinner ice cover [Muilwijk et al., 2024]. A quantification of these different drivers is beyond the scope of this paper and left for future analysis.

References

Wilken-Jon von Appen, Till M. Baumann, Markus A Janout, Nikolay V. Koldunov, Yueng-Djern Lenn, Robert S. Pickart, and Qiang Wang. Eddies and the Distribution of Eddy Kinetic Energy in the Arctic Ocean. 35(Special issue on the new arctic ocean):42–51, December 2022.

Heather C Regan, Camille Lique, Claude Talandier, and Gianluca Meneghello. Response of Total and Eddy Kinetic Energy to the Recent Spinup of the Beaufort Gyre. *JOURNAL OF PHYSICAL OCEANOGRAPHY*, 50, 2020.

Gianluca Meneghello, Edward Doddridge, John Marshall, Jeffery Scott, and Jean-Michel Campin. Exploring the Role of the "Ice–Ocean Governor" and Mesoscale Eddies in the Equilibration of the Beaufort Gyre: Lessons from Observations. *JOURNAL OF PHYSICAL OCEANOGRAPHY*, 50, 2020.

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.

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.

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.

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.

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.

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.

G. E. Manucharyan and P. E. Isachsen. Critical Role of Continental Slopes in Halocline and Eddy Dynamics of the Ekman-Driven Beaufort Gyre. *Journal of Geophysical Research: Oceans*, 124(4):2679–2696, April 2019. ISSN 21699291. doi: 10.1029/2018JC014624. Publisher: Blackwell Publishing Ltd.

Ross Tulloch, John Marshall, Chris Hill, and K. Shafer Smith. Scales, Growth Rates, and Spectral Fluxes of Baroclinic Instability in the Ocean. *Journal of Physical Oceanography*, 41(6):1057–1076, June 2011. ISSN 0022-3670, 1520-0485. doi: 10.1175/2011JPO4404.1. URL http://journals.ametsoc.org/doi/10.1175/2011JPO4404.1.

K. Shafer Smith and Geoffrey K. Vallis. The Scales and Equilibration of Midocean Eddies: Freely Evolving Flow. *Journal of Physical Oceanography*, 31(2):554–571, February 2001. ISSN 0022-3670, 1520-0485. doi: 10.1175/1520-0485(2001)031¡0554:TSAEOM¿2.0.CO;2. URL http://journals.ametsoc.org/doi/10.1175/1520-0485(2001)031<0554:TSAEOM>2.0.CO;2.

Katharine A Giles. Western Arctic Ocean freshwater storage increased by wind-driven spin-up of the Beaufort Gyre. *NATURE GEOSCIENCE*, 5, 2012.

Torge Martin, Michel Tsamados, David Schroeder, and Daniel L. Feltham. The impact of variable sea ice roughness on changes in Arctic Ocean surface stress: A model study. *Journal of Geophysical Research: Oceans*, 121 (3):1931–1952, 2016. ISSN 2169-9291. doi: 10.1002/2015JC011186. URL https://onlinelibrary.wiley.com/doi/abs/10.1002/2015JC011186. _eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2015JC011186.

Morven Muilwijk, Tore Hattermann, Torge Martin, and Mats A. Granskog. Future sea ice weakening amplifies wind-driven trends in surface stress and Arctic Ocean spin-up. *Nature Communications*, 15(1):6889, August 2024. ISSN 2041-1723. doi: 10.1038/s41467-024-50874-0. URL https://www.nature.com/articles/s41467-024-50874-0.