Reviewer 1

Below, we have provided a response in blue text to each comment. Modifications to the manuscript are provided in quotes with line numbers of the revised manuscript referenced, where possible. New or revised figures are provided in the revised manuscript and supplementary material.

General Comments

The manuscript investigates moderate to severe surface marine heatwaves (MHWs) on the Newfoundland and Labrador Shelf during the summer and fall of 2023. It provides a comprehensive analysis by integrating ocean model reanalysis, in situ observations, and atmospheric data to examine the physical drivers and characteristics of these events. The study identifies key processes, such as increased stratification and reduced vertical mixing caused by calm weather conditions, which contributed to the persistence of surface warming. It also offers valuable insights into the vertical distribution of MHWs and their implications for marine ecosystems. Additionally, the manuscript highlights the utility of ocean model nowcasts and reanalysis products for real-time monitoring and analysis of MHWs.

While the study presents a well-rounded examination, some areas could benefit from further elaboration. These include a quantitative assessment of the role of advection and a deeper contextualization of the findings within broader climate and oceanographic frameworks. The manuscript is generally well-written, with clear and concise language.

Thank you for the feedback on the manuscript. We find the comments constructive and helpful for improving the quality of the manuscript.

Specific Comments

Methods

- Line 93: The text suggests that the thresholds are smoothed using a 31-day rolling mean and not the climatological mean. Was the climatological mean also smoothed, as recommended by Hobday et al. (2016)?

  We did not apply the 31-day rolling mean to the climatological mean. Our interpretation of the Hobday et al. (2016) recommendation was that the smoothing should be applied to the climatological threshold (i.e., the 90th percentile) but that smoothing was not needed for the mean. In turn, we recomputed the climatological means with the 31-day rolling mean and found very small differences in the mean, maximum, and cumulative intensities. In one MHW in the NNS region, the MHW started one day later. There were no other changes to the MHW start date or duration.

The figures and tables have been revised to account for the smoothed climatological mean and we have revised the text as follows: *"The climatological mean and 90th and 10th percentiles were determined using an 11-day window (see Hobday et al. (2016) for details) and the percentiles and climatological mean were smoothed using a 31-day rolling average." (Lines 111-113)*

Results

- **Figure 1**: The bathymetry lines are difficult to discern. Consider using a darker or more distinct color to improve visibility.

  Thank you for the comment and suggestion to improve the figure. We've moved the bathymetry data to a general overview panel in Figure 1. We've retained the region definitions on the marine heat wave map for reference. We believe this modification improves the clarity of the plot while also providing important bathymetric information. See the new Figure 1.

- **Figure 1**: Including an additional panel or a separate figure showing a map of the broader region would provide helpful geographic context. This could include the Labrador Current and bathymetry to frame the study area.

  We agree that a general overview plot describing the broader region and general circulation patterns would be informative. We have incorporated this plot into Figure 1, where we provide the bathymetric data, transect and region definitions, and schematics of the Labrador Current and Gulf Stream.

- **Figure 3**: For Flemish Cap, where samples were taken on different dates inshore and offshore of the 200m isobath, do the reanalysis data align with the AMZP measurements?

  For the reanalysis data, we had calculated the mean anomalies over the two AZMP sampling dates. We made this choice in order to simplify the analysis because there were regions along the transect that were not sampled at all in the summer of 2023. We have now revised the plot so that the reanalysis data at sampled stations align with the AZMP sampling dates. So for stations inshore of 200km, the reanalysis data on July 20 is presented and for stations offshore of 200km, the reanalysis data on July 30 is presented. For the locations along the transect that were not sampled by AZMP in 2023, we present the reanalysis mean over the two sampling dates.

We have updated Figure 3 and revised the caption to include the following:

"For Seal Island, the AZMP occupation occurred on July 25. For Flemish Cap, the stations inshore of 200 km were sampled on July 20 and the others were sampled on July 30. GLORYS12V1 data (product ref. no. 1) matched to the AZMP sampling dates are shown in shaded contours, and AZMP data (product ref. no. 2) are shown in the coloured circles which appear as lines extending from top to bottom." (Lines 211- 214).

and

"For Flemish Cap, GLORSY12V1 data at locations offshore of approximately 400 km, which were not sampled by AZMP in July 2023, are taken as the mean of July 20 and July 30." (Lines 215-216)

- **Figure 3**: The temperature anomaly cross-section along Flemish Cap shows a deepening of positive anomalies offshore. Is this expected? Is it indicative of a specific process?

  There are two deepening patterns. The first is an overall deepening from 10 m to 20 m offshore and corresponds to the depth changes of the climatological warm surface layer (Cyr et al. 2024c, Fig. 27), suggesting that the mixed layer is generally thicker offshore. The second pattern corresponds with sporadic deep anomalies. We have not determined if these deep positive temperature anomalies offshore are related to the surface MHW that occurred at approximately the same time. At Flemish Cap, we note three areas of deep positive temperature anomalies in the GLORYS12V1 contours: one at approximately 400 km, one at approximately 700 km, and one at approximately 800 km. The first two are associated with positive salinity anomalies, which potentially indicates a displacement of the warm, salty slope water transported by the Labrador Current. The process responsible for the anomalies at 800 km is not clear. Given the short format of this article, we decided to focus on the surface MHWs and anomalies and leave the investigation of subsurface and bottom MHWs for future work.

  Additional references

Cyr, F., Coyne, J., Snook, S., Bishop, C., Galbraith, P.S., Chen, N., Han, G.: Physical Oceanographic Conditions on the Newfoundland and Labrador Shelf during 2023, Can. Tech. Rep. Hydrogr. Ocean Sci. 382: iv + 54 p., 2024c.

- The role of advection is mentioned but not directly quantified or illustrated. Hovmöller diagrams of salinity and temperature anomalies along the Labrador Shelf could demonstrate the progression of warm, fresh water during the MHWs.

  Thank you for the suggestion. We agree that the role of advection could be better described with a Hovmöller diagram. We have included this diagram for the SST anomaly, surface FWD anomaly, and stratification for two along-shelf transects, one for the outer shelf and one for the inner shelf (Figure 5). Both transects are shown in the updated Figure 1. Advection is most clearly seen in the FWD anomaly. In the supplementary material, we have included the same diagram for the SST, surface FWD and stratification for both 2023 and the 1993-2022 climatologies (Figures S3 and S4 in supplementary material).

  We have added the following paragraph to the revised manuscript:

  "Finally, the role of advection is illustrated by examining the evolution of surface temperature and freshwater density anomalies as well as the vertical maximum of the squared-buoyancy frequency along the shelf (Fig. 5). First, advection is evident where periods of positive freshwater density anomaly and high stratification that are seen in May through June in the upstream parts of the transects (approximately 0 km to 200 km) gradually propagate downstream. These anomalously fresh conditions arrived at Seal Island by the time of the mid-July MHW, increasing the stratification to above typical conditions (see Fig. S4 for climatological stratification). Throughout the shelf, there is typically a link between periods of increased freshwater density and increased stratification (see Fig. S3 and S4), suggesting advected and/or local fresh water input plays an important role in establishing stratification in this region. Advection may also impact sea surface temperatures through the transport of warm water masses. However, during the July MHW, advection of warm anomalies is not apparent in Fig. 5. Rather, this event was nearly simultaneous and wide-spread across the entire shelf. Advection of warm water may have been a contributor for the September through October MHW downstream of Seal Island, although, a more detailed analysis is warranted in the future." (Lines 260-270)

If available, heat flux anomalies (e.g., latent, sensible, and shortwave radiation) could provide insights into the role of air-sea interactions during the onset of the MHWs. This aligns with the introduction, which suggests atmospheric fluxes are crucial in this region.

Thank you for the suggestion. We have downloaded the suggested heat flux variables from ERA5 in order to document the important role that air-sea interactions play during these events. We have modified Figure 4 to include a time series of the net surface heat flux, Q, which is the sum of the net surface short-wave radiation, net surface long-wave radiation, surface latent heat flux, and surface sensible heat flux. We do not account for the transmission of the short-wave radiation through the mixed layer, as is typically done in mixed-layer temperature budget analyses (e.g., Schlegal et al., 2021). We have also included the time series of each of these components as a plot in the supplementary material (see Figure S2 in supplementary material).

Indeed, the net surface heat flux during the onset of the July MHW was high, approaching the 90^{th} percentile. See the new Figure 4.

We have added the following text to the Methods and Results sections of the revised manuscript:

Methods: *"Additionally, the role of air-sea interaction was examined using the following ERA5 variables: net surface short-wave radiation (Q_swr), net surface long-wave radiation (Q_lwr), surface latent heat flux (Q_lh), and surface sensible heat flux (Q_sh). Following Denexa et al. (2024), the sum of these four components was used to determine the net surface heat flux (Q) and Q_swr was taken as the surface value. All heat flux and radiation variables are positive downwards and represent a daily average. The ERA5 daily averaged 2-metre air temperature was also analysed. Climatologies for all ERA5 variables were calculated in the same way as the MHW climatologies." (Lines 97-102)*

Results: *"Additionally, heat transfer between the ocean and atmosphere is an important element to consider (see Fig. 4 (g) and (h), and Fig. S2). During the July MHW, the 2-metre air temperature from ERA5 was extremely high: at times, it was greater than the annual maximum of the climatological 90th percentile (Fig. 4 (h)). Furthermore, the net surface heat flux was anomalously high during the first few days of the July MHW event but approached anomalously low values as the event reached its end. Similarly, the September and October MHWs exhibited higher than average air temperature and surface heat flux, although not every period in 2023* *with these conditions resulted in a MHW (e.g., mid to late January, mid-May, December)." (Lines 243-248)*

Additional references

Denaxa, D., Korres, G., Bonino, G., Masina, S., and Hatzaki, M.: The role of air–sea heat flux for marine heatwaves in the Mediterranean Sea, in: 8th edition of the Copernicus Ocean State Report (OSR8), edited by: von Schuckmann, K., Moreira, L., Grégoire, M., Marcos, M., Staneva, J., Brasseur, P., Garric, G., Lionello, P., Karstensen, J., and Neukermans, G., Copernicus Publications, State Planet, 4-osr8, 11, https://doi.org/10.5194/sp-4-osr8-11-2024, 2024

- Local atmospheric conditions could be further explored with air temperature anomalies. Data from meteorological stations or reanalysis products like ERA5 might complement the wind data and provide a fuller picture. For example, ERA5 monthly maps suggest positive anomalies in 2m air temperature in August 2023 for the region (see https://climatereanalyzer.org/research_tools/monthly_maps/).

  Indeed, the 2m air temperature was positively anomalous during the MHW periods, particularly for the July MHW (see Figure 4). We have incorporated this additional information in the revised manuscript, as described in the response to a previous comment.

Discussion

- The discussion could benefit from better contextualization of the findings within the framework of previous studies and broader atmospheric and oceanographic patterns. For instance, only three references are cited in the first section of the discussion.

  We have revised the discussion to better place these findings within the context of other studies. For example, we have added the following sentences to the discussion:

  "Recent work by Sun et al. (2024) indicate a strong correlation between changes in the oceanic mixed layer depth and the occurrence of MHWs globally, highlighting an important connection between mixed layer restratification and surface MHWs." (Lines 291-293)

  "Previous work by Schlegel et al. (2021) indicates that latent heat flux is an important driver during the onset of MHWs. Indeed, during the beginning of each

MHW on the NL Shelf in 2023, the net surface heat flux was higher than typical (Fig. 4 (g)) driven by positive anomalies in the surface latent heat flux and the surface long-wave radiation (Fig. S2). Yet, not all periods of anomalously positive net surface heat flux resulted in a MHW, suggesting a combination of oceanic and atmospheric processes are at play in these surface MHWs." (Lines 303-307)

Additional references

Sun, W., Wang, Y., Yang, Y., Yang, J., Ji, J., and Dong, C.: Marine heatwaves/cold-spells associated with mixed layer depth variation globally. Geophy. Res. Lett., 51(24), e2024GL112325, https://doi.org/10.1029/2024GL112325, 2024.

- **Factors Contributing to the 2023 MHWs**:
    - The manuscript mentions the relationship between the North Atlantic Oscillation (NAO) and SST anomalies based on previous studies. Does 2023 align with these observations?

      This is an interesting question, but we have not analyzed the link between SST anomalies and NAO in this manuscript. Typically, negative NAO anomalies are associated with warmer and saltier conditions on the NL Shelf (e.g., Petrie, 2007). Other work by co-authors (Cyr et al., 2024c) suggests that the winter NAO, defined as the average of monthly values from December to March, was normal in 2023. The year 2023 experienced both cold SST anomalies in the spring and warm SST anomalies in the summer and fall. In this case, it is likely that the combination of the normal winter NAO, high summer heat flux, and high stratification explain the high summer and fall SST anomalies. We leave a more detailed analysis of the relationship between the NAO and the 2023 SST anomalies to future work.

      Additional references

      Cyr, F., Coyne, J., Snook, S., Bishop, C., Galbraith, P.S., Chen, N., Han, G.: Physical Oceanographic Conditions on the Newfoundland and Labrador Shelf during 2023, Can. Tech. Rep. Hydrogr. Ocean Sci. 382: iv + 54 p., 2024c.

Petrie, B: Does the north Atlantic oscillation affect hydrographic properties on the Canadian Atlantic continental shelf? Atmosphere-Ocean, 45(3), 141–151, https://doi.org/10.3137/ao.450302, 2007.

- While the introduction highlights the role of air-sea fluxes, this aspect is not thoroughly examined in the study or explored in the discussion.

  We have included the suggested analysis of the air-sea fluxes and have added the following text to the discussion in the revised manuscript:

  "The role of air-sea interactions and heat transfer between the atmosphere and the ocean are also important. During the July MHW, the 2-metre air temperature was extremely high, exceeding the annual maximum of the 1993-2022 climatological 90th percentile for nearly half of the duration of the event. The 2-metre air temperature was also higher than normal during the other MHWs in 2023. Previous work by Schlegel et al. (2021) indicates that latent heat flux is an important driver during the onset of MHWs. Indeed, during the beginning of each MHW on the NL Shelf in 2023, the net surface heat flux was higher than typical (Fig. 4 (g)) driven by positive anomalies in the surface latent heat flux and the surface long-wave radiation (Fig. S2). Yet, not all periods of anomalously positive net surface heat flux resulted in a MHW, suggesting a combination of oceanic and atmospheric processes were at play in these surface MHWs." (Lines 300-307)

- Beyond the factors discussed, are there additional processes or datasets that could provide further insight? Discussing data limitations and future research directions would strengthen this section.

  We have revised parts of the discussion as follows:

  "A more thorough investigation quantifying the magnitude of these factors and relationships with large-scale atmospheric conditions is considered for future work in the NL Shelf region. For instance, a heat budget analysis in the mixed layer (see Oliver et al., 2021 as an example) could quantify the role of various elements such as air-sea interaction, transport, vertical mixing, etc., in establishing MHW conditions. Furthermore, processes such as mesoscale eddies (e.g., Sun et al., 2024) and changes in coastal and shelf-break upwelling (e.g., Reyes-Mendoza et

al., 2022) are likely to influence surface temperatures in the NL Shelf region. Higher resolution modelling experiments could also be used to explore and quantify controls on MHW conditions, particularly when examining shelf-scale processes that are not resolved by or well-constrained by global reanalysis products." (Lines 318-325)

Additional references

Reyes−Mendoza, O., Manta, G., and Carrillo, L.: Marine heatwaves and marine cold-spells on the Yucatan Shelf-break upwelling region, Continental Shelf Research, Volume 239, 104707, https://doi.org/10.1016/j.csr.2022.104707, 2022.

Sun, W., Wang, Y., Yang, Y., Yang, J., Ji, J., and Dong, C.: Marine heatwaves/cold-spells associated with mixed layer depth variation globally. Geophy. Res. Lett., 51(24), e2024GL112325, https://doi.org/10.1029/2024GL112325, 2024.

- **Sensitivity to Climatological Period**: Consider moving this discussion to the results section.

  Thank you for the suggestion. We acknowledge that this section is not a main discussion point, yet we felt it important to include, because of ongoing discussion in the MHW literature on this topic. We have decided to move this section to the Supplementary Material and have provided an important reference (Smith et al., 2025) to provide a rationale for considering this analysis.

  Additional references

Smith, K. E., Sen Gupta, A., Amaya, D., A. Benthuysen, J. A., Burrows, M. T., Capotondi, A., Filbee-Dexter, K., Frölicher, T. L., Hobday, A. J., Holbrook, N. H., Malan, N., Moore, P. J., Oliver, E. C. J., Richaud, B., Salcedo-Castro, J., Smale, D. A., Thomsen, M., and Wernberg, T.: Baseline matters: Challenges and implications of different marine heatwave baselines, Prog. Oceanogr., 231, 103404, https://doi.org/10.1016/j.pocean.2024.103404, 2025.

Reviewer 2

Below, we have provided a response in blue text to each comment. Modifications to the manuscript are provided in quotes with line numbers of the revised manuscript referenced, where possible. New or revised figures are provided in the revised manuscript and supplementary material.

Review: An analysis of the 2023 summer and fall marine heat waves on the Newfoundland and Labrador Shelf: the impact of stratification, winds, and advection

General remarks.

This paper analyses the strong 2023 Marine Heat Wave on the region of Newfoundland and Labrador Shelf including some studies about the stratification, winds, and advection. The paper is interesting, and it could be a great contribution for the regional studies. I find that the paper is lacking depth in some of the sections.

We appreciate the constructive comments on the manuscript, all of which have supported a clearer and more comprehensive revision which now includes Supplementary Material. Below, we have provided a point-by-point response to the numbered comments in the General remarks provided by the reviewer, as well as in-text responses to the other comments.

(1) The introduction is very short, and it does not set the floor for the MHW and the effects of the stratification on them, there is no mention on Ocean Heat Content (OHC). I suggest the authors expand their research about those variables and the vertical structure of marine heatwaves. Additionally, there are several self-cited papers in the introduction, and I believe you could find also alternative references.

To the introduction, we have now included additional references regarding the impact of stratification on MHW as follows:

"Other studies link abrupt sea ice melt and strong stratification with intensified surface MHWs in the Arctic (see e.g. Barkhordarian et al., 2024; Richaud et al., 2024) and recent work by Sun et al. (2024) identifies a strong relationship between mixed layer depth shoaling, restratification, and MHW occurrence globally." (Lines 51-54)

With respect to Ocean Heat Content, we have decided to analyze the vertically averaged temperature instead, which is proportional to the Ocean Heat Content. The temperature is more relevant to studies related to ecosystem impacts. Additionally, we have focused our study on surface MHWs and leave the vertical structure in this region to future work.

We recognize that self-citations can be an issue in situations where authors disregard other relevant work in favor of their own or in situations where self-citations are not relevant to the current study. We don't believe either of those situations apply here. In the paragraph describing the general oceanographic conditions in the study area, we included relevant literature besides studies that have been conducted by the authors (e.g., Templeman 2021; Lazier and Wright, 1993; Fratantoni and Pickart, 2007). The three self-citations describe the interannual variability in the region and the connection to ecosystem characteristics, which are important research topics for the authors' institution. These citations are intended to motivate the current work.

Regardless, there is a wealth of literature regarding the oceanography of the Newfoundland and Labrador Shelf and we have now included some additional recent and relevant studies. The revisions are described in the inline responses below.

Additional references

Sun, W., Wang, Y., Yang, Y., Yang, J., Ji, J., and Dong, C.: Marine heatwaves/cold-spells associated with mixed layer depth variation globally. Geophy. Res. Lett., 51(24), e2024GL112325, https://doi.org/10.1029/2024GL112325, 2024.

(2) The figures are nice, and I think the maps could represent most of the studies shown here; however, some of the colours are not visible, such as the isobaths. I recommend the labels outside of the Figure 1a since it takes over the data that is supposed to be observed.

Thank for suggesting improvements to the figures. We have revised Figure 1 to include a general overview plot with bathymetry information, transect and region definitions, and schematics of the general circulation. We have removed bathymetry contours from other plots in order to improve their clarity.

(3) Since you are basing a lot of your work on Glorys, you should extract the most out of it. For example, I would like to see a trend on the SST for the years you are studying over the NL region, also a trend on the subsurface heat content and the freshwater content. Your definition could be used for this. Additionally, the stratification is often split on the text on temperature driven and salinity driven, sometimes those two compensate and may differ from your conclusions. If you add a section on this stratification, I believe you will make this important component very clear.

The 1993-2023 times series of the SST anomaly, 0 to 20m vertically averaged temperature anomaly, and 0 to 20 m freshwater density anomaly are now available in the Supplementary Material (Figure S1)

We have also included a new stratification plot along the Flemish Cap and Seal Island transects (Figure 3 (e) and (f)) and a Hovmöller diagram showing how the stratification evolves along the shelf with temperature and salinity anomalies (Figure 5). These additions are discussed in more detail in a response to a later comment.

Finally, we have added a discussion on temperature and salinity contributions to the stratification in the Supplementary Material (Figures S6 and S7) which is discussed in more detail in response to a later comment.

(4) The title mentioned advection and I cannot really see any estimates of this, in the comments I have attached I suggested a couple of metrics that could be done.

Thank you for the comments regarding advection. We have revised the manuscript title to remove emphasis on stratification, winds and advection. The new title is *"An analysis of the 2023 summer and fall marine heat waves on the Newfoundland and Labrador Shelf".*

We have also included a new figure (Figure 5) which is a Hovmöller diagram of the SST anomaly, surface FWD anomaly, and stratification along the NL Shelf to demonstrate advective pathways. In the supplementary material, we provide Hovmöller diagrams of the 2023 SST, surface FWD, and stratification as well as the 1993-2022 climatologies (Figures S3, S4). These figures elucidate the role of freshwater advection in the region and its impact on stratification.

(5) The section of sensitivity feels a little out of place from the main body of the paper, I suggest that is sent to the supplementary material.

We have moved the section on sensitivity to the climatological period to the Supplementary Material.

(6) The correlation with productivity is very weak and I suggest adding some data about the phytoplankton blooms and things like that, it is rather qualitatively, and I think you have some tools to quantify this.

We have reduced the discussion on productivity and leave this as an area for future work. The subsection on Connection with the ecosystem has been replaced with following paragraph:

"Finally, impacts of MHWs on the NL Shelf ecosystem is an important area for future work. One area of interest is the vertical distribution of MHWs (e.g., Fig. S5) because not all elements of the marine ecosystem are impacted by high sea surface temperatures. Furthermore, regional differences in MHW intensity, frequency, and duration are important elements when considering ecosystem impacts. Tools such as ocean model reanalyses, analyses, and forecasts can aid in near real-time monitoring by linking surface MHWs with vertical characteristics such as stratification and by exploring spatial structures in remote areas that are difficult to study directly with observations. These results suggest that ocean model nowcast and reanalysis products can complement observational methods for studying MHWs in near-real time over large geographic areas and at multiple depths." (Lines 327-334).

Particular points:

L42: how is this anomaly on heat flux expressed, it is unclear.

In the study referenced, the air-sea heat flux is represented as a sum of the surface short-wave radiation, surface long-wave radiation, surface sensible heat flux, and surface latent heat flux all divided by product of the sea water density, sea water specific heat capacity, and mixed layer depth. The anomaly is the departure from a climatological state. Given the constraints on the manuscript length, we have opted to leave it up to the reader to look up those details in the cited study.

L43: this part seems like suggestions, and we cannot really know what was the study about, if this is numerical models/observations/hybrid?

We have revised to *"… but that the decay is more often associated with oceanic processes like advection and mixing." (Lines 45-46)*

And we have added some context into the type of data used in this study:

"Schlegel et al. (2021) applied statistical methods to a combination of remotely-sensed sea surface temperature data and atmospheric and oceanic reanalyses to link latent heat flux…" (Lines 42-42)

L53-L56: References on those lines are self-referenced to the co-authors. I am wondering if the authors could add more references that are not their own.

We have rephrased these lines as follows: *"The region undergoes interannual variability cycling through warm and cold phases associated with changes in air temperature, sea ice conditions, and climate indices such as the NAO (Petrie, 2007; Urrego-Blanco and Sheng, 2012; Han et al., 2019; Cyr and Galbraith, 2021). These warm and cold phases are linked to* *marine ecosystem characteristics such as the timing of the spring phytoplankton bloom and primary and secondary productivity (Cyr et al., 2024a), as well as the productivity of higher trophic levels (Cyr et al., 2024b). Variability in the offshore transport of the Labrador Current (e.g., Jutras et al., 2023) is also linked with ecosystem characteristics such as marine bivalve growth as suggested by Poitevin et al. (2019). Seasonal ice cover in the region has important implications for stratification, and in turn, primary productivity (e.g., Wu et al., 2007)." (Lines 60-67)*

Additional references

Han, G., Ma Z., and Chen, N.: Ocean climate variability off Newfoundland and Labrador over 1979–2010: A modelling approach, Ocean Modelling,144, 101505, https://doi.org/10.1016/j.ocemod.2019.101505, 2019.

Jutras, M., Dufour, C.O., Mucci, A., and Talbot, L.C. : Large-scale control of the retroflection of the Labrador Current, Nat. Commun., 14, 2623, https://doi.org/10.1038/s41467-023-38321-y, 2023.

Petrie, B: Does the north Atlantic oscillation affect hydrographic properties on the Canadian Atlantic continental shelf? Atmosphere-Ocean, 45(3), 141–151, https://doi.org/10.3137/ao.450302, 2007.

Poitevin P., Thébault J., Siebert V., Donnet S., Archambault P., Doré J., Chauvaud L., and Lazure P.: Growth Response of Arctica Islandica to North Atlantic Oceanographic Conditions Since 1850, Front. Mar. Sci. 6:483. doi: 10.3389/fmars.2019.00483, 2019.

Urrego-Blanco, J., and Sheng, J.: Interannual Variability of the Circulation over the Eastern Canadian Shelf. Atmosphere-Ocean, 50(3), 277–300. https://doi.org/10.1080/07055900.2012.680430, 2012.

L70: I would like to know why you use this factor modifying the salinity. Is this a common practice on reanalysis products such as Glorys?

The recommendation by McDougall et al. (2021) to treat EOS-80 ocean model prognostic variables as Conservative Temperature and Preformed Salinity scaled by u_ps applies to models with long spin-up periods, such as climate-based simulations. GLORYS12V1, however, regularly assimilates observed data and does not have a long spin-up period. Regardless, because GLORYS12V1 uses the EOS-80 equation of state, which incorrectly represents Potential Temperature and Practical Salinity as conservative variables, there is a discrepancy when comparing these variables directly with observations. That discrepancy is not fully resolved by following the McDougall et al. (2021) recommendation because of the data assimilation. So we are left with an inconsistency no matter how we interpret the GLORYS12V1 variables. We have opted to follow the McDougall et al. (2021) recommendations anyways to build awareness of these issues in the ocean modelling community. On the NL Shelf, any errors introduced by this interpretation are expected to be small. See Andres et al. (2024) for a more complete discussion.

Reference

Andres, H. J, Soontiens, N., Penney, J., and Cyr, F.: Seasonal variations of the cold intermediate layer on the Newfoundland and Labrador Shelf, Progress in Oceanography. Volume 229, 103379, https://doi.org/10.1016/j.pocean.2024.103379, 2024.

L76: what does it mean a high frequency station?

Rephrased to *"high-frequency sampling station"* to emphasize that this station is sampled more often than other places on the NL Shelf. *(Line 90).*

L81: I think the products used in this work could be named explicitly even they are on the table. Those products are well known by the community, and it is quite distractive to go to the table. For instance: "10m winds were obtained from ERA5 (Table 1)…."

We appreciate the suggestion to improve the clarity and readability of the manuscript. We are, however, required to follow specific style guidelines for the Copernicus Ocean State Report 9 where datasets are all described in Table 1 and referenced by the product number in the text. Regardless, we have attempted to follow this suggestion by referring to both the product number and conventional name (e.g. ERA5, GLORYS12V1) in the text.

L83: It is uncleared how is a rolling mean that aligned with the MHW, we do not know yet what is the duration of MHW. Also, if it is a rolling window, it would span all the timeseries with a smoothing of 11 days so it would always align with the whole time series, or is the size of the window the one meant to aligned? This is also a bit confusing as a MHW definition has 5 days of persistent excess of temperature, would you only look at 11 days MHW?

We recognize that the phrasing of this sentence has caused some confusion. We were attempting to justify the choice of an 11-day rolling average for the wind time series which was selected to smooth out high-frequency variability and is also consistent with the 11-day averaging window used in the MHW definition. We have removed this sentence to avoid this confusion.

L86: The description of Table 1 could be a bit more descriptive.

We have revised the caption to: *"Table 1: Overview of the data products used in this study." (Line 104)*

L110: Was the calculated stratification not smoothed? This quantity could be a bit noisy and hard to identify a single maximum value unless is in a context of spatial or temporal average. Was there any particular treatment performed on this variable?

For the squared-buoyancy frequency calculated from GLORYS12V1, no smoothing was performed because we did not find this field particularly noisy (see revised Figure 3). When computing the maximum squared-buoyancy frequency from the AZMP profiles, we first interpolated the temperature and salinity fields to the GLORSY12V1 depth levels, then we calculated the squared-buoyancy frequency, then we computed the vertical maximum. Interpolating to the coarser GLORYS12V1 depths was a form of smoothing. We have rephrased as follows:

"First, the stratification was assessed by calculating the squared-buoyancy frequency, (N^(2) (z)) over the entire water column using the GSW Oceanographic Toolbox (McDougall and Barker, 2011) and then, its vertical maximum, N_max^2, was used as a measure of stratification. A large value indicates strong stratification which can limit the vertical exchange of heat and salt content. This quantity was analysed as a spatial average over each region and at the grid cell closest to Station 27 where comparisons with observed data were made. In order to compare modelled and observed profiles of N^(2) (z) at Station 27, the temperature and salinity fields were first interpolated to GLORYS12V1 depth levels, then N^(2) (z) was calculated, and then its vertical maximum was determined. " (Lines 131-137)

L113: Why was 20m chosen as the upper-most part to use estimate both temperature and freshwater content?

We chose 20 m because it is the approximate lower bound of the stratified part of the water column in the summer (see stratification plots in Figure 3 (e) and (f)). We have also provided time series of these variables over other parts of the water column at Flemish Cap and Seal Island in the supplementary material (Figure S5).

We have revised this line as follows: *"Second, the depth-averaged temperature and freshwater density were used to examine the daily time evolution of temperature and freshwater content in the uppermost 20 m spatially averaged over the NL Shelf region (see Supplementary Material Fig. S5 for additional depth bins)." (Lines 139-141)*

L139-140: Figure 1 is a great plot, I have a bit hard time looking at the isobaths, could you perhaps change the colors for them? Particularly hard to see on Fig1,b. Also, why is the licensed information important?

Thank you for the comment. We agree that the isobaths were difficult to see. In our revision, we have provided the bathymetry information in a general overview panel in Figure 1 and have removed the isobaths from these plots. We have retained the region definitions as a point of reference. We believe these changes have improved the clarity of the plot. (see Figure 1)

The license information pertains to the Ecosystem Production Units (https://open.canada.ca/data/en/dataset/9a515ef8-0e2a-479e-9b25-55658eae30be) which were used to define the analysis sub-regions. We are following the recommended attribution statement under the Open Government License – Canada.

L150: Table two is a nice table I would recommend making ts and te a bit more explicit as well as D(days) as MHW days? Or something like that. Also what does the variable ***icum*** **(℃ days)** mean? I cannot see any discussion about this, and it would be great what is the meaning or the purpose of using this metric. It remains to me unclear how is N2 estimated, is this for every single profile, since you mention is both space and time average (time over the MHW) are you using Glorys? If not, what is the standard deviation from your datasets?

Thank you. We have revised the table headers to Start date (ts), End date (te) and D MHW days. To better describe the metrics, we have revised the methods section as follows: *"Some additional MHW metrics, including the start and end dates (ts and te), duration or number of MHW days (D), and mean, maximum, and cumulative intensities (imean, imax, icum), respectively, suggested by Hobday et al. (2016) are reported in Table 2. The mean intensity is the mean of the temperature anomaly, the maximum intensity is the maximum of the temperature anomaly, and the cumulative intensity is the integrated daily temperature anomaly over the MHW period." (Lines 123-127)*

With respect to N2, for each day we calculate the vertical maximum at every GLORYS12V1 grid cell, then we average that value over all grid cells in the area of interest, then we perform a time average over the MWH period. We felt this more appropriate than spatially averaging the salinity and temperature fields first, and then calculating the vertical maximum of N2 because it allows us to describe the spatial variability of the stratification as in the new Figure 5. For example, during the July MHW over the shelf, vertical maximum of N2 is strongest and most variable in coastal areas of the NNS region.

We have clarified the calculation of N2 in response to a previous comment.

L168-169: I find that the addition of Sea Ice extent until this moment not appropriate. I would think that sea ice is an important variable for this region. It is likely that it has a large influence on the stratification and so on. Would it make sense to include it in the climatology?

We have provided a reference to the impact of the seasonal sea ice cover on the stratification in the introduction*: "Seasonal ice cover in the region has important implications for stratification, and in turn, primary productivity (e.g., Wu et al., 2007)." (Lines 66-67)*

We have also added a time series of the Sea Ice Volume over the NL Shelf and its climatology to Figure 4 (e). Some other relevant variables such as the ERA5 net surface heat flux and the 2-metre air temperature are also included.

L172: we cannot see the unusual cold spring, you have the data from that month, maybe worth to add this in a supplementary material.

The unusually cold spring is evident in the cold SST anomalies from May and June in Figure 2 (a) and (b).

We have now referenced that figure in the text: *"In addition to unusually cold spring SSTs (Fig. 2 (a)-(b)), …" (Line 202)*

L174: not clear what does it mean the signal at depth, which depth?

Rephrased to *"Both transects displayed a very warm surface layer reaching to approximately 10 m in depth." (Line 204)*

L180: recommend start the plot by mention it is a vertical section of temperature and salinity (this is just as style but recommended).

Thank you for the suggestion. We have rephrased this line as follows: *"Figure 3: Vertical cross section of temperature anomalies (top), salinity anomalies (middle), … " (Line 210)*

L188: I think authors should include the stratification plot in Figure 3, this will make their point more explicit. Additionally, I suggest adding the Mixed Layer Depth as a dashed line in the plots.

Thank you for the suggestion. We have updated Figure 3 to include the vertical cross section of the squared-buoyancy frequency from GLORYS12V1 and AZMP data, as well as the mixed layer depth from GLORYS12V1 as a grey line.

We have added the following text to the manuscript: *"The squared-buoyancy frequency and mixed layer depth during those occupations, shown in Fig. 3 (e) and (f), indicate stratified conditions in the upper 20 m of the water column." (Lines 222-223)*

L190: The discussion about stratification looks very appropriate and I do believe that adding the section with stratification to it would benefit this discussion, which I think it is a great finding.

In the supplementary material, we have computed the temperature and salinity contributions to the stratification as follows:

$N_T^2 (z) \simeq -g\alpha\, \partial T/\partial z$,

$N_S^2 (z) \simeq g\beta\, \partial S/\partial z$,

where α and β are the coefficients of thermal expansion and haline contraction, respectively, g is the acceleration due to gravity, T and S are the conservative temperature and absolute salinity from GLORYS12. We then evaluate these quantities at the depth of maximum squared-buoyancy frequency (N^2_{max}) and then interpolate to the Outer and Inner Shelf transects. The results are shown in Figure S6. 1993-2022 climatological fields are shown in Figure S7.

We have included the following description in the Supplementary Material and reference this figure on this line in the revised manuscript.

"5 Temperature and salinity contributions to stratification

Temperature ($N_T^2 (z)$) and salinity ($N_S^2 (z)$) contributions to the stratification were approximated as follows (see e.g., Cyr et al., 2024):

$N_T^2 (z) \simeq -g\alpha\, \partial T/\partial z$,

$N_S^2 (z) \simeq g\beta\, \partial S/\partial z$,

where α and β are the coefficients of thermal expansion and haline contraction, respectively, g is the acceleration due to gravity, T and S are the conservative temperature and absolute salinity. We computed $N_T^2 (z)$ and salinity $N_S^2 (z)$ to determine if changes in the squared-buoyancy frequency were driven by changes in temperature or salinity. Calculations for α, β, and g were carried out using the Python implementation of the Gibbs-Seawater (GSW) Oceanographic Toolbox (McDougall and Barker, 2011) at every grid cell in the GLORYS12V1 domain. The GLORYS12V1 (product ref. no. 1) temperature and salinity outputs were interpreted as conservative temperature and preformed salinity scaled by a factor of *u_ps =35.16504/35g kg-1 and absolute salinity was calculated using GSW. Vertical temperature and salinity gradients were calculated using a second-order central differences approximation, except at the upper and lower boundaries where a first-order approximation was employed. Then, N_T^2 (z) and N_S^2 (z) were evaluated at the depth where the squared-buoyancy frequency, N^2 (z), attains its maximum (N_max^2,). Values are linearly interpolated to the Outer and Inner Shelf transects and compared with N_max^2 (Fig. S6 for 2023, Fig. S7 for the 1993-2022 climatologies). Vertical salinity gradients were estimated to be the larger contributor to the stratification for the upstream portions of the transect (e.g., upstream of Seal Island, particularly for the Inner Shelf). For downstream regions in 2023, the vertical temperature gradients were the leading contributor to the stratification during the July MHW."*

L195: The source of freshwater anomaly should be discussed further, I believe the authors should propose a mechanism for it, this would be very useful for this manuscript.

We agree that the source of the freshwater anomaly is an interesting and important question. Answering that question is not the focus of this study so we have included some references in the discussion that provide a possible explanation for the freshening trend in recent years. The text reads as follows:

"Although the source of these fresh conditions was not analysed in this work, other studies suggest that increased Arctic sea ice melt and freshwater release from the Beaufort Gyre are responsible for recent freshening trends in the North Atlantic (Wang et al., 2024; Yashayaev, 2024)." (Lines 284-286)

Additional references

Wang, Q., Danilov, S., and Jung, T: Arctic freshwater anomaly transiting to the North Atlantic delayed within a buffer zone. Nat. Geosci. 17, 1218–1221, https://doi.org/10.1038/s41561-024-01592-1, 2024.

Yashayaev, I.: Intensification and shutdown of deep convection in the Labrador Sea were caused by changes in atmospheric and freshwater dynamics. Commun Earth Environ 5, 156, https://doi.org/10.1038/s43247-024-01296-9, 2024.

L197: Indeed, wind speeds are probably very well related to this event, but heat flux should be the one reported too… Additionally, is there anything related with coastal upwelling due to wind? Additionally, is there any delay on the occurrence of low winds and the MHW? Similar comment for lines 223-225 about the winds.

Indeed, the air-sea heat flux is an important variable to consider. We have included the ERA5 net surface heat flux, which is the sum of the net surface short-wave radiation, net surface long-wave radiation, surface sensible heat flux, and surface latent heat flux, to Figure 4.

There may be a delay between the onset of low winds and the occurrence of the MHW, however, it is difficult to be certain. In Figure 4 (f), the lowest wind speeds typically precede or coincide with the MHW start date, however, there are some caveats to consider. For one, the MHW was analyzed over the entire NL Shelf region while the winds were analyzed at Station 27 to give a general picture of the large-scale atmospheric conditions. A more detailed analysis reconciling the spatial and temporal differences in these variables could be considered for future work.

We have not analyzed any wind-induced coastal upwelling dynamics for this manuscript. While coastal upwelling may indeed impact sea surface temperatures near the coast, we have focused our analysis across the entire shelf. We leave an exploration of wind-induced coastal upwelling as an area of future work, which has been added to the discussion:

"Furthermore, processes such as mesoscale eddies (e.g., Sun et al., 2024) and changes in coastal and shelf-break upwelling (e.g., Reyes-Mendoza et al., 2022) are likely to influence surface temperatures in the NL Shelf region. Higher resolution modelling experiments could also be used to explore and quantify controls on MHW conditions, particularly when examining shelf-scale processes that are not resolved by or well-constrained by global reanalysis products." (Lines 321-325)

Additional references

Reyes−Mendoza, O., Manta, G., and Carrillo, L.: Marine heatwaves and marine cold-spells on the Yucatan Shelf-break upwelling region, Continental Shelf Research, Volume 239, 104707, https://doi.org/10.1016/j.csr.2022.104707, 2022.

Sun, W., Wang, Y., Yang, Y., Yang, J., Ji, J., and Dong, C.: Marine heatwaves/cold-spells associated with mixed layer depth variation globally. Geophy. Res. Lett., 51(24), e2024GL112325, https://doi.org/10.1029/2024GL112325, 2024.

L209: Again, I suggest writing Glory's and not the product referenced on table 1.

Thank you for the suggestion to improve the clarity of the manuscript. We have included references to GLORYS12V1 where appropriate. In addition, we have kept the reference to the product numbers in Table 1 in order to comply with the Copernicus Ocean State Report 9 style conventions.

L211-213: Why don't you add the stratification from Glorys?

The 2023 GLORYS12V1 stratification (represented by maximum squared-buoyancy frequency) is provided in the blue line in Figure 4 (b). The climatological mean from GLORYS12V1 is in black and its 10th and 90th percentiles are in grey dashed.

We have clarified the caption as follows: *"Figure 4: Time series plots for 2023 in blue, the 1993-2022 climatology in black, and the 1993-2022 10th and 90th percentiles in grey dashed lines. Variables from GLORYS12V1 (product ref. no. 1) are (a) sea surface temperature averaged over the NL Shelf, (b) maximum squared-buoyancy frequency at Station 27, (c) depth-averaged temperature from 0-20m averaged over the NL Shelf, (d) freshwater density from 0-20m averaged over the NL Shelf, and e) sea ice volume over the NL Shelf. ERA5 (product ref. no. 3) variables include (f) 10-metre wind speed at Station 27, (g) net daily-average, surface heat flux averaged over the NL Shelf (where positive indicates a downward flux), and (h) 2-metre air temperature averaged over the NL Shelf. Maximum squared-buoyancy frequency data at Station 27 from AZMP (product ref. no. 2) are shown in b) for 2023 in large dark brown dots and for 1993-2022 in small light brown dots." (Lines 251-258)*

L218-220: Was the fresh core below the surface after the warming in July, this paragraph suggest that it is not a simultaneous process, I understood previously that this was simultaneous.

In Figure S5 (d), the freshwater density anomalies from 0 to 20m along the Flemish Cap transect approach the 90th percentile a few days before the July MHW occurs along the transect. The fresh conditions in this layer persisted until November 2023. This suggests the anomalously fresh conditions slightly precede the MHW.

L229-230: The statement about advection could potentially be solved with the use of Glorys, one could estimate the transport that goes between regions, and this could show this heat transport or even the freshwater transport.

We appreciate the suggestion to consider heat and freshwater transport to analyze the role of advection. We have expanded our discussion of advection by including Hovmöller diagrams of SST anomaly, surface FWD anomaly, and stratification for two along-shelf transects (see Figure 5). Given the short format of the manuscript, we leave the analysis of ocean heat and freshwater transport for future work and highlighted that point in the discussion:

“For instance, a heat budget analysis in the mixed layer (see Oliver et al., 2021 as an example) could quantify the role of various elements such as air-sea interaction, transport, vertical mixing, etc., in establishing MHW conditions.” (Lines 319-321)

Major comments:

Figure 5 is a great schematic, but I think that using only fresh water is quite incomplete. Assuming that atmospheric forcings are the same one would have to look at stratification with both temperature and salinity. Moreover, if one only looks at freshwater, i.e., salinity only, then heat fluxes does not do much mixing other than evaporation and making the layers saltier; thus, one will have to use both statements that this paper has talked about earlier. I suggest modifying this schematic to something with stratification.

Thank you for the suggestion and for highlighting the important role that vertical temperature gradients play in establishing stratification. We have revised this figure (now Figure 6) by removing the emphasis on freshwater in establishing stratification.

The section of sensitivity to climatological period is quite incomplete and not clear at all. It is lacking supporting figures. I suggest the authors make a correlation of the climatology with other indices such as AMO, NAO, SPG or other indices that show those periods mentioned here. Perhaps even the coauthors could think about removing this section, which is not relevant to the study presented here. Moreover, there is no link to this on the introduction, if previous studies have been done on it should be also mention on the introduction.

We agree that the motivation for this section was not clear and that it is not a main finding in the manuscript. We included this section because the choice of the climatological period can influence whether or not a MHW is detected. We were attempting to describe the sensitivity of our results to that choice. It was not our intent to link our findings to other climate indices as suggested by the referee. That effort, while interesting, is outside of the scope of our study.

We have clarified the motivation for this section by including some references describing the sensitivity of MHW to the climatological period. We have also moved this section to supplementary material.

Additional references

Smith, K. E., Sen Gupta, A., Amaya, D., A. Benthuysen, J. A., Burrows, M. T., Capotondi, A., Filbee-Dexter, K., Frölicher, T. L., Hobday, A. J., Holbrook, N. H., Malan, N., Moore, P. J., Oliver, E. C. J., Richaud, B., Salcedo-Castro, J., Smale, D. A., Thomsen, M., and

Wernberg, T.: Baseline matters: Challenges and implications of different marine heatwave baselines, Prog. Oceanogr., 231, 103404, https://doi.org/10.1016/j.pocean.2024.103404, 2025.

Similarly, the following section of connection to the ecosystem lacks information in the introduction.

We have reduced the discussion on the connection to the ecosystem and leave this as an area for future work. See the response to a previous comment.

L257-258: The timing of the blooming could also use some of the data from Glorys, the products from Copernicus could help to show this and maybe add this to the supplementary material. Finally, I think that a lot of the references are based on the list of coauthors and seems this could bias the research work.

We agree that there are several Copernicus products that could be used to explore primary productivity and bloom timing, however, to our knowledge, the suitability of those products in this region has not been evaluated. We are also facing space constraints for this manuscript and feel that adding additional analysis on the primary productivity, including a careful evaluation of the Copernicus products, is outside of the scope of our study. Instead, we have reduced the discussion on the bloom timing and leave this question for future research.