We (the authors) present the referee responses in **bold** font while author responses will be in regular font. We only repost referee comments which contain suggestions. We also indicate the line number where some text was added/modified according to the new manuscript. We will type the line number in bold following our response to the comment. A marked manuscript follows where modifications from the original submission are shown in red text. We didn't activate 'track changes' until after we submitted our response to the online discussion and learned about the 'track changes' requirement. We had already made significant changes by that point.

Clark Pennelly and Paul G. Myers

Referee comment #1 (Anonymous)

2 Specific comments

62-66: In this sentence, I find it difficult that you 1) use model results only to explain a real world phenomenon and 2) cite yourself only.

We have included an additional 2 references, one using model results and the other an observational study. These studies investigated freshwater that enters the interior Labrador Sea, discussing freshwater pulses and their likely exchange from shelf to deep basin (observational study, Schmidt and Send 2007) or freshwater which leaves the Labrador Current (model study, McGeehan and Maslowski, 2011): **L71 and L72**

73-77: There are other model studies showing the opposite, see e.g. Cael and Jansen (2020) and references therein.

Added 2 citations (Cael and Jansen 2020 as well as Latif et al 2000) and text that discuss that while freshwater addition local to the Labrador Sea reduces convection and AMOC strength, freshwater addition that is non-local to the Labrador Sea drives the opposite: **L83-L88**

130: It is not discussed at all why a factor of 5 is used to obtain the 1/60◦ horizontal resolution. Please add this.

We state that the factor of 5 is used to change the resolution from 1/12 to 1/60: **L149**

Fig. 3 and 4: The LAB60 North Atlantic Current seems to be less vivid and eddy-rich compared to both ANHA12 and AVISO. Can you discuss this?

We add some discussion about why the North Atlantic Current seems less vivid and eddy-rich. We suspect it might have to do with the nested boundary, but other aspects of this simulation close to the remaining boundaries appear fine. We have later plans to investigate downstream influences of the LAB60 simulation in the SPG12 and ANHA4 domain: **L423-L432**

The "Discussion" section is rather a summary than a discussion. A discussion section is not explicitly required (https://www.geoscientific-model-development.net/for_ authors/manuscript_preparation.html → Manuscript composition), so either rename the section or add a discussion. Personally, I would like to see a discussion. For instance, the videos indicate that the LAB60 setup exhibits a model drift and is far from equilibrium (drag the slider of the video player with the mouse from start to end rather fast and you can see a large-scale accumulation of the runoff and Irminger Water tracers in the respective videos). Would a potential model drift influence the LSW time series or the described eddy dynamics? In addition, the shown model data is particularly suited to discuss ongoing questions about meso- and submesoscale energy transfers during convective/unstable situations. Furthermore, your results indicate that even if an ocean model performs under a high spatial resolution, buoyant water needs to be provided by e.g. the boundary current in the first place to be available for eddies. If this is the case, a nested model configuration like the presented one would have a severe handicap given the coarser resolutions of the parents which provide the boundary current.

We have added 2 paragraphs to the discussion section that discuss model drift, Labrador Sea Water, potential boundary issues as well as others who have ran simulations of varying resolution within the Labrador Sea, particularly with the passive tracers as we use. We show that the model drift is significantly smaller in this configuration compared to ¼ and 1/12 degree via a new figure: **L417-440**

3 Technical corrections

• sections are not numbered

Sections are now numbered

• its de Steur et al. 2009 (not 2018), Treguier (not Trequier) and Yashayaev (not Yashauaev); Fi* references not in alphabetical order

We have corrected these (and some other) references/citations

• 125 & 130: Please specify "temporal refinement".

We help describe what 'temporal refinement' means by including the time step for all domains in this section: **L143 and :149**

• Table 2: Please reference LIM2 and CORE as you did for other settings.

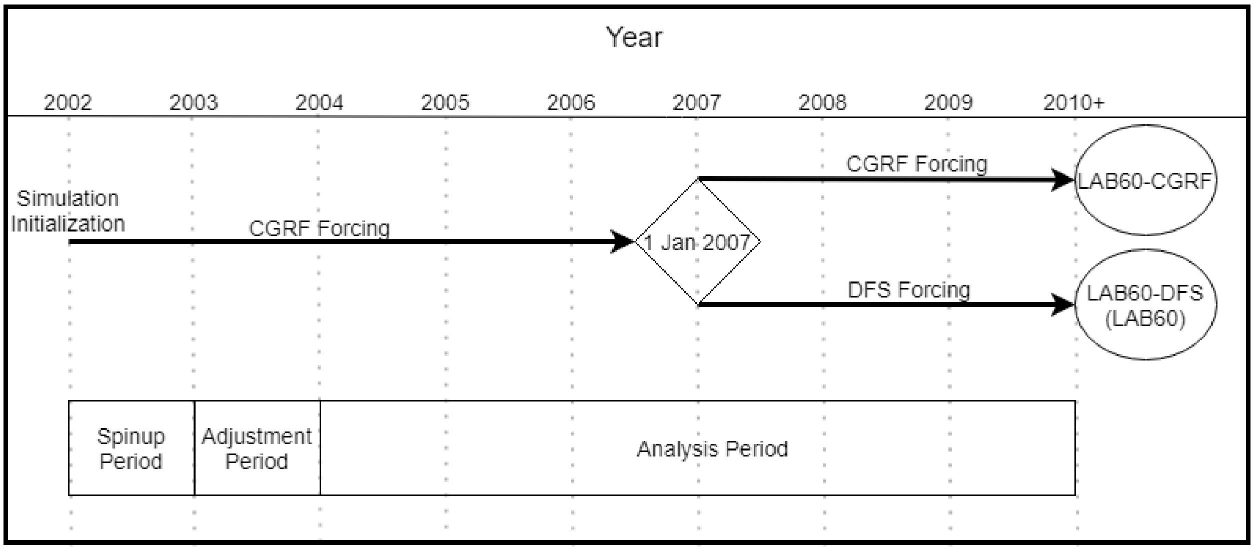
We have included CGRF and DFS into this table. LIM2 and CORE have references here now as well.

• Table 2: Please add the atmospheric forcings (CGRF and DFS) and their respective time periods

See above

• 160-185: LAB60 was forced by CGRF from 2002-2006 (5 years) and by DFS from 2007-2011 (5 years). If this is correct, I find it difficult to plot one LAB60 time series in Fig. 9. Can you at least indicate the two different forcing data sets in the plot/caption?

We have made a new figure (Figure 2, below) that better explains the breakup of the LAB60 simulation with both the CGRF and DFS5.2 atmospheric forcing products.



• 189 & 329: Please specify which sigma/density is used.

We state the density used: potential density: **L206, L207, L343**

• 202: Did the simulation length really increase or rather decrease when the number of CPUs increased?

We have better described that an increase in CPUs increased the number of simulated days per job submission on the high performance computing system: **L224-226**

• 225: configuration"s"?

We have better clarified that the lower resolution simulations we compare against LAB60 are different configurations.

• 232: Please define how you computed the eddy components in the model and AVISO data.

We have better defined how we calculate the eddy components in our EKE equation, both for the model and AVISO data. **L263-269**

• Fig. 5 and Video 1: It is more informative to show relative vorticity normalized by the planetary vorticity, ζ/f, to learn about the transition from meso- to submesoscales.

We have normalized vorticity against the planetary vorticity. However, little difference is noted across the new figure/video.

• 250 & 265: Please define meso- and sub-mesoscales in the introduction and how you separate them.

We define mesoscale and sub-mesoscale in the introduction and how we separate them (by size): **L314**

• 256: Please define convective energy (CE) including the mixing depth to which you refer to in Fig. 6 b. On this snapshot, all CE values are >= 500 J m−3 . However, a winter situation is shown (17 January 2003) and I would expect CE values < 0 J m−3 indicating unstable situations. Is this a misunderstanding?

We have included the reference depth in our definition now, 2000m. On the original Fig. 6b snapshot (which has since changed to 26 July 2007 as per Reviewer 2's comment), CE values would only be 0 if there existed no potential density change between the surface and 2000m. LAB60 does not have a mixed layer which reaches that deep (see Fig. 9) and thus always has positive CE. Furthermore, values less than 0 do not occur as the model's vertical mixing scheme quickly deals with unstable vertical situations. **L298-307**

• 295: First, you find the LSW with σΘ > 27.68 kg m−3 (line 189; I assume you used σΘ in this step). Then, you calculate σ1 of this water mass. Then, I don't understand why you define the "yearly maximum density of this water mass as the thickest depth where the density changes by 0.001 kg m−3 ". I don't understand how a "depth" can be "thick" and to which density the 0.001 kg m−3 change refers to. Can you reformulate this here and in the caption of Fig. 9? Formulated as it is, I would have problems reproducing this quantity.

We have completely rewritten (but not changed the calculation) the description of how we determine LSW layer thickness. **L341-346**

• Videos: Adding the sea ice edge and some MLD contours would make the videos even more helpful.

We have added a sea-ice edge and a 1000 m MLD contour in the MLD video. We have also updated all videos to the end of 2013.

Referee comment #2 (Jan Klaus Rieck)

General comments

1. You emphasize the need for a long simulation to study the decadal variability of the Labrador Sea and state that your simulation is suitable for that. However, at least at the time of submission, there were only 7 years (excluding spin-up) of the simulation finished and your statement of having a simulation of more than ten years do not hold. If the simulation does now (time of revision) extend over the stated period, this is fine, if not there need to be adjustments to the manuscript.

Additionally, you should think about rephrasing the manuscript at some points concerning the suitability of a ∼10 year-long simulation to study decadal variability.

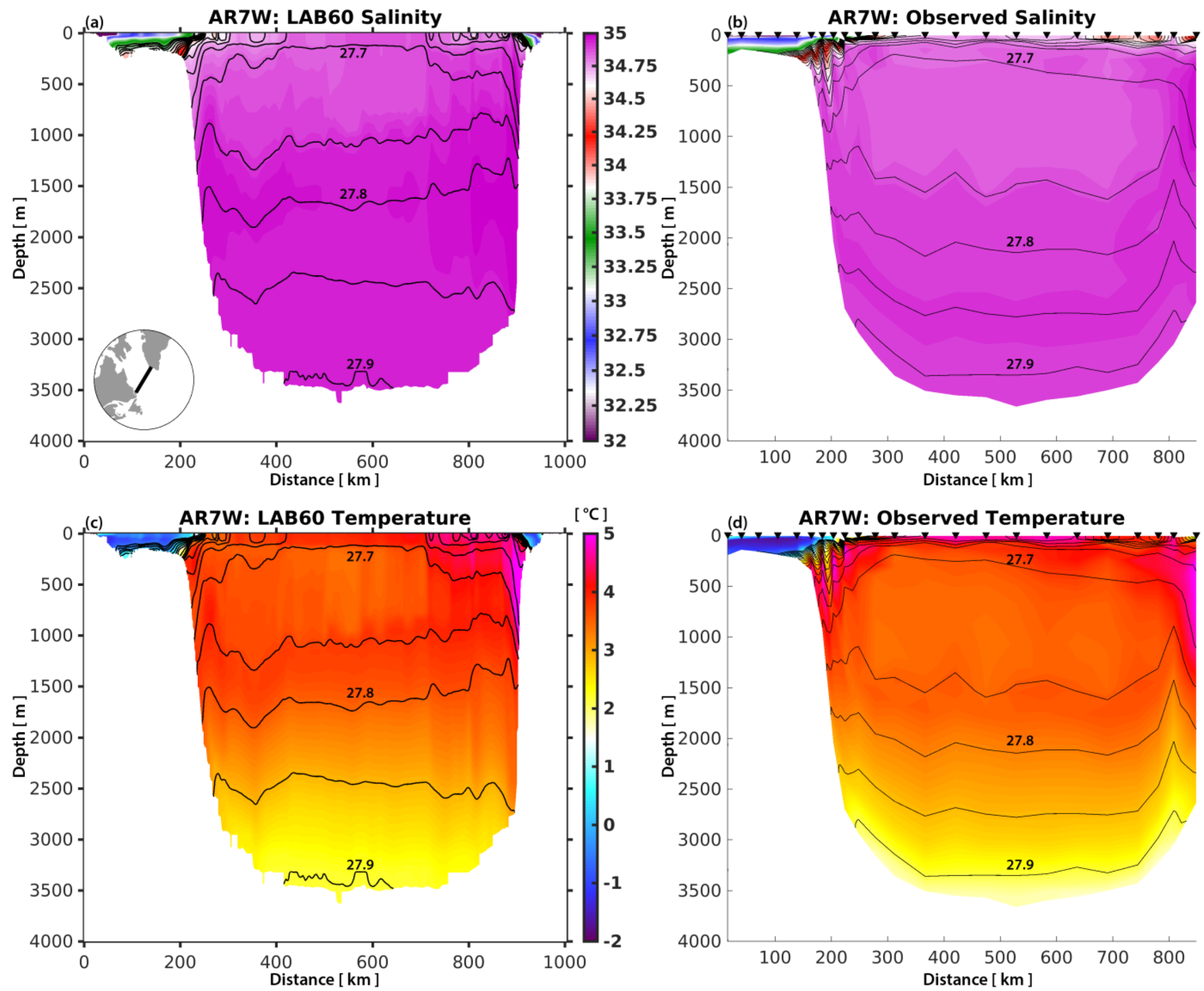
We have changed the writing of the manuscript to shift away from decadal variability to interannual variability. Additionally, we mention, and show (figures/movies) data from 2004 through 2013, 3 additional years since our original submission.

2. In my eyes, you do not satisfactorily advertise the advantages and improvements of LAB60 in comparison to other, existing high-resolution simulations carried out with the same model (e.g. the VIKING20X simulations at 1/20◦ [Rieck et al., 2019]). I do think that the presented LAB60 simulation has advantages over the other simulations mentioned and is a valuable addition to the suite of models/configurations simulating the Labrador Sea, but you should make these more clear. Please refer to the specific comments below for more details on this suggestion!

We have added additional text that should better illustrate how LAB60 offer advantages over other high resolution simulations in the Labrador Sea. We discuss how our simulation is much longer in simulation length than the other 1/60 simulations and includes passive tracers which high-resolution simulations often do not have. **See L109-111, L122, L215-217, and L417-440**

3. The current speed, convective energy, mixed layer depth, etc. are all valuable properties to investigate and clearly show the differences between the different horizontal resolutions for the processes of interest. However, considering this is the description paper of the model experiment, I suggest to add some analyses of temperature and salinity. Depth sections of temperature and salinity along AR7W for example could be compared to observations and should be familiar to most readers, thus providing a valuable reference future studies could compare their simulations to. Additionally this would give the reader some insight into the vertical structure of the simulation, as most quantities shown in the manuscript are surface values or depth-integrated.

We have included a T/S/density figure of LAB60 and observations across AR7W (below) as well as some text describing the model versus observations. **L369-L375**



4. There are many, many sentences starting with "While ...". This is not incorrect, however the readability would be greatly increased by a bit more work on the language. Additionally you could put more effort in smooth transitions between paragraphs, especially in the introduction.

We have changed many of our transition sentences to increase readability as well as reduced our use of 'while'.

5. There are hardly any specific numbers given in the manuscript. The properties are often described as being "large" or "smaller" etc. This makes the results hardly reproducible and also very hard to compare to other studies/models, especially given the fact, that the color scales of the figures are continuous and it is hard to read any values from the figures. Please refer to the specific comments for more details on this remark

We have added specific numbers and/or range of values throughout the manuscript and removed vague descriptors. Colorbars in many figures have been changed to be easier to read.

Specific comments

Abstract

l. 10: The restratification after convection could also be mentioned here, as this is a process that is expected to be differently resolved depending on the horizontal resolution.

We include more writing about restratification that occurs after convection. **L10**

ll. 11-12 “We implemented [...]”: As you mentioned the 1/60◦ domain of the Labrador Sea before, this sentence reads as if they implemented additional nests into the 1/60◦ domain.

Clarified how the nests are used in our configuration: **L11**

l. 12 “[...] spans over 10 years”: See general comments above. (At least at the time of submission, this was not true.)

We have clarified here (and in a few other locations) that our simulation is still being carried out. As of this revision, there is 10 yeas of non-spinup model output (2004-2013) and we will run the simulation with DFS forcing through the end of 2017 (when DFS ends). We will eventually swap to another forcing set, though it is still undecided which one we will use. **L12, L127**

l. 16: Maybe better: “[...] impacts the simulation of the Labrador Sea.” or “[...] impacts the representation of the Labrador Sea in the model.”

Changed to make clearer: **L16**

Introduction

ll. 23-25: Confusing, first you describe that the current flows northwards and then you say it combines to be the WGC. In my opinion descriptions of current systems should be successively downstream, otherwise it is very hard to follow.

Reordered the description of the currents to be downstream of one another. **L24-25**

ll. 28-29 “[...] now called the Labrador Current [...]”: Please specifiy from which point on the current is called Labrador Current. This is not clear to me at this point.

We now state that the Labrador Current begins in proximity to Hudson Strait: **L28-29**

ll. 31-42: The paragraph describing the eddies in the Labrador Sea is a bit short, considering that resolving eddies is the major improvement and advantage of very high-resolution configurations. You

could for example mention the ongoing debate over which type of eddies in the Labrador Sea is most important for the restratification and how your new simulation could help in solving this issue.

We have added a few more sentences that describes eddies in the Labrador Sea. We also mention the debate on which eddies influence the stratification. **L44-52**

33: "[...] instabilities that occur within the boundary currents along the shelf break." The boundary currents are a quite substantial ingredient to the instabilities and should be mentioned.

We have made this sentence clearer. **L34**

ll. 41-42: This statement requires a reference as it is not obvious that eddies generated at a western boundary should travel eastward into the basin.

We include a citation to a numerical modelling study (Pennelly et al., 2019) that shows the eddy fluxes from the WGC and Labrador Current provide a net flux towards the interior of the Labrador Sea. **L43-44**

ll. 43-47: Listing all the sites of deep convection seems unnecessary here, as they are never referred to again.

We have removed non-Labrador Sea convection locations since we do not refer back to them.

ll. 48-49: Weak stratification is a criterion for deep convection, the cyclonic circulation is not strictly necessary, please clarify this. For example "[...] weak stratification which is often achieved by a cyclonic circulation, [...]"'.

We have made it clearer that cyclonic circulation isn't a requirement but rather helps set the overall weak stratification required for deep convection: **L55-56**

l. 53 "[...] relatively drier air [...]": Relatively drier compared to what?

Changed to 'dry air' as we are not referencing against anything at this point: **L61**

l. 59: You could mention the role of convective eddies in the restratification process (Lilly et al., 2003; Rieck et al., 2019).

We added text which discusses the roles of convective eddies in the restratification process and used the suggested references. **L67 and before in L44-52**

ll. 60-62: I do not understand what you want to convey with this sentence. Please clarify this, maybe you should consider the next sentence when rephrasing, as it seems that there is a repetition of the information that there is buoyant water transported towards the interior.

We have rephrased this confusing sentence: **L68-72**

ll. 67-68: It is not clear what "throughout the North Altantic" refers to. The DWBC is part of the North Atlantic as well, but is mentioned seperately.

We have cleared up this part regarding where newly formed Labrador Sea Water flows to. **L73-74**

l. 74: You should briefly describe how polar amplification is causing additional freshwater and preferrably also include a reference for this statement.

We briefly describe polar amplification in relation to ice-albedo feedback loop and how the additional melt enters the boundary currents. **L79-81**

l. 78: What kind of information does satellite altimetry provide and what is it used for?

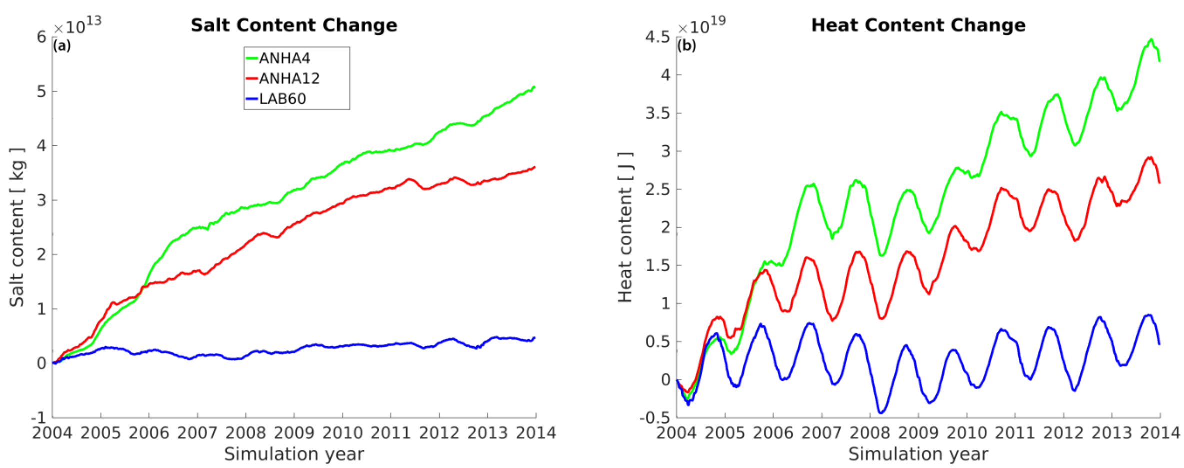
We add some text regarding satellite altimetry data. **L89-90**

l. 87: "larger spatial extent" compared to what?

We clarified what we originally meant by 'larger spatial extent': **L99**

ll. 90-92: One ofyour goals defined at the beginning is to investigate the role of horizontal resolution in simulations of the Labrador Sea. Here, it now seems as if this question has already been answered by an earlier study. You should make clear how your simulation is different to the earlier ones and how it can help in solving the question of how resolving eddies affects the Labrador Sea. Additionally you do not show any investigations into the numerical drift of your simulation, despite stating that the numerical drift is a major problem of simulations of the Labrador Sea even at high resolution.

We add discussion about how our simulation is useful in context to others. We include an additional figure (below) that shows numerical drift of the lower-resolution simulations as well as LAB60 (which has almost no drift). **L361-368**



ll. 96-97: You should carefully rephrase this sentence. Stating that the multi-decade 1/20◦ simulation resolves eddies in the Labrador Sea makes it hard to justify the need for a 1/60◦ simulation.

We have clarified that 1/20 degree simulations may be lacking or misrepresenting the submesoscale that higher-resolution simulations are needed for.**L109-111**

ll. 101-102: Instead of vaguely stating that these simulations have a length of “perhaps only a few years”, you could exactly state how long the existing very high-resolution simulations of the Labrador Sea are.

We have added information on roughly how long these high-resolution simulations are: **L122-123**

ll. 105-115: See general comment 1.

We have edited these lines so that we are writing about our LAB60 simulation in regards to interannual variability rather than decadal variability. **L127-129**

Methods

ll. 122-123: I suggest briefly describing the extent of the domain here and use the figure as an additional source of information and not the only source.

We have added a brief description to the ANHA4 domain but not the SPG12 or LAB60 spatial extent of their domain. Figure 1 shows the spatial extent of each domain: **L141-L142**

ll. 125-126: I suggest briefly describing the extent of the domain here and use the figure as an additional source of information and not the only source.

Same as above

l. 124: The mansucript would benefit from a short explanation of ARGIF’s concept of parent and child domains at this point.

We have added some text that described briefly how AGRIF treats the boundary conditions between parent and nest. **L139-141**

l. 134: You should cite Barnier et al. (2006) at this point.

We have included a citation to Barnier et al 2006 in regards to partial cells: **L154**

l. 144: I am not sure whether you should phrase this as the “usual NEMO method”. There are many ways to compute the mixed layer depth implemented in NEMO.

We have clarified this sentence so the reader understands that it was our usual methods of calculating the MLD, not the only one. **L163-165**

l. 150: Stating that “[...] smoothing between domains ocurred [...]” makes it sound like you only had a passive role in that. It should be made clear, that you actively decided to smooth between domains.

We have made it more clear what we meant by bathymetric smoothing along the nested boundaries. **L169-171**

ll. 152-153: Where and how exactly are the boundary conditions applied? Is there a sponge layer? Etc.

We state how and where the boundary conditions are applied as well as the lack of a sponge layer. **L172-175**

ll. 155-159: It seems random that you give a detailed explanation of how not explicitly including icebergs in the model could affect the freshwater budget of the subpolar North Atlantic, but do not mention other factors, like the choice of initial fields that could also significantly influence the freshwater budget.

We have removed some text regarding freshwater from icebergs. We did keep text that states AGRIF doesn't work with the iceberg model, primarily to state that we turned solid freshwater into liquid freshwater and used the same volume.

l. 160 "[...] including [...]": Is there any part of the atmospheric forcing that is not listed afterwards? If not, then "including" is redundant.

Removed 'including'

ll. 169-170: What period does "long-term" refer to here and over which area is the heat loss calculated? These numbers should be made reproducible for comparison with future studies/forcing datasets/model simulations.

We clarify the period which 'long-term' refers to**. L191**

ll. 174-175: You never declared your interest in conducting a simulation past 2017, so the need for a different forcing set is not obvious here. Your goal to have a simulation that extends (almost) until present should be stated as it could be quite important for potential collaborators on the analysis of the produced model output!

We clarify here, and in other locations, that we intend to not only drive this simulation up to present time (currently it is in 2015), but to keep it at the near-present time by using recently released forcing. **L12, L127-129**

ll. 177-179: I guess that the lack of interannual variability is caused by the missing deep convection due to the weak forcing. You should clarify this.

We clarify that the LAB60-CGRF is missing deep convection after a certain point which we attribute it to weaker forcing. **L200-201**

ll. 179-182: Do the different spatial and temporal resolutions have any consequences for the observed behaviour in Fig. 1? Otherwise I suggest to move this information to the part were the forcing datasets are described in general.

We migrate the information on the atmospheric forcing resolution from here to the area where we discuss these datasets.

ll. 182-185: You state that the remainder of the manuscript will only deal with LAB60-DFS, however later in the Methods section you describe the start of the computation at the Graham cluster and the spin-up period, which were done under CGRF atmospheric forcing if I understand correctly. This is confusing. I understand that describing such a complicated simulation pathway (switching forcing, switching computing cluster) is not an easy task. However, you should try to make it more clear. Is the whole used simulation from 2002-2011 called LAB60-DFS, or only the part from 2007-2011 where the DFS forcing is actually used?

We have added a new figure that should quickly and easily describe the previously confusing sentences. See Figure 2.

l. 186: It is not clear to me what "internal testing" refers to in this context. Why is it internal?

We have made 'internal testing' a bit more clear by simply stating that it was during our 'early testing'. **L202-204**

l. 187: You should specify what "overhead" means. I guess it refers to the additional computational costs/time, but this needs to be made clear.

We removed 'overheard' and instead state that each passive tracers takes additional computer resources

ll. 187-193: A list with three items (the three passive tracers) would be a beneficial structural element at this point. Additionally, you should explain the choices made regarding the thresholds for the definition of the different water masses.

We list the tracers in bullet point form as suggested: **L205-207**

ll. 194-195: You should clarify what "here" refers to, also there seems to be word missing between "such" and "resolution".

We have clarified this sentence

ll. 208-209: It is not clear to me how you learned that your simulation is unstable from interpolating data. Additionally, "quickly go unstable" is rather unspecific.

We have written a bit more about what went wrong during the spinup period when instabilities built and crashed the model. **L231-236**

l. 211: You probably mean the opposite: Large (long) time step first, then decreasing to small (short) time step. Please clarifiy.

Our spinup process, in regards to how we changed the numerical time step, was written correctly. We started with a very short timestep (2 seconds) which we then increased over time to the final value (48s). We did clarify our spinup process paragraph significantly. **L231-236 was modified**

ll. 217: At the end of the Methods section, the mansucript would greatly benefit from a clear short description of the simulation used for the analysis, making clear that the spin-up was done under CGRF forcing from 2002 to 2003, then there are 2004-2006 under CGRF forcing, followed by 2007-???? under DFS forcing. Maybe a simple schematic could help here, otherwise the reader has to skip back and forth through the Methods section to gather this information.

Figure 2 was produced to make this transition from CGRF to DFS more clear.

Model Simulation Results

ll. 220-222: Compared to what do the large differences occur? If you refer to the differences between LAB60, SPG12, and ANHA4, then it sounds like you want to use the large differences (compare the simulations) to understand the large differences. This sentence should be rephrased for clarification.

We have made this sentence more clear: **L250**

ll. 224-225: At which depth are the current speeds compared? Additionally, you should provide some numbers here, "greater" and "slower" are not very specific.

We have added text to state the current speeds were calculated from the top 50m for the simulations. **Multiple lines across the results section: 254, 255, 256, 276, 278, 280, 282-286, 297-298**

l. 230: Which shelf breaks? Shelf breaks have not been mentioned before in the manuscript.

We mention which shelf breaks we are referring to: the Labrador coast and the western side of Greenland: **L257**

l. 231: At which depth is the eddy kinetic energy investigated?

We have clarified that EKE was calculated from geostrophic velocities derived from the sea level anomaly: **L263-264**

l. 231-253: You should use values when comparing the EKE in different regions and among different simulations. Using mostly larger and smaller makes it hard to keep track of how which result compares to which. Comparing numbers makes this a lot easier in most cases (additionally a comparison to other simulations and/or observations could be enabled).

We include EKE values when comparing the different simulations. **See 3 comments up on the many lines changed.**

l. 231-232: You should clarify how you compute geostrophic velocities, and discuss that (at 1/60◦ resolution) your simulation might resolve submesoscale processes and features that are important for the restratification (among others) and are not completely represented by geostrophic currents.

We clarify how we compute geostrophic velocities. **L263-269**

l. 232: In the definition of EKE, you should specifiy what the primes and overbars denote. Specifically, over which period the currents are averaged to calculate the deviations from. The choice of this period can have an influence on the results (Kang and Curchitser, 2017).

See above: **L265-266**

l. 232: AVISO has not been introduced to the reader at this point. You should describe the data you use in the Methods section. Which data is used from AVISO, SSH or the geostrophic currents? Also, please note that many of the commonly used SSH products are not distributed by AVISO anymore (since 2017) and it might be useful to update the data and use the new versions distributed by CMEMS (https://marine.copernicus.eu).

We now include some text regarding AVISO data earlier in the methods section, as well as which data we used from AVISO. **L142-244**

l. 233 "[...] EKE coming from [...]": One can not necessarily infer any direction of propagation from the maps of EKE. In these cases where it is likely that the high levels of EKE in one region are caused by propagation of (mostly) eddies into that region, I would suggest writing something along the lines of : "High levels of EKE can be found along the west coast of Greenland, extending into the interior of the basin at ?? North...". You should check the whole manuscript for this formulation ("[...] EKE coming from [...]") and adjust it.

We have changed many sentences which originally stated 'EKE came/coming from' to 'EKE extending' or something similar. **L270-273, 278-279, 282-287**

l. 235-236: The result, that EKE is closely bound to the Labrador Current and the shelf break in the western Labrador Sea does not receive enough attention in my opinion. As far as I know, whether these boundary current eddies impact the deep convection region and the restratification or stay too close to the basin's boundary is still a matter of ongoing debate (e.g. Chanut et al., 2008; Gelderloos et al., 2011; Rieck et al., 2019) and a 1/60◦ simulation could clearly help in sovling this issue.

We add more text regarding the lack of EKE extending from the Labrador Current into the interior Labrador Sea, suggesting that boundary current eddies here likely do not influence the stratification/restratification of the Labrador Sea. **L282-287**

l. 236 "[...] has lower levels of EKE [...]": Lower compared to what?

We have changed many sentences to indicate a range of EKE values rather than just 'lower/greater/etc'

l. 238-240: See above. EKE "coming from" somewhere and "entering" does not seem to be the best way do describe these results.

We have changed sentences with 'EKE coming/entering/etc' to be more clear and accurate.

l. 242-243: See above. You could mention at some point earlier in the manuscript that "the EKE coming from the west coast of Greenland" is related to, or mostly consists of, Irminger Rings. That would probably help in describing the results later on (e.g. by using the phrase "Irminger Ring path" or something similar).

We have changed this sentence to state that the EKE signature here is related to Irminger Rings: **L271-273**

l. 244 "AVISO observations": See comment above on AVISO.

We have clarified our writing regarding AVISO observations

l. 246-253: I suggest that you additionally investigate EKE at depth. EKE at depth in the central Labrador Sea could be an indicator of the presence of convective eddies (which should be resolved at this resolution in contrast to other simulations with up to 1/20◦) and could even be compared to observation of Fischer et al. (2018).

We decided to not include any investigation of EKE at depth which could be evidence of convective eddies. We have future goals to look into these eddies from the results of this simulation.

l. 254: I suggest you use a different date to show a snapshot from, as you mention earlier that 2003 is still in the spin-up phase and you will only present model results from 2004 ongoing. This is not consistent.

We have changed the date of this figure to be outside the spinup/adjustment phase. **L307 and Fig. 7**

l. 255-256: Again, no numbers, just "very strong" and "reduced".

We have included numbers in place of 'very strong', 'reduced', and other vague descriptors. **L311 and 312**

l. 256: A brief explanation of convective energy would be extremely helpful here. The meaning of convective energy does not coincide with what the reader might intuitively think of when reading "convective energy" (the energy of convection).

We add further explanation on what convective energy means: **L299-306**

l. 261-264: If you observe the described properties and processes in your simulation, I strongly suggest to show that and not just speculate. Additionally, there could be observational support for these speculations in Lilly et al. (2003) so I suggest checking that.

We include references to Lilly et al., 2003 for observational support on our speculation. Furthermore, this is one major objective of the last chapter of C. Pennelly's PhD thesis. **313-314**

ll. 276-277: From the sentence, it is not clear to me whether the path of strong stratification is located between the 2500m and 3000m isobaths everywhere, or the path starts at the coastline between these isobaths. I suggest to formulate this more clearly.

We have made this sentence more clear

ll. 280-281: This sentence sounds like the small convective energy is required to achieve weak stratification, whereas the convective energy is basically just another measure of stratification. I suggest rephrasing this. Addtionally, this fact has already been mentioned before.

We have removed this as it was already mentioned earlier, which we also clarified.

ll. 285-286 "[...], limiting the mixed depth between the 2000m and 3000m isobath.": It is not clear to me what exactly you want to convey with this part of the sentence.

We have clarified this sentence in regards to the mixed layer: **L333-337**

l. 287: You probably mean that the region where the mixed layer is deeper than a certain threshold is larger. The ocean has a mixed layer everywhere, so you cannot really reduce its spatial extent.

We have clarified this sentence: **L333-337**

l. 293: The bottom of the mixed layer returns to the near-surface, the mixed layer is always connected to the surface.

We have clarified this sentence by stating the 'bottom of the mixed layer'. **L341**

ll. 295-296: There are several questions regarding the definition of the Labrador Sea Water. 1. How can you define the maximum density as the thickest depth? What is a "thickest depth"? 2. Referred to what does the density need to change by 0.001 kg/m3? 3. Why do you calculate the MLD based on gradients and then for the definition of the LSW you use thresholds, wouldn't it be more consistent to also use a threshold for the MLD then? 4. How does this way of defining LSW compare to the way you defined your LSW tracer and what implications does this have?

We have clarified how we calculate Labrador Sea Water, these sentences have been completely rewritten in a manner that should make more sense. The calculation has not changed. In our introduction, we state that the thresholding of MLD doesn't work well for deep convection as T/S compensate with little change in density. We do state that our LSW tracer is very different than how we calculate LSW from the output of our model: we couldn't factor any potential drift while the tracers are being formed. The result is they show different aspects: The tracer shows newly formed Labrador Sea Water while our LSW calculations show how the thickness and density within our region of interest evolve in time. Both examine Labrador Sea Water in their own way. **L342-347**

ll. 297-298: Where could stair-stepping patterns emerge? Between years? And what are stair-stepping patterns? The same as staircase patterns?

We clarify what we meant by stair-stepping/staircase. **L349**

l. 316: I am not completely sure what "enters the interior 2000m and 3000m isobath" means. Do you want to convey that the water mass propagates into regions where the water is between 2000 and 3000m deep? Please rephrase this sentence to make this more clear.

We clarify this sentence regarding propagation into deeper water

ll. 318-319: Stating that water ends up in the Labrador Current sounds like this water will never leave the Labrador Current. However, I suspect that the water still in the Labrador Current has just not yet left the current to the South or East due to the short integration time of your simulation. Using the phrase "ends up" is thus rather misleading.

We change the phrasing of this sentence to be clearer

l. 323: I am not sure what "within the 2000m and 3000m isobath" means.

We clarify this sentence in regards to the different isobaths: **L389**

l. 324: What is a "thicker amount"? Do you mean a "larger amount"?

We did mean a 'larger amount' and have fixed it

ll. 328-329: Could you state how your definition of the tracer compares to your earlier definition of LSW?

We added a sentence regarding the difference between our LSW tracer and our LSW calculation. **L396-398**

Discussion

ll. 337-339: In the manuscript you do not really describe how submesoscale processes impact deep convection so it is irritating that you mention it in the discussion. I suggest that you add a paragraph to the Results section briefly showing that your simulation resolves the submesoscale and how that could impact deep convection and water mass formation. One of the key reasons to carry out a 1/60◦ simulation probably is that it resolves the mesoscale in the Labrador Sea and starts to resolve the larger end of the submesoscale range. I think you should make it more clear that your simulation is capable of doing this and not just showing the end result (LSW for example) and speculate that the differences to lower resolutions are due to the missing (sub-)mesoscale.

We have added a bit more discussion in regards to mesoscale to submesoscale process here, though it is just text and not additional figures. Rather than include additional figures in this manuscript, we are currently writing up another manuscript which further investigates these processes in much more detail. **See L418-433**

ll. 348-349: At this point you should compare your results from the 1/60◦ simulation to earlier studies with lower resolutions to point out the differences and espcecially improvements achieved by increasing resolution. At least for the Greenland meltwater, there are several studies investigating the fate of this tracer in simulations with lower resolutions (e.g. Böning et al., 2016 and others...).

We have added some comparison of our LAB60 simulation to earlier low-resolution studies, particularly ones with similar passive tracers as the ones we use. **434-441**

Tables

l. 526: In the Methids section you state that you refer to the whole configuration is LAB60. In this table it looks like you refer to the parent domain as ANHA4, the first nest as SPG12 and only the second nest as LAB60. This should be made consistent.

We have added additional text to try and make it more clear that while we call this configuration 'LAB60', the entire configuration contains 3 domains: ANHA4, SPG12 and LAB60.

Figures

In general I suggest to use larger fonts in the figures, especially for the titles (The titles should be at least as large as the manuscript font size.). Additionally, you could use some summarizing titles stating the property to be seen in the individual subplots (additional to the LAB60/SPG12/ANHA4/AVISO titles). I strongly recommend adding the units to the colorbars and also suggest using different colorscales, as these continuous scales sometime make it nearly impossible to read accurate values from the figure. It is not easy for example to distinguish between values of 0.2 m/s and 0.3 m/s in Figure 3 or 200 cm2/s2 and 500 cm2/s2 in Figure 4. (The colorscale used for the supplementary video showing LAB60s MLD is a good example of a discrete color scale where one can read values from the plots easier!)

We have remade most figures with larger font. Some figures have been updated so their titles are a bit more descriptive rather than just 'ANHA4', they now include the proxy being investigated (I.e. "ANHA4 MLD"). We have changed many colorbars to show more discrete features.

l. 552: Speed at which depth?

We now state the speed was calculated over the top 50m

l. 557: Eddy kinetic energy at which depth?

We now clarify that EKE was calculated via the geostrophic velocities resulting from the sea level anomaly.

l. 563: Relative vortcity at which depth?

We now state vorticity was calculated over the top 50m

l. 568: Speed at which depth?

We now state that speed here was just shown for the surface.

Technical corrections

Abstract

ll. 9-10 "The transport of these fluxes [...]": Transport and fluxes are used synonymously here and thus this should just read "These fluxes [...]" or "This transport [...]".

Done

Introduction

ll. 32: Frajka-Williams

Fixed the misspelling of Frajka-Williams

ll. 80-83: This sentence should be split for better readability.

We have made this sentence more readable

l. 89: "[...], both which" should be rephrased

We have changed this fragment to be more readable

l. 105: "high resolution" should be "high-resolution"

We have hyphenated this and many other instances where we missed it before

Methods

l. 123 "includes a nest": To be precise, it includes two nests.

We have changed our wording choice to be more precise.

l. 133 “horizontal grid resolution”: I suggest using “horizontal grid spacing” here.

Changed

l. 136 “[...] primarily only [...]”: You should decide on either “primarily” or “only”.

Changed

l. 137-139 “All domains used [...]”, “Lateral diffusion used [...]”, etc.: This should be rephrased to something like “[...] scheme was used in all domains.”, “A Laplacian operator was used/implemented to compute lateral diffusion [...]”, etc.

We have reworded how we describe the various domains and their schemes

l. 151: “boundary nests” should be “the nest boundaries”.

Changed

l. 171: “which were” should be “which was”.

Changed

l. 175 “[...] Fig. 1 identifies [...] between [...]”: should be “[...] Fig. 1 depicts [...] the difference in mixed layer depth between [...]”.

Changed

l. 190: “pathways which” should be “pathways along which”.

Changed

l. 194: “masses” should be “water masses”.

Changed

l. 194: “before in the past” should be either “before” or “in the past”.

Changed

l. 202: “increase in simulation length” should probably be “decrease in simulation length”.

We have reworded this sentence to make it clearer that more CPUs allowed us to produce more simulated days in the same amount of requested job time.

l. 207: “[...] the occurrence of seasonal sea ice.”

Changed

Model Simulation Results

l. 222: “ANHA12” should be “SPG12”.

We did not make this change as we are purposely comparing the LAB60 configuration against the ANHA4 and ANHA12 configuration, not SPG12

l. 243: “produce” should be “produced”.

Changed

l. 244: “they match” should be “it matches”.

Changed

ll. 252-253: duplicate mention of “supplemental”/“supplementary”.

Removed the extra mention of ‘supplemental’ here and in a few more instances

l. 255: “show” should be “shows”. l. 270: “ANHA12” should be “SPG12”.

Changed

l. 271: “supplies” should be “supply”.

Changed

ll. 275-276: duplicate use of “visible”.

Changed

l. 283: “depth” should be “depths”.

Changed

l. 283: “observation” should be “observations”.

Changed

ll. 299-301: Please rephrase this sentence, the “though” seems unnecessary and “has this [...] being less dense.” does not seem right.

We have rewritten a large portion of this paragraph to make it more clear- this sentence has been corrected

l. 305: “between the” should be “in all three”.

Changed

l. 306: “indicate that deep mixing is easier” should be something like “indicates that deep mixing is more likely”.

Changed

Discussion

l. 350: “project” should be “projects”

Changed

References

Some of the following references were already included in our manuscript. Many others were added as suggested by this reviewer.

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Chanut, J., Barnier, B., Large, W., Debreu, L., Penduff, T., Molines, J.M., and Mathiot, P.: Mesoscale eddies in the Labrador Sea and their contribution to convection and restratification. Journal of Physical Oceanography, 28(8), 1617-1643, 2008.

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Kang, D., and Curchitser, E. N.: On the Evaluation of Seasonal Variability of the Ocean Kinetic Energy. Journal of Physical Oceanography, 47, 1675-1683, 2017. DOI: 10.1175/JPO-D-17-0063.1

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Our Marked manuscript is below: Red text shows where modifications from the original submission occur.

Introducing LAB60: A 1/60° NEMO 3.6 numerical simulation of the Labrador Sea

Clark Pennelly[1*] and Paul G. Myers[1]

[1]1-26 Earth Sciences Building, University of Alberta, Edmonton, Alberta, Canada, T6G 2E3

[*]*Correspondence to*: Clark Pennelly (pennelly@ualberta.ca)

Abstract

A high-resolution coupled ocean-sea ice model is set up within the Labrador Sea. With a horizontal resolution of 1/60°, this simulation is capable of resolving the multitude of eddies which transport heat and freshwater into the interior of the Labrador Sea. These fluxes strongly govern the overall stratification, deep convection, restratification, and production of Labrador Sea Water. Nested domains within our regional configuration reduce computational costs, allowing for a simulation that will span over 15 years up to near-present time. Three passive tracers are also included: Greenland runoff, Labrador Sea Water produced during convection, and Irminger Water which enters the Labrador Sea along Greenland. We describe the configuration setup and compare against similarly forced lower-resolution simulations to better describe how horizontal resolution impacts the Labrador Sea.

1. Introduction

The Labrador Sea, between Canada and Greenland, plays a crucial role in the climate system. Situated between the Canadian Arctic and the North Atlantic, multiple current systems influence this deep basin. Cold and fresh Arctic water flows south through Fram Strait along Greenland (de Steur et al., 2009), producing the East Greenland Current (EGC). The EGC flows to the southern tip of Greenland, merging with warm and salty Irminger Water to become the West Greenland Current (WGC) before flowing northwards along the western coast (Fratantoni and Pickart, 2007). The WGC flows cyclonically around the Labrador Sea as well as into Baffin Bay. Significant amounts of freshwater are supplied to this current system from both Davis

(Cuny et al., 2005; Curry et al., 2011; Curry et al., 2014) and Hudson Strait (Straneo and Saucier, 2008) as it travels around the Labrador Sea. The current system is called the Labrador Current where it merges with the outflow from Hudson Strait (Lazier and Wright, 1993). The Labrador Current travels southwards along the eastern coast of North America eventually leaving the Labrador Sea.

Numerous eddies are generated throughout the Labrador Sea, both from high lateral density gradients which exist during the convection season (Frajka-Williams et al., 2014) as well as from baroclinic and barotropic instabilities that occur within the boundary currents (Chanut et al., 2008; Gelderloos et al., 2011). The continental slope along the west coast of Greenland has a pronounced change in topography that induces instability of the current system, generating eddies (de Jong et al., 2016). These eddies, known as Irminger Rings, contain a significant amount of freshwater at the surface as well as subsurface heat. Irminger Rings (15-30km radius) typically travel southwestwards into the interior of the Labrador Sea and have a lifespan of up to two years (Lilly et al., 2003). Eddies generated along the Labrador Coast also contain a significant amount of freshwater (Schmidt and Send, 2007; McGeehan and Maslowski, 2011; Pennelly et al., 2019). Regardless of where they are produced, these boundary current eddies often export their properties towards the centre of the basin (Pennelly et al., 2019), influencing the deep convection which occurs. Convective eddies are generated from baroclinic instability which arises from large horizontal density gradients during the convective season (Marshall and Schott, 1999). Convective eddies are much smaller with a radius between 5 and 18 km (Lilly et al., 2003). These eddies are less studied than the other eddy types, partly due to a lack of observations (Lilly et al., 2003) as well as their small size which requires high-resolution models to adequately resolve. Research into the role of each of the above eddies and their role in restratifying the Labrador Sea is still ongoing; there is no consensus on which eddy may be more important, though many have narrowed it down to Irminger Rings and convective eddies (Chanut et al., 2008; Gelderloos et al., 2011; Rieck et al., 2019).

Deep convection is a rather rare occurrence, only known to occur at a few places in the ocean. The reason so few places exist is the stringent criteria to produce deep convection: weak stratification that can be enhanced via isopycnal doming as a result of cyclonic circulation, and intense air-sea buoyancy loss (Lab Sea Group, 1998; Marshall and Schott, 1999). Cyclonic circulation and the lateral input of salty Irminger Water helps keep the Labrador Sea weakly stratified. Furthermore, the Labrador Sea experiences strong heat loss during the winter period due to the very cold mid-latitude cyclones which frequent the region (Schulze et al., 2016). The overlying cold and dry air forces a significant flux of heat from the ocean to the atmosphere. This loss of heat promotes the surface layer to increase in density, overturning the weakly stratified water column such that the mixed layer can exceed 2000m in depth (Yashayaev, 2007), producing a thick uniform water mass known as Labrador Sea Water (LSW).

Once the convective winter ends, the Labrador Sea quickly restratifies itself within 2-3 months (Lilly et al., 1999), primarily due to large horizontal density gradients that form convective eddies (Lilly et al., 2003; Rieck et al., 2019) as a result of the deep convection period (Frajka-Williams et al., 2014). The boundary currents continuously shed eddies with relatively buoyant water towards the interior Labrador Sea (Straneo, 2006), increasing stratification. This occurs along the west Greenland and Labrador coasts, though research suggests that the former supplies more freshwater (Myers, 2005; Schmidt and Send, 2007; McGeehan and Maslowski, 2011; Pennelly et al., 2019).

LSW is exported out of the Labrador Sea primarily by the Deep Western Boundary Current (Kieke et al., 2009), though it also spreads eastwards at a slower rate. While LSW is the lightest component within the Deep Western Boundary Current, it is one of the water masses which make up the lower limb of the Atlantic Meridional Overturning Circulation (AMOC). As the overturning circulation transports a significant amount of heat and dissolved gasses between the equator and polar regions, changes in the production of deepwater can influence the overturning circulation and ultimately the climate (Bryden et al., 2005). With polar amplification driven by the positive ice-albedo feedback loop, additional freshwater from melted ice enters the EGC and WGC (Bamber et al., 2012). The Labrador Sea is experiencing an increase in freshwater that can be capable of capping convection and preventing LSW from being formed, ultimately reducing the AMOC strength (Böning et al., 2016). However, a non-local increase in the surface freshwater flux may promote AMOC strengthening (Cael and

Jansen, 2020) or compensate the local effects of additional freshwater (Latif et al., 2000). Long climate simulations allow investigation into any AMOC regime shifts that shorter, higher-resolution simulations may miss. With such different conclusions, freshwater's influence on the AMOC is not fully known and may vary at different convection regions.

While satellite altimetry provides a wealth of information including sea surface height anomalies, geostrophic currents, and waves, hydrographic cruises within the Labrador Sea are often limited to the restratification period when the Labrador Sea is more hospitable for scientific operations. Argo floats, autonomous drifting profilers which can sample down to 2000m, have become a popular instrument to acquire in-situ data. However, they still lack coverage within the Labrador Sea which can experience deep convection below their sampling depth (Yashayaev, 2007). Numerical modelling is a useful tool to explore this data-sparse region, though it has its limits. Simulations within the Labrador Sea often experience a drift in model data, producing a Labrador Sea which slowly increases in salinity, and thus density (Treguier et al., 2005; Rattan et al., 2010). Coarse-resolution simulations suffer even further, often overproducing the spatial area of deep convection (Courtois et al., 2017), primarily as a result of not resolving important small-scale features including eddies. These eddies supply the Labrador Sea with significant heat (Gelderloos et al., 2011) and freshwater fluxes (Hátún et al., 2007), both strongly impact the stratification, convection, and production of deep water. Increased horizontal resolution helps produce these eddies and their important fluxes into the interior of the Labrador Sea but numerical drift still is present within high-resolution simulations, albeit reduced in severity (Marzocchi et al., 2015).

Numerous high-resolution simulations have been carried out within the North Atlantic. VIKING20X (Rieck et al., 2019), and its predecessor VIKING20, are global 1/4° simulations which have a high-resolution 1/20° nest. VIKING20X is a multi-decade simulation which is capable of resolving eddies within the Labrador Sea. However, simulations with 1/20° horizontal resolution may not resolve sub-mesoscale processes (Su et al., 2018) that can impact stratification by carrying heat and freshwater; higher-resolution is needed. The 1/50° HYCOM (Chassignet and Xu, 2017), 1/60° NATL60 (Fresnay et al., 2018) and eNATL60 (Le Sommer et al., in prep) provide great insights on the importance of resolving eddies. However, computational expense with such high-resolution simulations is very high, both in computer time and operational costs. This often forces higher-resolution simulations to have a reduced length, perhaps only a few years. The Labrador Sea experiences significant interannual variability (Fischer et al., 2010) and such short simulations may completely miss any connection between LSW production and changes in the AMOC. As such, any high-resolution simulation which is capable of resolving the fine scale features within the Labrador Sea should be carried out for many years to further understand the climate system. Resolving the full North Atlantic at high resolution (1/60°) and carrying out a simulation for longer than 10 years would currently be extremely expensive; the above 1/60° simulations are 5 or so years in length. However, one can incorporate nested domains to increase horizontal resolution with a relatively minor increase in computing cost.

To simulate the Labrador Sea as accurately as possible, we set up a complex numerical configuration which achieves very high resolution within the Labrador Sea while keeping computing costs low such that we will produce over 15 years of simulated data. This simulation will be kept up to near-present time, lagged a few months depending on the availability of forcing data. The high resolution allows for explicit representation of eddies which are crucial to controlling the stratification within the region. We will first describe the model configuration in detail and then compare against similarly-forced lower-resolution simulations to understand how changes in horizontal resolution impacts model results in the Labrador Sea.

2. Methods

The numerical model used for our high-resolution simulation is the Nucleus for European Modelling of the Ocean (NEMO; Madec, 2008), version 3.6, which is coupled to a sea-ice model, LIM2 (Fichefet and Maqueda, 1997). The 1/4° Arctic Northern Hemisphere Atlantic configuration (ANHA4; Fig 1a) is used and includes a double nest via the Adaptive Grid Refinement in FORTRAN package (AGRIF; Debreu et al., 2008). The AGRIF software allows for high-resolution nests to communicate along their boundaries, passing information back and forth between domains. The parent ANHA4 domain extends from Bering Strait, though the Arctic and North Atlantic, to 20°S in the South Atlantic. The parent domain's nest uses a spatial and temporal refinement factor of three, bringing resolution to 1/12° and the time step to 240s

(Table 1) in the North Atlantic Sub Polar Gyre domain (SPG12; Fig 1b). An ANHA4 configuration with a SPG12 nest has been evaluated before by investigating how model resolution influences Labrador Sea Water formation (Garcia-Quintana et al., 2019) as well as eddy formation and eddy fluxes in the North Atlantic Current (Müller et al., 2017; Müller et al., 2019). Another nest is implemented within the SPG12 domain, using a spatial and temporal refinement of five, increasing the horizontal resolution from 1/12° to 1/60° and reducing the time step to 48s within the Labrador Sea (LAB60; Fig 1c). All nests allow two-way communication such that the parent domain supplies boundary conditions while the daughter domain returns interpolated values to all associated parent grid points. All domains have different horizontal grid spacing but they share the same vertical grid which is set to 75 geopotential levels (Fig. 1d) using partial steps (Barnier et al., 2006). This simulation involves three domains (ANHA4, SPG12, and LAB60) although we primarily discuss what occurs within the 1/60° nest.

A total variance dissipation scheme (Zalesak, 1979) was used in all domains to calculate horizontal advection. A Laplacian operator was used to compute lateral diffusion in all domains, while a bi-laplacian operator was used for lateral momentum mixing. As some model parameters are grid-scale dependent, Table 1 displays these settings. As lateral boundary conditions have been shown to be very important at producing Irminger Rings in high-resolution simulations (Rieck et al. 2019), we used no-slip lateral boundary conditions within the LAB60 domain while the other domains had free-slip conditions. Model mixed layer depths were calculated via the vertical gradient in temperature and salinity (Holte and Talley, 2009) as opposed to a 0.01 kg m^{-3} change in potential density between the surface and the bottom of the mixed layer; the latter method can produce deeper mixed layers than observations suggest (Courtois et al., 2017). Settings not listed in Table 1 indicate that all domains have an identical value or option; some of these important settings are shown in Table 2.

Model bathymetry was interpolated from the 1/60° ETOPO GEBCO dataset (Amante and Eakins, 2009) to each domain's grid with bathymetric smoothing along nest boundaries was carried out in order to conserve volume where the parent domain supplies boundary conditions to the daughter domain. All domains were initialized from GLORYS1v1 (Ferry et al., 2009), a global reanalysis ocean simulation, at the beginning of 2002. Monthly open boundary conditions (3D T, S, U, V, and 2D SSH and ice values) across Bering Strait and 20° S were supplied to the ANHA4 domain. These boundary conditions were linearly interpolated from monthly values, overriding the values within the boundary without the use of a sponge layer. Runoff was supplied via Dai et al. (2009) while we also included Greenland runoff as estimated from a surface mass-balance model (Bamber et al., 2012). Without an iceberg model functioning with the AGRIF software, we treated all solid runoff as a liquid, thus capturing the full freshwater mass at the cost of accuracy in the spatial and temporal placement of freshwater emitted from icebergs.

Precipitation, shortwave radiation, downward longwave radiation, 2 meter specific humidity, 2 meter temperature, 10 meter meridional and 10 meter zonal winds originally were supplied from the Canadian Meteorological Centre's Global Deterministic Prediction System's Reforecast product (CGRF; Smith et al., 2014). While high in temporal (hourly) and spatial resolution (33 km in the Labrador Sea), we found the air-sea fluxes were slightly too weak to sustain deep convection after 2010. Rather than start completely over, we switched the atmospheric forcing in 2007 (Fig. 2) when LAB60's mixed layer was still similar to observations. Starting on 1 Jan 2007, we used the DRAKKAR Forcing Set 5.2 (DFS; Dussin et al., 2016). DFS supplies data at 3 hour increments for wind, temperature, and humidity, while precipitation and radiation are daily. DFS has a spatial resolution which is approximately 45 km within the Labrador Sea. Our own analysis of the CGRF data showed a 2002-2015 average yearly heat loss of 47 W m^{-2} from the interior Labrador Sea while DFS removed 53 W m^{-2} (Pennelly and Myers, submitted). Increasing the horizontal resolution likely increased the horizontal buoyancy fluxes and rendered the CGRF's air-sea heat loss, which was appropriate in our ANHA4 and ANHA12 configuration, inadequate. The decision to swap to DFS was based on its greater heat loss, promoting a better mixed layer depth throughout the Labrador Sea, though a different forcing product will eventually be needed as DFS does not currently extend past 2017. Supplemental Fig. 1 depicts the difference in mixed layer depth between the LAB60 simulation forced by CGRF, when forced with CGRF through 2007 and then forced by DFS, as well as what ARGO observations suggest. The weaker air-sea heat loss as forced by the CGRF product leaves the mixed layer with little interannual variability that doesn't compare well with observations.

Early testing showed that adding passive tracers increases the computing resources required by about 20% per passive tracer. To keep the simulation from requiring too many resources, we limited LAB60 to three passive tracers:

1. Liquid runoff from Greenland
2. Irminger Water (T> 3.5°C, S>34.88) which flows westward past Cape Farwell (Fig. 3b)
3. Labrador Sea Water (σ_θ>27.68 kg m^{-3}) formed within the mixed layer of the Labrador Sea (Fig. 3c)

Runoff from Greenland was included due to the importance of Greenland's freshwater contribution to changes within the Labrador Sea. Water mass definitions for Irminger Water and Labrador Sea Water were selected based on previous studies (i.e. Kieke et al., 2006; Myers et al., 2007). Note that there is no maximum density criteria given to our Labrador Sea Water tracer- the tracer is formed throughout the water column until it reaches the bottom of the mixed layer. Figure 3 illustrates both the source regions as well as the tracer extent as of 1 Jan 2010. While these water masses have been studied before (Kieke et al., 2006; Myers et al., 2007; Böning et al., 2016), there has been no attempt to use them as passive tracers at a resolution higher than 1/20° (Böning et al., 2016).

The LAB60 simulation originally started on the Graham cluster of Compute Canada. Other high-resolution simulations often use thousands of computer processors but our simulation could not run on more than 672 CPUs on this cluster as it would stall during domain construction. The years 2002-2007 were carried out on Graham, after which a new allocation on a different high performance Compute Canada cluster, Niagara, became available to us. The LAB60 simulation on Niagara did not suffer from the same issue as it did on Graham and we were able to use many more processors. Initial testing found a substantial increase in the number of days simulated per job submission when the number of CPUs was increased from 672 to 3000; tests using 4000 CPUs showed no further improvement. Thus, we carried out the remainder of the LAB60 simulation with 3000 CPUs. Each job submission required around 22 hours to carry out, providing 40 days of model output. The real time to finish each 40 day submission naturally varied across the year, increasing during winter which we attribute to the sea-ice model.

A spin-up period (Fig. 2) was required as the model quickly went unstable and crashed. We attribute this to the interpolation of the 1/12° GLORYS1v1 data onto the LAB60 grid; the resulting data were not smooth enough and numerical noise was generated, leading to model failure. To reduce this noise, a gradual spin-up procedure took place. First, we kept the numerical timestep very low (2s in LAB60) when the model was initialized. We also set the 1/60° nests' eddy viscosity and diffusivity values to be equal to those within the SPG12 nest. We gradually increased the timestep and reduced the viscosity and diffusivity values over the first year (2002) to what is within Table 1. Other than also increasing the timestep to stay in line with LAB60, no other values were changed across the coarser ANHA4 and SPG12 domains. To allow LAB60 to adjust to the final settings, we consider the 2003 year to be an adjustment year (Fig. 2).

To assess the validity of LAB60, model results were compared against AVISO satellite data (https://www.aviso.altimetry.fr/), specifically U/V geostrophic velocities which are derived from the sea surface height. Argo profiler data (http://www.argo.net/) was also used to assess the mixed layer. Bottle data from cruise 18HUD20080520, accessed from CCHDO (https://cchdo.ucsd.edu/cruise/18HU20080520) on 10 April 2018 was used to compare observations across the AR7W section.

3. Model Simulation Results

To understand what is gained by resolving the Labrador Sea at 1/60°, we compare the output of our LAB60 simulation with similarly forced ANHA simulations at both 1/4° (ANHA4) and 1/12° (ANHA12). The large-scale circulation (top 50m) is shown for our 3 simulations (Fig. 4) as well as AVISO geostrophic velocities. All simulations have greater speed within the West Greenland Current (ANHA4: up to 0.8; ANHA12: 0.8; LAB60: 0.6; AVISO: 0.4 m s^{-1}) and Labrador Current (ANHA4: up to 0.6; ANHA12: 0.6; LAB60: 0.4; AVISO: 0.4 m s^{-1}) as altimetry observations suggest slower speeds here. However, Lin et al., (2018) found maximum speed up to 0.74 m s^{-1} along the west coast of Greenland. Both the ANHA4 and ANHA12 configuration have larger values further up the western coast of Greenland, as well as connecting the West Greenland Current and the Labrador Current; features that do not occur in both LAB60 and observations.

As LAB60 and observations have less average speed occurring within these boundary currents, we suspect that all configurations have some large differences in eddy activity, particularly where these boundary currents are.

Eddy kinetic energy (EKE: $0.5(\overline{U_g'^2} + \overline{V_g'^2})$, Fig. 5) was calculated from geostrophic velocity anomaly based on the sea level anomaly (SLA) from the 2004-2013 mean state:

$$U_g' = -\frac{g}{f}\frac{SLA}{\Delta y}$$

$$V_g' = -\frac{g}{f}\frac{SLA}{\Delta x}$$

where g is the gravitational constant, *f* is the Coriolis parameter, and Δy and Δx are model grid length. Overbars indicate the 2004-2013 mean value while primed variables indicate a deviation from the mean state. AVISO observations were already supplied as geostrophic velocities. High levels of EKE can be found along the west coast of Greenland (Fig. 5), extending into the interior of the basin around 62° N, as well as along the Labrador coast's shelf break. The path extending from the west coast of Greenland is mostly due to Irminger Rings which leave this coast and travel westward (Chanut et al., 2008). While the EKE extending from west Greenland enters the interior of the Labrador Sea, that which stems from the Labrador coast does not penetrate far into the interior. The ANHA4 simulation has low EKE along the west coast of Greenland (around 100 $cm^2\ s^{-2}$) and along the Labrador Coast's shelf break (10-30 $cm^2\ s^{-2}$). The ANHA12 simulation shows improvement, having much higher EKE extending from west Greenland (100-300 $cm^2\ s^{-2}$) however the EKE does not quite extend into the interior of the Labrador Sea but instead remains in the northern Labrador Sea. Furthermore, there is additional EKE along the Labrador shelf break (30-50 $cm^2\ s^{-2}$) compared against ANHA4. The LAB60 simulation shows further improvement as the EKE signature from the west Greenland coast is greater (100-1000 $cm^2\ s^{-2}$) and now enters into the interior of the Labrador Sea. A notable increase in EKE also occurs along the Labrador shelf break (100-200 $cm^2\ s^{-2}$) and within the interior Labrador Sea (10-100 $cm^2\ s^{-2}$). LAB60 matches well against observations along the west coast of Greenland and the Labrador shelf break (both above 1000 $cm^2\ s^{-2}$) as well as the interior Labrador Sea (10-100 $cm^2\ s^{-2}$). LS60's higher interior EKE may be partially from convective eddies that are formed during the wintertime. However, LAB60 has lower EKE within the Northwest Corner where ANHA4, ANHA12, and the observations exceed 1000 $cm^2 s^{-2}$ over a wide area. LAB60 matches the spatial distribution albeit with reduced EKE.

The differences in the EKE field between these configurations identify that each simulation is resolving features of varying spatial scales. The ANHA4 simulation, with low EKE within the Labrador Sea, does not adequately resolve eddies in this region, as illustrated with a snapshot of normalized model relative vorticity (Fig. 6). However, the larger scale meanders within the North Atlantic Current are visible. ANHA12 shows a greater degree of mesoscale features (50 to 500 km), though distinct eddies within the Labrador Sea are also not resolved. LAB60 resolves eddies along both the west coast of Greenland as well as the Labrador Coast. A video showing LAB60's normalized relative vorticity is shown in Supplementary Video 1.

A few Irminger Rings are shown in Fig. 7, a snapshot in time from 26 July 2007. A newly spawned ring (Fig. 7c) shows very strong surface speeds (up 0.6 m s^{-1} for Ring A; Fig. 7a) while older eddies to the south have reduced speeds (up to 0.3 m s^{-1} for Ring B; Fig. 7a). To investigate the stratification strength, we calculate the amount of energy needed to produce a neutrally stratified column extending down to some reference depth, *h*. This proxy, called convective energy, is given by:

$$Convective\ energy(h) = \frac{g}{Area} \int \int \left[h\, \rho_\theta(h) - \int_0^h \rho_\theta(z)\, dz \right] dA$$

where *g* is the gravitational constant, *Area* is the total surface area over our region of interest (Fig. 1c), *h* is the reference depth (2000m used in this study), $\rho_\theta(z)$ and $\rho_\theta(h)$ are the potential density at each grid cell and the potential density of the grid cell at the reference depth, and *A* is the surface area of each grid cell. A strongly stratified column of water corresponds to a high convective energy value. A snapshot of convective energy (Fig. 7b) shows that most of these eddies have substantially higher amounts compared to the background Labrador Sea, suggesting that the cool and fresh WGC water, as well as warm and salty Irminger Water keep these eddies strongly stratified. However, these eddies age within the Labrador Sea, and while a new eddy has strong stratification (>3000 J m^{-3}), an eddy which has evolved over many months (Fig. 7d) has weaker stratification (about 2000 J m^{-3}). Older eddies may have very weak stratification as they may have experienced two convective winter periods of buoyancy removal. This has been noted before, as Lilly et al. (2003) found aged Irminger Rings with a mixed layer that surpassed 1000m.

These differences in resolving the mesoscale (50 to 500 km) and sub-mesoscale (<50 km) processes within each simulation produced significant changes within the Labrador Sea as seen from modeled convective energy values as averaged from 2004-2013 (Fig. 8). Resolving few eddies, the ANHA4 simulation's interior Labrador Sea lacks the buoyancy flux and remains very weakly stratified across a wide region. The ANHA12 simulation partially resolves some mesoscale features and eddy fluxes from the Greenland coast which supplies buoyancy to the Northern Labrador Sea and has higher convective energy. Furthermore, the spatial extent of the weakly stratified region has shrunk and resides primarily within the Labrador Sea, as opposed to ANHA4 which spills out of the basin. LAB60, fully capable of resolving buoyant eddies from the Greenland and Labrador coast, as well as convective eddies, has a much stronger degree of stratification in the interior region. A visible path of strong stratification appears around 60°N along this coastline, eventually extending away from the coastline around 62°N. This path is consistent with the general path that simulated Irminger Rings take (Chanut et al., 2008). Supplemental Video 2 shows the convective energy of the LAB60 simulation from 2004 through the end of 2013.

The ANHA4 simulation experiences weaker stratification in the Labrador Sea than ANHA12 and LAB60, driving a deeper maximum mixed layer that also covers a larger spatial extent (Fig. 9). However, the maximum mixed layer depth as simulated by ANHA4 and ANHA12 greatly exceed what Argo observations suggest (Fig. 9d). ANHA12 has higher EKE within the WGC, supplying more buoyancy to the northern portion of the Labrador Sea, reducing both the vertical extent of the mixed layer as well as the spatial extent where the mixed layer is deeper than 1000m. LAB60 has higher EKE than ANHA12, and the vertical and spatial extent of deep mixing is reduced even further. LAB60's mixed layer is far more similar to what ARGO observations suggest, suggesting the additional eddy fluxes to be fairly accurate. The evolution of LAB60's mixed layer depth is shown in supplemental video 3 from 2004 through the end of 2013.

After the bottom of the mixed layer returns to the near-surface, a newly formed LSW mass is left behind. To account for density drift, we allow the LSW classification to evolve in time, unlike our LSW passive tracer. We calculated LSW density and thickness by binning by potential density, referenced to 1000 dbar, with bin lengths of 0.001 kg m^{-3}. This was carried out within the black outlined polygon in Fig 1c for each daily output file per year. The density bin which had the thickest layer across the year was set as the maximum density of LSW for that year. The minimum density was defined to be 0.02 kg m^{-3} less than the maximum density. Linear interpolation occurred between years to allow for a gradual shift in density to prevent staircase patterns from emerging. Large differences in both the density as well as the thickness are present between the simulations shown in Fig. 10. The ANHA4 and ANHA12 simulations have similar density values of LSW while the LAB60 simulation is less dense. While the interannual variability matches fairly well across all configurations, the density values suggested by LAB60 match far closer to ARGO observations (32.34 to 32.36 kg m^{-3}; Yashayaev and Loder, 2016) during the same time period. We suspect the denser LSW formed by ANHA4 and ANHA12 is primarily attributed to the lack of buoyancy coming from Greenland. As similar air-sea heat losses should occur in all three configurations, the weaker stratification of ANHA4 and ANHA12 indicates that deep mixing is more likely producing not only a denser LSW layer, but also a thicker one. Yashayaev and Loder (2016) also investigated the thickness of LSW (their Fig. 8), and while our simulations do not quite capture the same interannual variability and amplitude suggested their analysis using ARGO profilers, LAB60 is far more accurate than the lower-resolution configurations.

All simulations encounter some degree of numerical drift within the Labrador Sea (Fig. 11), judging from the salt and heat content change as calculated between the surface and seafloor within the polygon in Figure 1 since 2004. ANHA4 experiences the most drift in both salt and heat, helping us understand why LSW is so dense in this simulation. ANHA12 also experiences drift, though slightly less severe. LAB60 has a small but gradual increase in both salt and heat content although it is difficult to state if this is drift or simply interannual to decadal variability. Regardless of the cause, LAB60's change in both heat and salt content is very minimal compared against the lower-resolution simulations.

When compared against observations across the Atlantic Repeat Hydrography Line 7 West (AR7W; Fig 12), LAB60 is slightly warmer (about 0.25 °C) and saltier (about 0.05 kg m^{-3}) throughout the interior. This causes LAB60 to be slightly denser with isopycnals residing higher than observations during this cruise suggest. Observations were not carried out above Greenland's continental slope, although they show some presence of the warm core of the WGC which the model captures. Salinity values close to the Labrador coast compare well while LAB60 is slightly warmer (about 0.5 °C) above the continental shelf.

The three passive tracers implemented within the full LAB60 configuration (Fig. 3) show where Greenland runoff, Irminger Water, and Labrador Sea Water travel to. These tracers were selected because they either contain a significant amount of buoyant water compared to the Labrador Sea, or are produced via convection in the Labrador Sea. From this image on 1 Jan 2010, we see a large portion of Greenland's runoff (Fig. 3a) resides within Baffin Bay as well as along the Labrador Coast. Some of this tracer is present where the ocean depth is greater than 2000m. A few Irminger Rings are identifiable, due to their thicker freshwater cap, which are in water deeper than 3000m. Little exchange appears to occur along the Labrador Current until the vicinity of Flemish Cap, after which a significant portion of the tracer propagates eastward. Supplemental Video 4 shows this the evolution of this tracer from 2004 through the end of 2013.

Irminger Water (T>3.5°C, S> 34.88; Fig. 3b) which flows west past Cape Farwell, enters the interior Labrador Sea with the greatest amounts where the seafloor is at a depth between 2000 and 3000m. Similar as above, individual Irminger Rings are visible, containing a larger amount of Irminger Water than the surrounding water. This water mass also flows along the Labrador Coast until it is in the vicinity of Flemish Cap. Supplemental Video 5 shows this the evolution of this tracer from 2004 through the end of 2013.

Our Labrador Sea Water tracer (Fig. 3c) is traced where the mixed layer produces water with a potential density above 1027.68 kg m^{-3} within the black contour identified in the figure. This definition differs compared to our method of classifying LSW as we did not implement any FORTRAN code to detect and compensate for density drift of our simulation, instead sticking to a strict density classification for this tracer. As this image was made at the start of the convection season, the current deep patch is a freshly produced layer that reaches up to 800m deep. After forming, LSW spreads southwards along the Labrador shelf break as well as to the southeast. Supplemental Video 6 shows this the evolution of this tracer from 2004 through the end of 2013.

4. Discussion

We describe a 10+ year long, high-resolution simulation which achieves 1/60° horizontal resolution in the Labrador Sea via two nests inside a regional configuration, resolving mesoscale and sub-mesoscale processes which strongly impact the deep convection which occurs here. We show that lower-resolution simulations fail to resolve these key processes that strongly control the production of Labrador Sea Water, an important water mass within the Atlantic Meridional Overturning Circulation. While the NATL60 and eNATL60 simulations were designed with the SWOT altimetry satellite mission in mind (NATL60 website: https://meom-group.github.io/swot-natl60/virtual-ocean.html), their integration period, like many other high-resolution simulations, is a handful of years. LAB60, although covering a much smaller region, could be a valuable asset to many users who require a lengthy period of high-resolution model output. We also have included three passive tracers which are often excluded in simulations at this resolution. Our three passive tracers highlight regions where each water mass enters the interior region of the Labrador Sea, demonstrating the pathways of buoyant Greenland melt and Irminger water. Furthermore, we trace Labrador Sea Water which is formed during the convective winter period.

We show that LAB60 has greater EKE than our lower-resolution simulation, resolving eddy fluxes including Irminger Rings, boundary current eddies, and likely convective eddies as indicated by greater EKE within the interior. Boundary current eddies still appear relatively disconnected from the interior basin, adding further support that these eddies have limited influence on convection and restratification (Rieck et al., 2019). We offer no additional support regarding the relative importance of Irminger Rings and convective eddies on controlling deep convection; this is currently being investigated for a later manuscript. Model drift appears very low, a large improvement over the ANHA4 and ANHA12 configurations. The drift might produce slightly denser LSW than observations suggest, however LAB60s density is much more accurate than ANHA4 and ANHA12. The boundaries of LAB60, supplied by the inner SPG12 nest, may influence the high-resolution nest. We note that the North Atlantic Current, which is close to the boundary, has less EKE and vorticity than the ANHA4 and ANHA12 simulations. Conversely, the WGC close to the eastern nested boundary has multiple jets which have been noted in hydrographic data (Pickart, personal communication). Boundary communication is always a concern in nested simulations and LAB60 is no different. More investigation will reveal any potential boundary issues but our results so far indicate no further areas of potential concern.

Others have investigated the Labrador Sea using numerical simulations with different resolution. Böning et al. (2016) traced Greenland meltwater with the 1/20° VIKING20 and 1/4° ORCA025 simulations, noting more meltwater entered the interior Labrador Sea at higher resolution partially as a result of greater WGC eddy fluxes but not from the Labrador coast. The minor amount of eddy fluxes from the Labrador coast has been noted earlier even at lower resolution (1/3°; Myers, 2005). Steadily increasing horizontal resolution has so far not changed this for the Labrador coast, though this is opposite for the WGC. LAB60 has a clear increase in EKE and likely greater eddy fluxes from the WGC into the interior of the Labrador Sea.

We have many ambitious research topics which we plan to use LAB60 to investigate. This includes, but is not limited to, the variability and structure of the West Greenland Coastal Current, Labrador Sea Water production, and the role of both Irminger Rings and convective eddies in controlling stratification in the Labrador Sea. This lengthy high-resolution simulation with three passive tracers will provide valuable information for many numerical studies within the Labrador Sea for years to come.

Code and/or data availability

The FORTRAN code used to carry out the LAB60 simulation can be accessed from the NEMO version 3.6 repository (https://forge.ipsl.jussieu.fr/nemo/browser/NEMO/releases/release-3.6). A few FORTRAN files were modified to handle our passive tracers. The complete FORTRAN files as well as the CPP.keys, namelists, and associated files can be found on Zenodo (Pennelly, 2020). Initial and boundary conditions, atmospheric forcing, and numerical output were too large to host on a repository and instead are hosted on our lab's servers as well as the Compute Canada Niagara server. These data can be requested by emailing the corresponding author.

Author Contribution

PM designed the layout of the LAB60 configuration which included the region of interest, numerical length, and which forcing and initial conditions to supply, as well as supervised CP. CP produced the configuration, modified the FORTRAN code, set up the configuration on the high-performance computing systems, carried out the simulation, and performed the analysis. The manuscript was prepared by CP with contributions by PM.

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The authors declare that they have no conflict of interest.

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Tables

Table 1: Domain settings for the ANHA4 parent domain, SPG12 and LAB60 nested domains. Other settings which are invariant to the domain are shown in Table 2.

Setting	ANHA4	SPG12	LAB60
Horz. Resolution	1/4°	1/12°	1/60°
X points	544	724	1179
Y points	800	694	2659
Timestep [s]	720	240	48
Horiz. Eddy Viscosity [$m^4 s^{-1}$]	1.5x10^11	1.5x10^10	3.5x10^8
Horiz. Eddy Diffusivity [$m^2 s^{-1}$]	300	50	20
Lateral Slip Conditions	Free slip	Free slip	No slip

Table 2: Model configuration settings which are identical between all three domains. **Bold** values indicate values which were changed when we migrated LAB60 from the Graham cluster to Niagara.

Configuration Setting		Value
Vertical grid		75 geopotential levels
Sea-ice model		LIM 2 (Fichefet and Maqueda, 1997)
Bulk formula		CORE (Large and Yeager, 2008)
Liquid discharge		Dia et al. (2009) + Bamber (2012: Greenland)
Solid discharge		Input as liquid
Surface Restoring		None
Initial conditions		Glorys1v1 (T,S,U,V,SSH,ice)
Open boundary conditions		Glorys1v1 (T,S,U,V,ice)
Atmospheric forcing:		
	2002-2006	CGRF (Smith et al, 2014)
	2007-2017	Drakkar Forcing Set 5.2 (Dussin et al. 2016)
Lateral momentum		Bilaplacian operator
Lateral diffusion		Laplacian operator
Vertical eddy viscosity		1x10^-4 $m^2 s^{-1}$
Vertical eddy diffusivity		1x10^-5 $m^2 s^{-1}$
Mixed layer scheme		Holte and Talley (2009)
Bottom friction		Nonlinear
Hydrostatic approximation		Yes
Passive tracers		Three (see Figure 2)
CPU requested		672 (**3000**), Broadwell 2.1 GHz (Skylake 2.4 GHz)
Time to complete 1 year		Approximately 700 (**200**) hours
Initialization date		January 1st, 2002

Figures

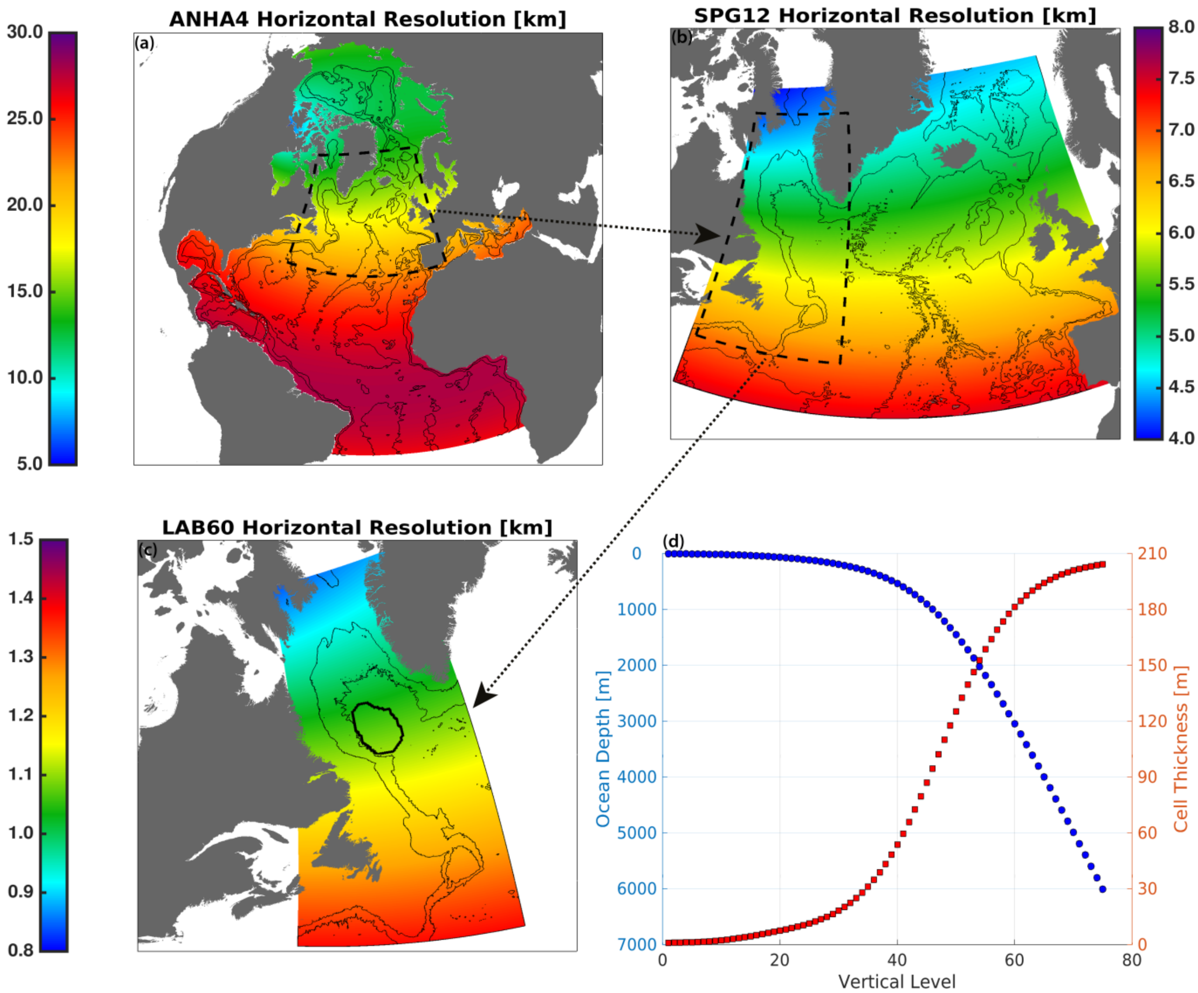

Figure 1: Domain setup for the (a) ANHA4 parent domain, (b) the SPG12 nest, and (c) the LAB60 nest. Horizontal grid resolution, in km, is identified by color. All domains share identical vertical grid structure (d). The thick black contour in (c) identifies a region of interest where calculations of LSW's density, thickness, and mixed layer depth are determined. The 1000m, 3000m, and 5000m isobaths are shown via the thin black contours.

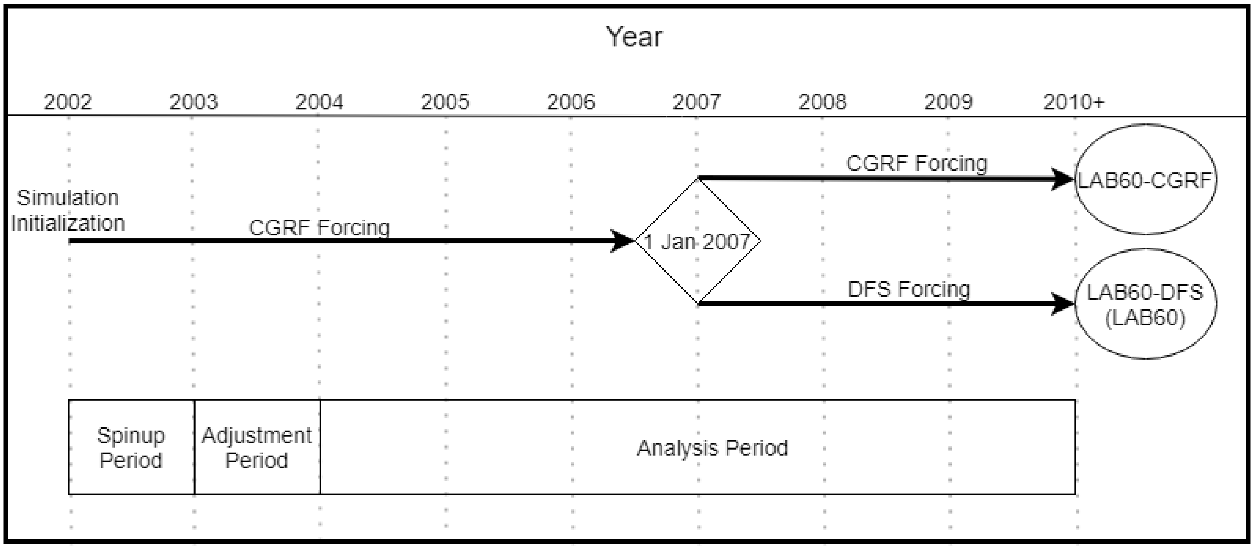

Figure 2: Diagram showing the multiple periods of the LAB60 simulation. The original simulation was initialized with CGRF atmospheric forcing in 2002, although a branch swapping to DFS occurred at the start of 2007. This DFS branch is what is primarily presented in this study.

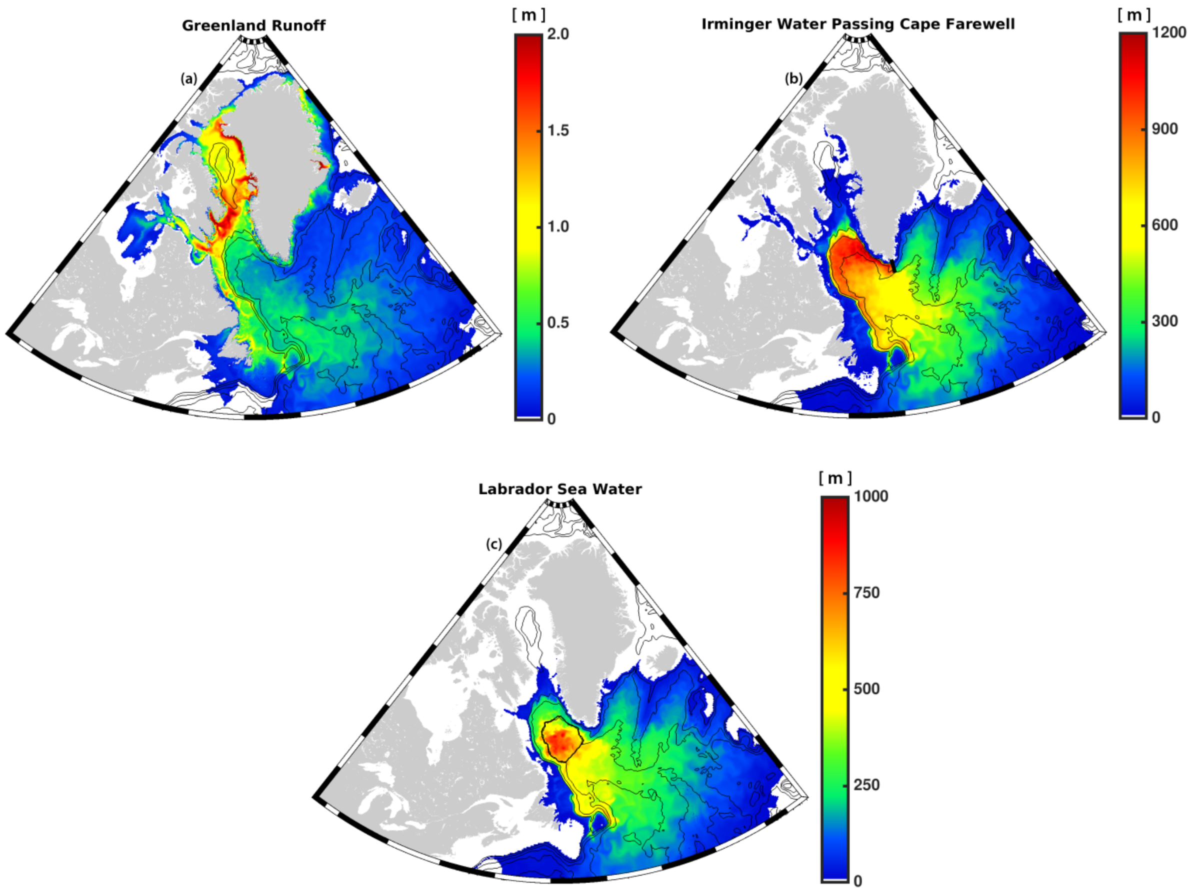

Figure 3: The three passive tracers used within our LAB60 simulation with source regions indicated by thick black lines: (a) Greenland runoff, (b) Irminger Water (T > 3.5°C, S > 34.88) which flows west past Cape Farwell, and (c) Labrador Sea Water (σ_θ>27.68 kg m^{-3}) produced each convective season. Images are from the simulation date 1 Jan 2010. Bathymetric contours are every 1000m. Units are the thickness, in meters, of the tracer. Note: as all three domains are included in this figure, spatial resolution changes within each subfigure.

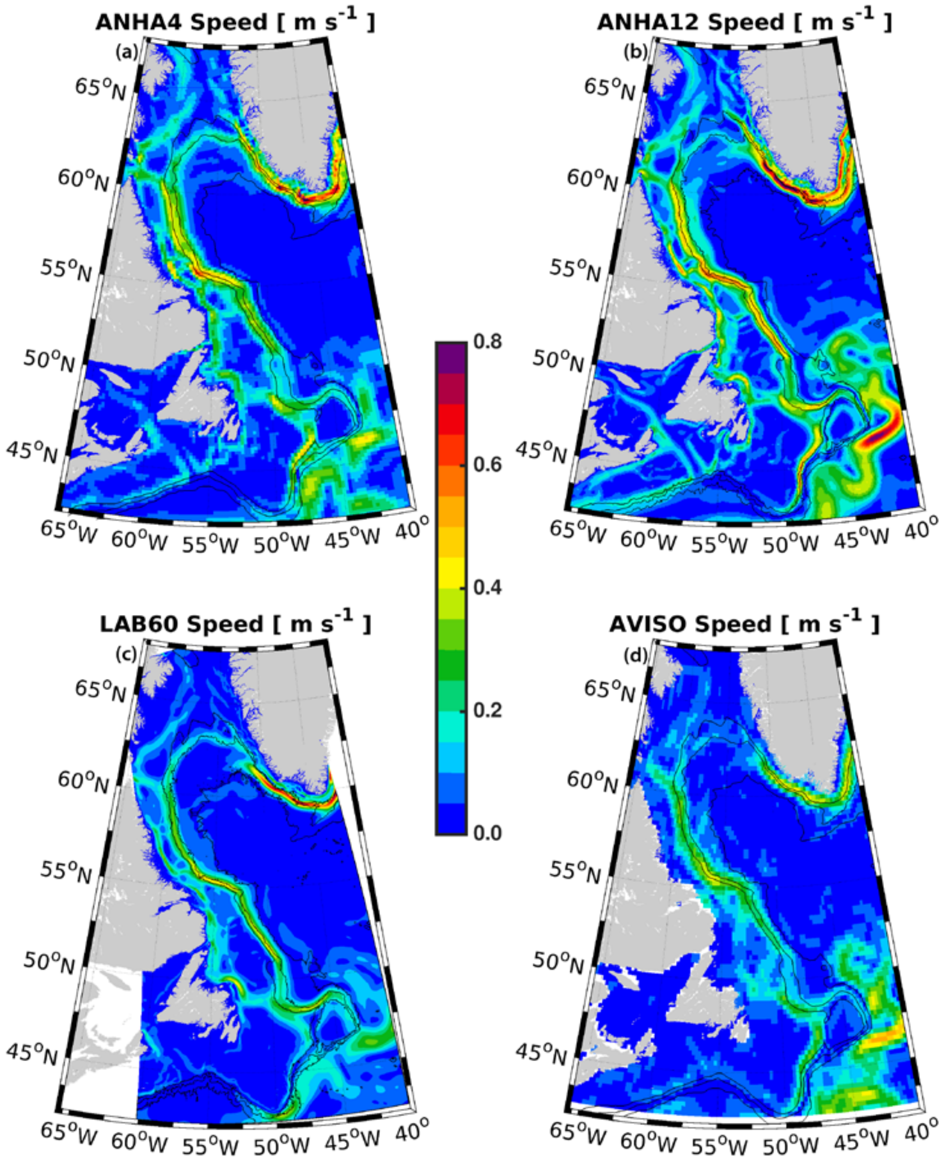

Figure 4: Top 50m average speed (2004-2013) for the (a) ANHA4, (b) ANHA12, (c) and LAB60 simulations, as well as (d) from AVISO observations. The 1000, 2000, and 3000m isobaths are shown by the black contour lines.

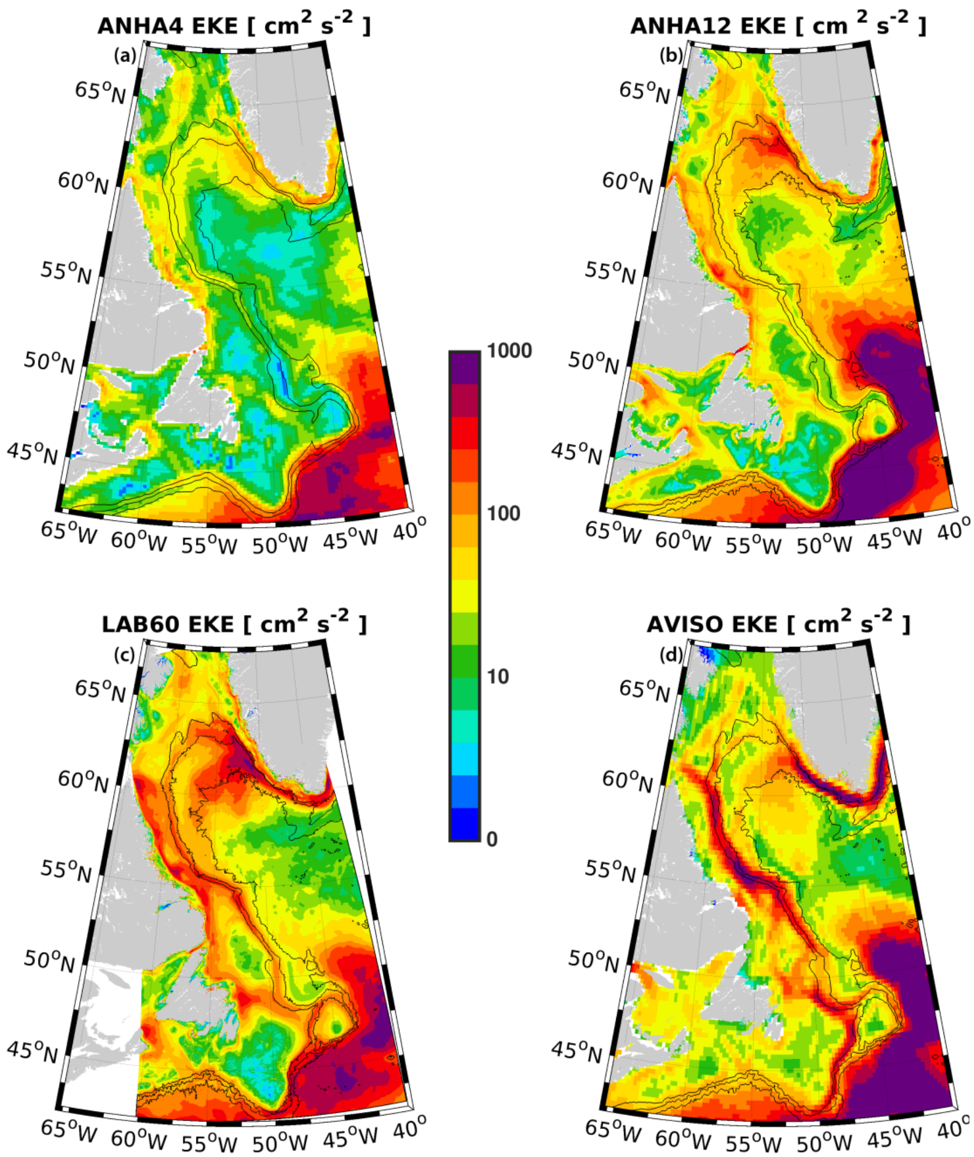

Figure 5: Eddy kinetic energy (EKE), as calculated from geostrophic velocities resulting from the sea level height anomaly, are shown for (a) ANHA4, (b) ANHA12, and (c) our LAB60 simulation, from 2004 to 2013. Observations via AVISO are identified in (d). The 1000m, 2000m, and 3000m isobaths are shown by the black contour lines. A log scale was used for clarity.

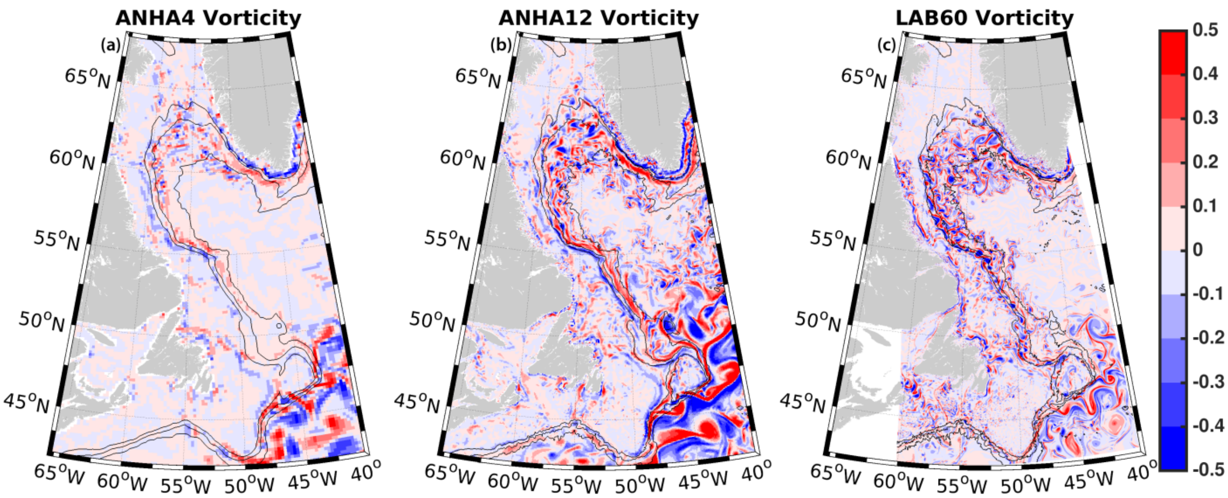

Figure 6: Top 50m relative vorticity, normalized by the planetary vorticity, as simulated by (a) ANHA4, (b) ANHA12, and (c) LAB60 on 16 March 2008. The 1000m, 2000m, and 3000m isobaths are shown by the black contour lines.

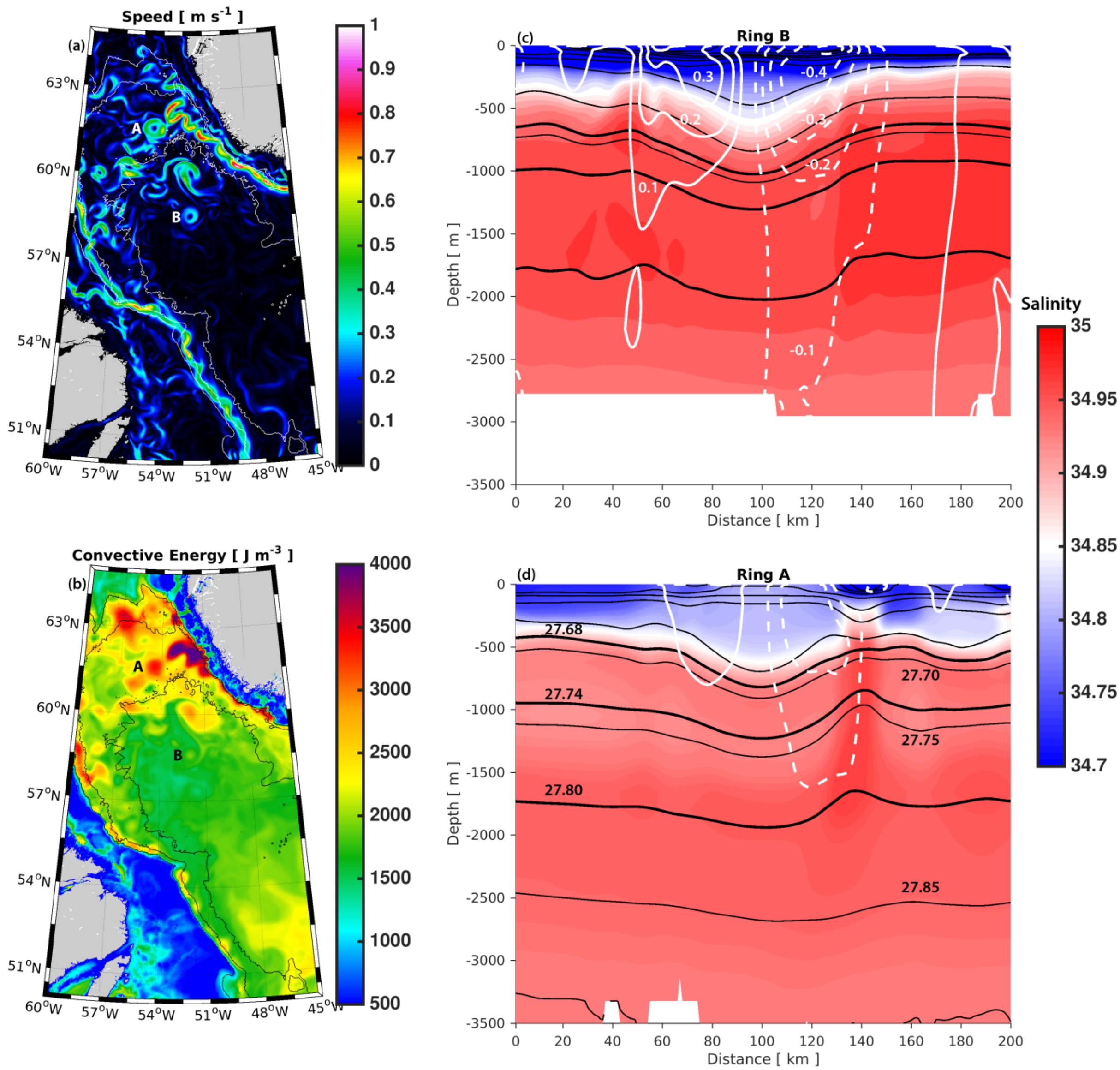

Figure 7: LAB60 snapshot (26 July 2007) of the surface speed (a) and convective energy (b) within the Labrador Sea. Two Irminger Rings are identified by their age with letters: Ring A is a young Irminger Ring, while Ring B is comparatively older. An east-west cross section through each of these Irminger Rings is shown in (c) and (d) where colors indicate salinity, black contours indicate potential density using a contour interval of 0.05 kg m^{-3}, and white contours indicate meridional velocity where southern flow is dashed and northern flow is solid, using a contour interval of 0.1 m s^{-1}. Thick black contours indicate the potential density classification of Upper Labrador Sea Water (σ_θ=27.68 to 27.74 kg m^{-3}) and Classical Labrador Sea Water (σ_θ= 27.74 to 27.80 kg m^{-3}).

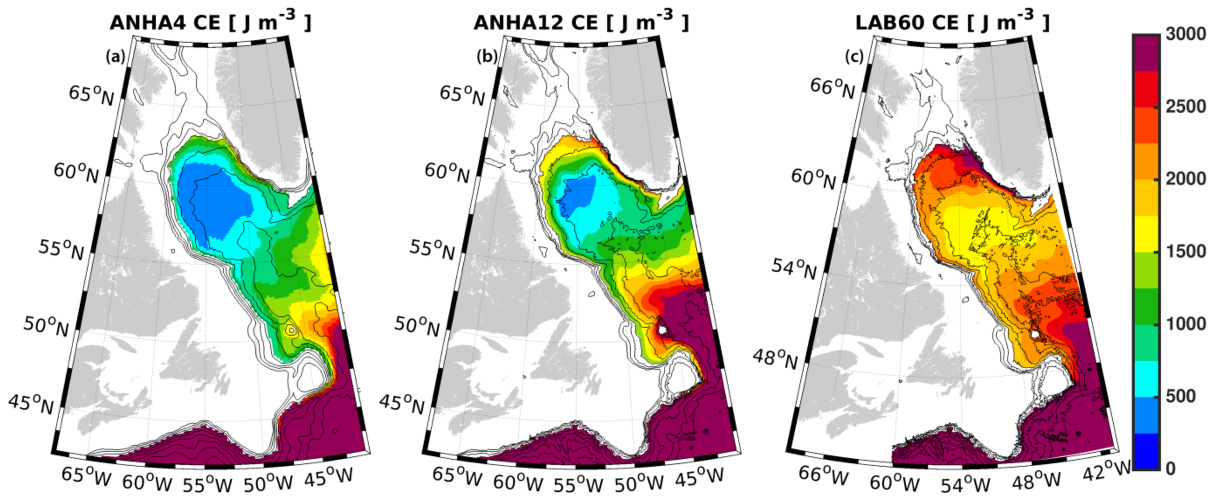

Figure 8: Convective energy (CE), the strength of stratification down to a reference depth of 2000m, is shown for (a) ANHA4, (b) ANHA12, and (c) LAB60. Convective energy was averaged from 2004 through 2013. Values where the depth of the seafloor was less than 2000m were removed to preserve clarity. Bathymetric contours (black lines) are shown every 500m.

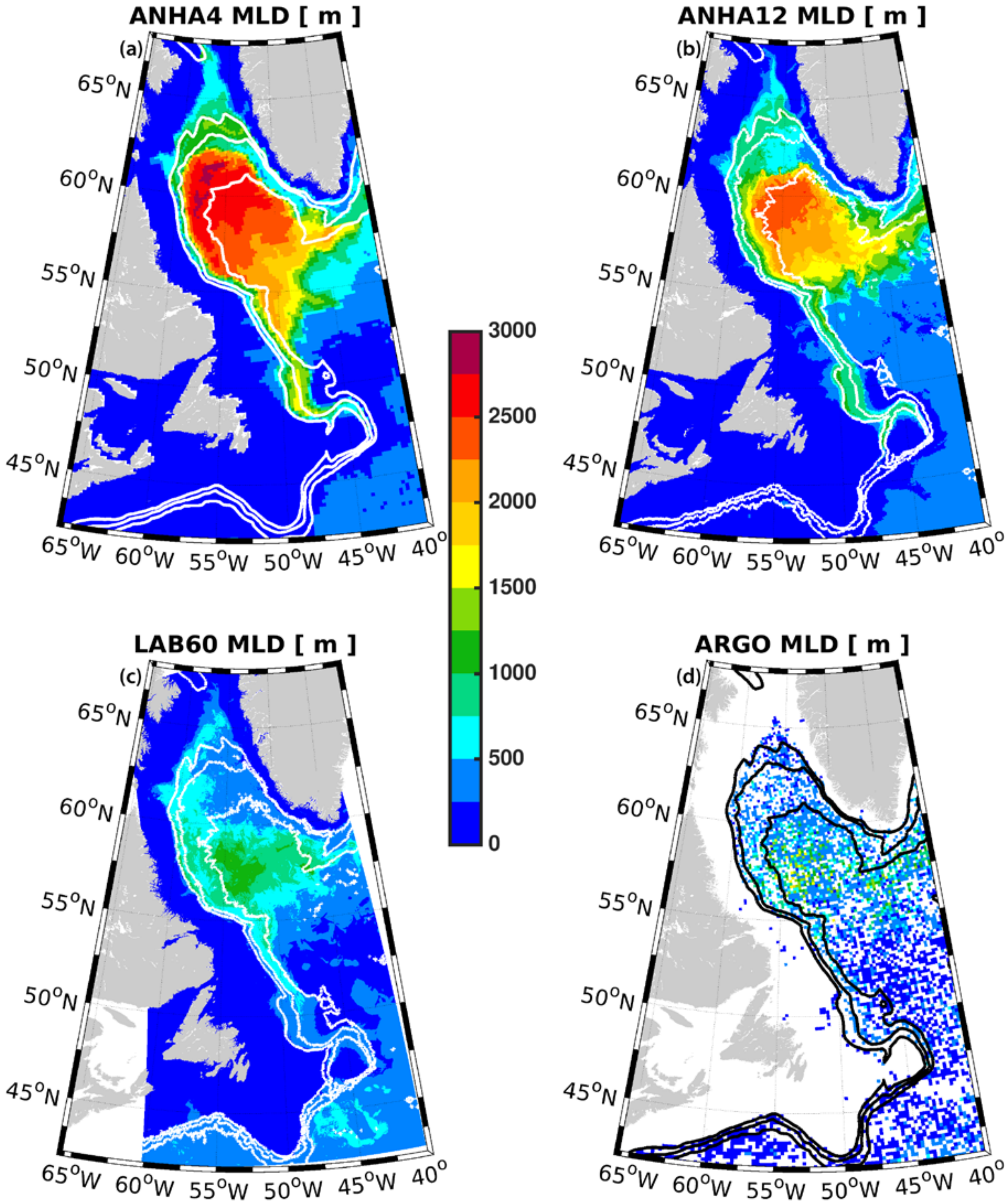

Figure 9: Maximum mixed layer depth for (a) ANHA4, (b) ANHA12, (c) LAB60, as well as (d) ARGO observations, where available, from 2004 through the end of 2013. For clarity, the ARGO data were placed on the same grid as ANHA4. The 1000m, 2000m, and 3000m isobaths are shown via the white and black contours

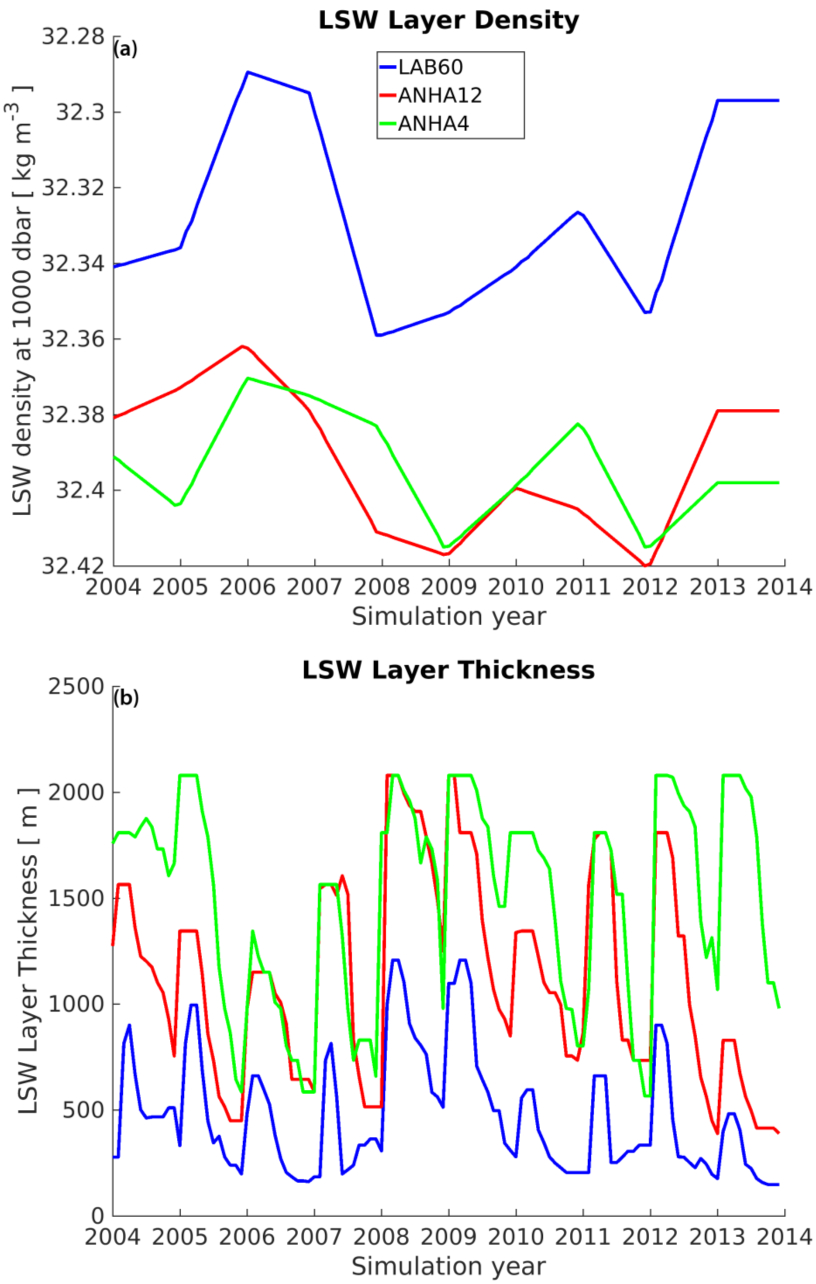

Figure 10: Labrador Sea Water (LSW) density (a) and thickness (b) for the LAB60, ANHA12, and ANHA4 configurations. LSW density was determined from the thickest layer where a 0.001 kg m^{-3} change in potential density (ref: 1000 dbar) occurred within the black polygon outlines in Fig 1c. The LSW layer was then calculated between this density and one which was 0.02 kg m^{-3} less dense.

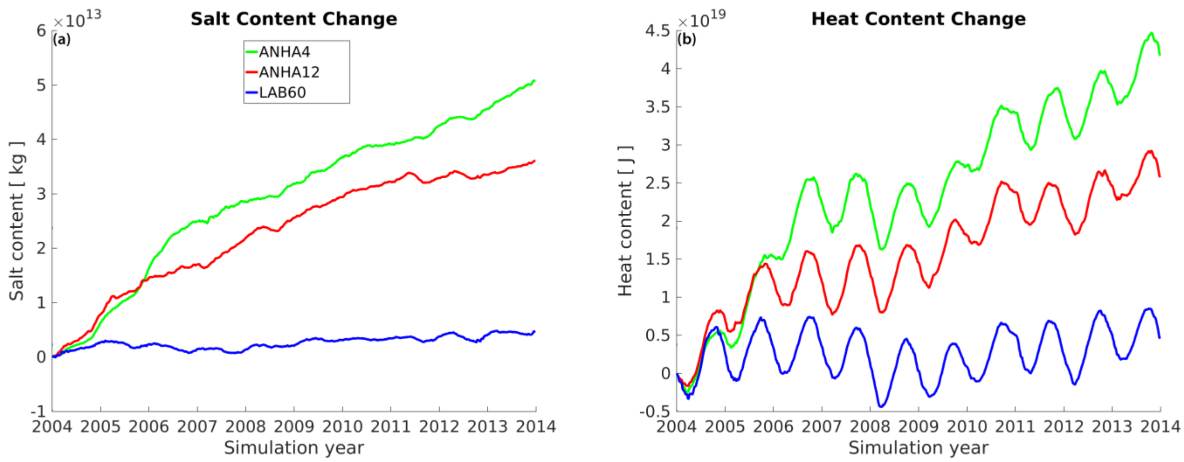

Figure 11: Numerical salt (a) and heat (b) drift in our three simulations as they evolve since 1 Jan 2004. Salt and heat content is calculated over the full ocean column within the polygon in Fig. 1c.

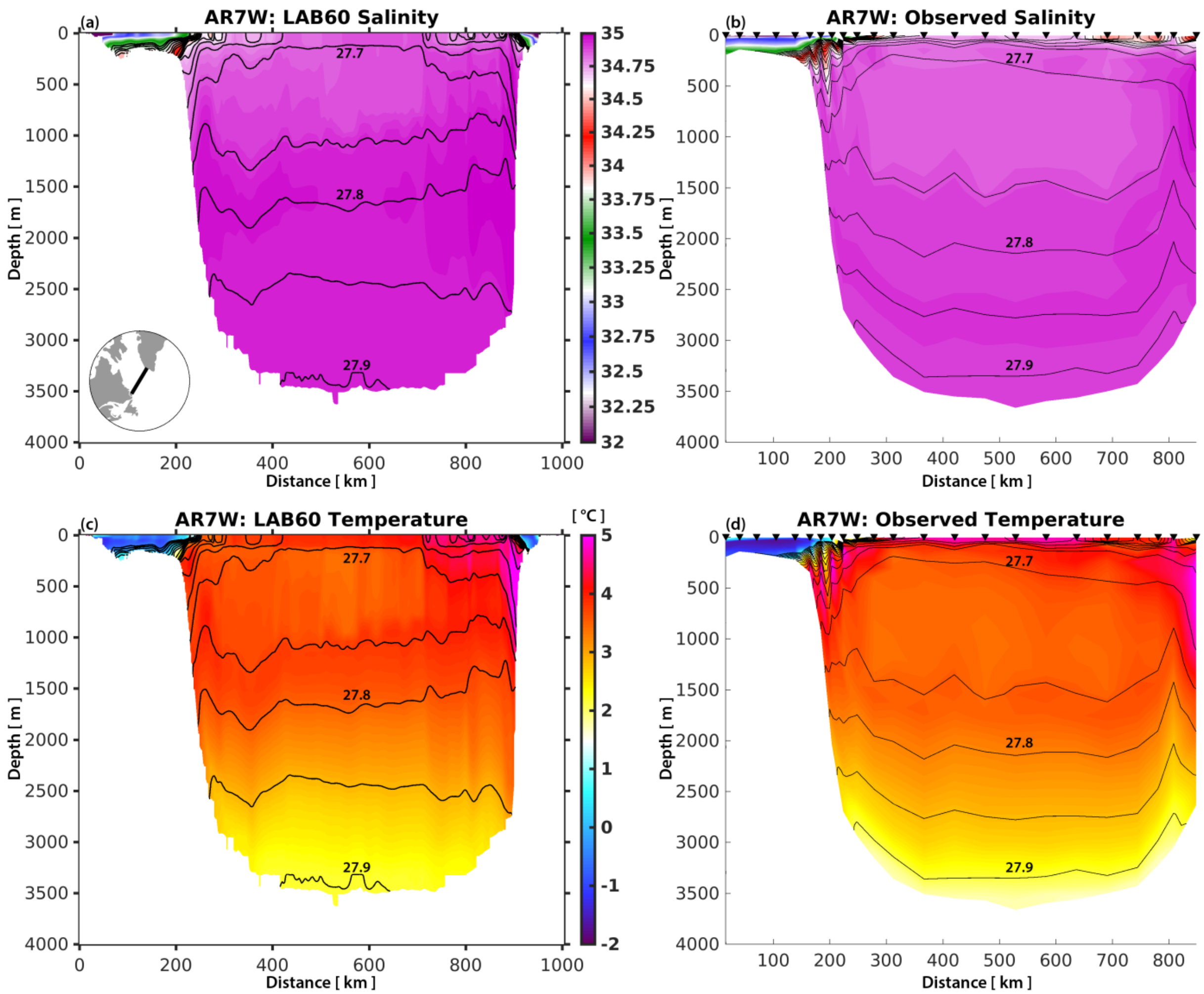

Figure 12: Salinity (top) and temperature (bottom) section across AR7W as determined by the LAB60 simulation (left) and observations (right) from May 2008. Downward triangles identify collection sites across the AR7W transit carried out by the CCGS Hudson. Potential density (black contours) isopycnal interval is 0.05 kg m^{-3}.