# Response to reviewer 1

May 7, 2018

The authors thank the reviewer for their careful reading of our discussion paper, and for their helpful and constructive comments regarding its content and improvement. The text of the review is reproduced below in black type; our comments are in blue; and changes to the original discussion paper are presented in italics.

This manuscript looks at the exchange of fresh shelf water into the Labrador Sea using a high resolution numerical model and Lagrangian trajectories. The authors find that much of the freshwater that reaches the interior of the Labrador Sea comes from the West Greenland Current (which isn't a new result). But they expand on this work, by showing two seasonal pulses, associated with different geographical positions (southeast, northwest) and different salinity waters. Where this work truly expands upon previous studies is showing the key role of wind-driven Ekman transport compared to the typical view of eddy driven exchange. Given this is an important topic (fate of enhanced high latitude freshwater on water formation in the Labrador Sea), this work is appropriate for the journal. It is a well written paper, easy to follow and understand. Thus it is definitely will be eventually suitable for publishing in Ocean Science. However, there are a few places where the manuscript could be improved upon. Thus I recommend minor revisions. Details of my comments are given below.

**Introduction General:** Although the introduction provides a good summary, it feels a bit short. More discussion of previous work related to offshore exchange in the Labrador Sea can be added. Both with respect to observational studies, but especially with respect to previous modelling works. Since the authors are going to dispute the commonly held paradigm that eddies are the main exchange mechanism from the WGC, they need to discuss the previous modelling works that have highlighted that mechanism (and then in the discussion try to bring out why the present results are different). Beyond papers listed such as Chanut et al, there are newer studies such as McGeehan and Maslowski, Gelderoos et al., Kawaski and Hasumi, Saenko et al., Dukhovskoy et al to name a few.
Thank you for the suggested papers.  We have highlighted previous model (in addition to Chanut et al.) that suggest that eddies are the main exchange mechanism from the WGC. Additional discussion was added.

Page 2, Line 11: ? in the references needs to be filled in
This has been fixed

Page 2, Line 28: But doesn't the Cooke paper use a very coarse resolution model, making it easy for freshwater to leave the Labrador Current. If so, this point could be clarified
Yes, Cooke's paper uses a ¼ degree model. We now also noted this in the manuscript.

> ***P3. L80.*** *Using a 1/4$^o$ model, Cooke et al. (2014) argue that the instabilities could indicate a direct connection between the Labrador Current and central basin salinities. Such a connection would further support the idea of a Labrador Current source to the fall freshening in the central Labrador Sea, but the dynamics are not further discussed and the coarse model allows freshwater to leave the Labrador Current more easily than might be the case in the real ocean.*

**General:** At some places in the manuscript the authors report salinities as dimensionless, and in others places use psu as a unit. At the very least the authors must be consistent.
Thank you for noting this. We made sure that this is consistent throughout the manuscript opting for the more modern dimensionless salinity.

Page 4, Line 19: More detail on the lateral boundary conditions in the region, and the impact of that choice would be useful.
We limit the information here to the sentence:

> ***P6. L.178.*** *" No-slip conditions are implemented at the lateral boundaries - except in the Labrador Sea where a region of partial slip is applied. This is done to favor the break up of the West Greenland Current into eddies (as observations have suggested)."*

Page 4, Line 31 – is used…
This has been changed as suggested.

Page 5, 1st paragraph: Changes implemented in the model are listed as 1), 2) and 4). Where is number 3?
This was a typo and has been fixed. We also re-worded this paragraph slightly

> ***P7. L.194.*** *To improve the NEMO 1/4$^{o}$ run, changes were incorporated in the 1/12$^{o}$ run used here to better represent boundary currents, interannual variability and depth of mixed layers. These changes were: 1) more consistent wind forcing reaching back to 1958 (more information at www.drakkar-ocean.eu/forcing-the-ocean/the-making-of-the-drakkar-forcing-set-dfs5), 2) steeper topography along the Greenland Coast and 3) use of a partial slip along western Greenland. Together with the changes in topography, the partial slip condition promotes the formation of eddies in this region which results in improved salinity and velocities fields (Figure 1). The simulation used in this study was previously used in other studies of the North Atlantic, one of which found that the model represents the variability of heat transport at 26.5$^{o}$ N.*

Page 5 – in terms of evaluation, given the importance of the West Greenland Current to the paper, it might be good to see further evaluation of the model representation of this feature. I.e. Don't just focus on the EKE in terms of observational comparisons.
Evaluating the West Greenland Current in the model would be useful to understand if the transport and freshwater content of the WGC in the model agrees with observations. Here we decided to concentrate on the EKE since this is regarded as a measure of the West Greenland Currents stability and the region from which eddies are most commonly shed.

Page 6, Line 22: Badly worded sentence with place/placed used an extra time
This sentence has been fixed

> ***P.10 l.286***. *To determine the impact of wind vs. eddies on surface freshwater fluxes into the Labrador Sea, we release particles at three different depths (0 m, 15 m, and 30 m).*

Section 2.6 – The calculation of Ekman transport is discussed here, but the sections for which it is computed are not shown until the white line in figure 7. Be good to show that earlier.

Additionally, how close is that line to the actual isobaths in the model? Does the line follow a model grid line?
We added the sections (shown in Figure 7) to Figure 2.
The sections do not follow a model grid line. Instead it they smooth the isobaths to create a straight line. However, this was tried with multiple lengths of sections (not shown) and we conclude that changing the angle and/or length of the sections does not change the overall results.

Page 10, line 12 – looks like there is weak EKE in late summer too.
We have re-worded this to be more quantitative rather than to refer to the EKE as "strong/weak"

> ***p.15 l.449*** *Three-monthly composites of EKE and wind speeds show that the northeast portion of the Labrador Sea experiences EKE of up to 500 $cm^2/s^2$ in the spring and winter, up to 400 cm2/s2 in the summer and up to 200 $cm^2/s^2$ in the fall.*

Section 4.2.1 – Does the 3 month averaging remove eddies and thus the damp the potential importance of this term?
This is a very interesting point. Averaging SSH in time would remove some eddy effects. However, here we have calculated EKE prior to averaging, meaning that periods of strong eddy activity will still have a large value in the 3 month averaging used. In addition, EKE does not only dictate eddy transport, but also indicate variability of the boundary current. When it is large/eddying, it is expected to result in the formation of eddies. For both these reasons, we believe that averaging in this case will not dampen the potential importance of this term.

Page 12, Line 20: The statement "in the NEMO model…" is not correct. The authors mean in their configuration of the NEMO model, with the given forcing, they find…
Changed as recommended.

Page 12, Line 32: With respect to the statement about higher resolution being needed, doesn't Chanut et al argue that at least 1/15 degree is needed?
Chanut et al use a 1/15 degree model and argue that it performs better than the 1/3 degree model. They do not compare their result to lower (i.e. 1/12 degree) or higher resolution models.

Page 13, line 21: Do any of the years mentioned stand out in terms of freshwater transport, melt from the Greenland ice sheet, very positive NAO, etc.?
We looked into this and nothing really stands out in terms of freshwater, runoff and NAO. The only relationship that might be important is the deep convection that was observed in 2007 – 2008. As for the other years, we are not sure what caused the presence of fresher water. It would be interesting to look at this closer in the model. Maybe a composite of these years, or an analysis targeted to these years versus the other years would help understand this question better.

> **p.20 l.592** *Our results show that water entering the Labrador Sea basin was freshest in in the mid-1990s, with other maxima in 1999, the early 2000s and mid-2000. The freshening in the mid-1990s is likely to be related to the freshening observed by Häkkinen (1999), with the freshest waters located on the shelves. Several other years stand out as well, such as 1999, 2003 -- 2004 and 2007 -- 2008. The water responsible for these freshening periods originates in the inshore part of the EGC. A surface freshening signal in 2007 -- 2008 was found in observations, as well as the model. This is also the year during which deep convection was observed again after a long period of absence (Våge et al.*

*2008). It is not clear what exactly caused the freshening periods since the NAO is neither strongly positive nor strongly negative and there is no obvious increase in Greenland runoff at these times.*

Table 1: within is one word; Additionally I don't like the phrasing "Crossing Later" – the authors can be more precise and quantitative.
We have made the term "Crossing Later" more precise, changing it to "Crossing after 7 mth" and the typo has been corrected.

Figure 1: Why are the observations and model field plotted for different time periods (1990-2009 vs 2002-2012)? Can't the results be subsampled to plot everything over the same time period to allow a fairer comparison? Also for the model mixed layer depth, is it based on the default NEMO threshold method? If so, Courtois et al, 2017 show this approach significantly overestimates the actual model mixed layer in deep convection regions.
Comparing observations and model fields for the same time period is a great suggestion and has been done. The mean of the model fields and ARGO data are now calculated for the timeperiod of 2002 – 2009.
Yes, the mixed layers are based on the default NEMO threshold method. Thank you for pointing out the Courtois et al. 2017 paper. We now reference it in the revised manuscript (p.7 l.210).

Figure 4 – Why does it say 'Salt' in the middle of Greenland?
'Salt' was removed from the figure

# Response to reviewer 2

May 7, 2018

The authors thank the reviewer for their careful reading of our discussion paper, and for their helpful and constructive comments regarding its content and improvement. The text of the review is reproduced below in black type; our comments are in blue; and changes to the original discussion paper are presented in italics.

**Overview:** In this manuscript the authors investigate the sources of freshwater transport in the Labrador Sea, the locations at which freshwater enters the central basin, the dynamical mechanisms responsible for this transport, and the controls on seasonal and decadal variability in the transport. Their tool is an unconstrained 1/12 degree multi-decadal integration of the NEMO coupled ocean/sea ice model, in combination with the offline Lagrangian particle advection tool ARIANE. The authors derive Lagrangian particle back-trajectories for waters in the upper 30m of the central Labrador basin over a 20-year period, and then compute statistics associated with the frequency at which particles cross into the basin and the salinities associated with the crossings.

The authors find that most of the particles originate from the shoreward and offshore branches of the East Greenland Current (EGC), in agreement with previous studies, and that the particle crossings occur predominantly in what they call the "Northeast" and "Southeast" sectors of the Labrador Sea. The waters entering from the inshore branch are fresher by 0.1 salinity units on average. The inflowing EGC inshore-sourced water exhibits substantial annual variability in both probability of particle crossings and, in the "Northeast" Labrador Sea, in its salinity. Based on this, the authors infer that inflow of relatively fresh EGC inshore-sourced water occurs in two peaks: one in September, and one around April.

The authors then contrast eddy kinetic energy (EKE, a proxy for eddy particle transport into the basin) and wind-driven Ekman transport as mechanisms underlying the diagnosed particle transport. Both EKE and Ekman transport exhibit seasonal cycles, though the Ekman seasonal cycle is much more pronounced in the "Southeast" section of the Labrador Sea, while EKE is more pronounced in the "Northeast" section. On interannual time scales, the probability of particles having entered the basin correlates significantly with the wind stress in both the Northeast and Southeast sections, but particularly strongly in the Northeast, where Ekman transport variations explain 50% of the variance in the particle crossing probability. Based on this, the authors infer that winds control interannual variations in freshwater inflow to the central Labrador basin.
We have based this statement on the quantitative result noted in Table 2. From this, we see that the Ekman transport variations explain more than 70 % of the variance in the particle crossing probability. In addition the paper concludes that wind controls interannual variations in freshwater inflow of the top 30 m to the central Labrador basin.

This manuscript addresses an important topic, the analysis is interesting and insightful, and in my opinion this work is worthy of publication in Ocean Sciences. However I have a long list of comments on the manuscript (see below), including some quite strong criticisms of the authors' methodology and the evidence supporting their central conclusions. My most major concerns relate to (i) the authors conclusion that freshwater enters the Labrador basin in two "pulses" each year, which does not seem to be supported by their calculations, and (ii) the authors' decision to focus their particle deployments and particle crossing analyses on the upper 30m of the water column, which inherently biases their results toward wind control of freshwater transport.

Therefore, major revisions of the manuscript, likely including substantial additional calculations, will be required to bring this up to a standard appropriate for publication. The manuscript itself is well structured but poorly written: as noted below, there were too many spelling errors, grammatical oddities, and instances of unclear phrasing to list in this review. The manuscript will therefore extensive proof-reading by a native English speaker during revisions.

**Comments/questions:**

At times I found it difficult to make my way through the manuscript due to the high density of grammatical and spelling errors, and awkward phrasings (in various cases so as to render the meaning unclear). I initially tried to catalogue these errors to pass them on to the authors, but quickly gave up due to the sheer number of them. During revisions the authors should pass the manuscript to a native English speaker for detailed corrections throughout, as I do not consider the current standard of writing to be suitable for publication. Additionally, in other places the writing is rather vague, and I have attempted to identify such instances in comments below.
We apologize for the errors in the manuscript. We note, however, that the other reviewer called the paper "well-written" and did not have the same comments regarding the language.

This reviewed version of this manuscript was sent to a professional editor for revision and we are positive that grammatical and spelling errors are no longer present.

p1, L10-12; p10, L6-7; p13, L4-5: I am not convinced that the authors' evidence supports this conclusion. I was initially confused by the authors' wording in the abstract, where they claim that they diagnose two peaks of freshwater transport into the LS; I wondered why they distinguished the first peak as being associated with "a large number of shelf water particles". After reading the manuscript, it became clear that the converse statement is more relevant: the second peak in the salinity anomaly (in the particles from the inner EGC entering via the "Northeast" section of the LS) is not associated with a large number of shelf water particles, at least not compared to the first. Given that the actual freshwater flux may be expected to be related to the product of the salinity anomaly with the number of particles, is this second peak even worthy of note?
It is true that the second peak is not associated with a particularly large number of crossings (compared to the first peak) but we do believe that it is still worth noting. Freshwater anomalies can occur because a large amount (large number of particles) of freshwater enters the region, or because a smaller amount of really fresh water enters the reason (e.g. during the second peak). Also not that during the first peak a large amount of salty water enters the basin in the Southeast. This could have the effect of balancing the high number of crossings of freshwater in the northeast. Hence the second peak might even be stronger in terms of how the freshwater impacts the basin, since in the fall the water entering in the southwest is much fresher.
Perhaps the authors could produce some quantitative estimates of the freshwater flux associated with this "peak" to support their conclusion, but my reading of their current results is that there is really only one peak in the freshwater transport into the LS, occurring around April.
We have estimated a freshwater flux from the number of particles that cross into the basin and their salinity (not shown). Unfortunately, the calculation is limited by the model's resolution. One issue is that more than one particle could cross within a Eulerian grid cell but the model would not distinguish this and would instead count the crossing twice. After further consideration, we did not feel that the calculation warranted publication.
Instead we use the probability of fresh/salty water entering the basin. Doing so did not change, but instead confirmed, the correlative findings (between particle crossing probabilities and potential forcing terms) which was also found when initially working with the an estimate of the freshwater flux.

p1, L16-21: This discussion should be accompanied by supporting citations.
Apologies for the omission. References have been added

p1, L19: "the salty basin" - does this simply refer to the central Labrador Sea? In general I found the authors' "basin" terminology to be ambiguous. They should clarify how they and previous authors distinguish basin from shelf, and ensure that nomenclature is consistent with previous studies.
Yes, "the salty basin" does refer to the central Labrador Sea. We define our definition of the basin on p.10, l.293 *"We refer to the Labrador Sea basin as the region that is offshore of the 2500 m isobaths"*. However, we see that it would be useful to the reader to mention this definition sooner, and have added the following in the introduction:

p.1 l.30 *Offshore of the boundary currents, in the salty basin*, […]

p2, L11: There appears to be a missing citation here (replaced instead with a "?").
This has been fixed.

p2, L23-24: Do the authors' findings not contradict this? By my reading, the authors diagnose a much stronger Spring pulse of freshwater than in Fall. In the Discussion (p13, L7-8) the authors explicitly state that the opposite is true, and that their findings are consistent with Schmidt and Send 2007. I think a more candid discussion of differences between the authors' findings and previous results is required, as currently this is difficult to reconcile.
Our findings indeed support Schmidt and Send's findings. We find a spring pulse, by itself it is stronger than the fall peak, but considering the large number of particles with high salinity that enter the basin at the same time in the model, the overall effect of freshening on the basin is small according to our metrics. The fall peak seems weaker at first glance, but considering that there is relatively fresh water entering in the southeast also, the peak becomes much more significant. We have added an additional comment to clarify this in the "*Seasonality of crossings*" section.

p3, L8; p4, L33; p5, L20; p9, L12; p13, L13 (and more; I gave up listing them): At various points the authors make vague statements such as "substantial buoyancy is lost", "the model well represents", or "a strong WGC". Without some quantitative measure, descriptions like "substantial", "well" and "strong" become simply subjective judgements on the part of the authors.
We have edited the manuscript with an eye on such statements and have reworded them on many occasions.

p4, L5-6: Please check the value given for the bi-Laplacian viscosity. If this value were used, the time scale for viscous mixing at the grid scale (4km) would be on the order of 10,000 years!
Apologies for this typo, it should have read $3 \times 10^{11}$ $m^4/s$ . This has been corrected.

p4, L9: Is "integrated" the correct word here. If I understand correctly, DRAKKAR is a reference surface forcing dataset with components drawn from various existing datasets, rather than a model that is integrated forward in time.
We can see how "integrated" could be interpreted incorrectly in this context. We have changed the sentence to:
*"It is used for the period 1958 – 2012".*

p4, L24: Please state the data source used for the river runoff.

Reference has been added.

p4, L26: In addition to bottom friction, pressure forces also exchange momentum between the ocean and the solid earth.
Thank you for pointing that out.

p5, L2-4: The authors appear to have omitted item 3) from their list of 4 changes to the NEMO model. Also, what changes were made to the (presumably sea floor) topography?
The typo of the list numbers has been corrected.
We changed number 2) in the list to "2) steeper topography along the Greenland Coast" to highlight the changes we were referring to.

p5, L9-11: I disagree with this statement. The correct location and magnitude of the ML depths shows that NEMO accurately represents the ML depths. It is a point in favor of NEMO accurately representing the LS state and circulation in general, but is hardly a clear-cut demonstration of the model fidelity.
We agree that the initial discussion overstated the model fidelity based on the measure of ML depths. We have softened the statement to:

> ***p.7 l.207:*** *In the NEMO N06 model, the deepest winter mixed layers in the Labrador Sea basin are located in the western basin, consistent with observations (Pickart et al., 2002; V_age et al., 2008; Schulze et al., 2016), (Figure 1). The model tends to over210 estimate the mixed layers in the Labrador Sea basin (Courtois et al., 2017), but the agreement of the mixed layer depths and location indicates that the boundary current, and advection of freshwater and heat into the basin, are represented well. Without this representation the basin strati_cation would be weaker and mixing would be stronger. This in turn would result in mixed layers in the wrong location that are much deeper than in the observations. The relationship between fresh shelf water and mixed layers in the basin can be seen in a previous model study (McGeehan and Maslowski, 2011).*

p5, L11-12: Is this statement based on model experiments, or is it simply a speculation?
It is based on theory and a comparison with the previous version of the NEMO model (not shown) that did not have realistic mixed layer depths.

p5, L19: The model and ARGO salinity distributions look qualitatively different to me: there are many ARGO profiles measuring relatively low salinity in the middle of the LS basin, and the shape of the high-salinity region looks to be quite different. Perhaps this is simply due to my subjective interpretation of Fig. 1. To remove the ambiguity here, the authors could provide quantitative metrics of the similarity between the modeled and Argo-derived salinities. Perhaps some of the apparent disagreement stems from the seasonal cycle in the measurements? The authors hint at this on L24. but do not show any data on the model vs. Argo differences in the seasonal cycle.
It is true that there are some differences in the ARGO and model data. However, there are also similarities, such as the general distribution of salty and freshwater in the basin and the magnitude and amplitude of the seasonal cycle. While we do not show the seasonal cycle, it is described:

> **P. 8, L 236:** *"Seasonal cycles of the basin-averaged salinities in NEMO and from Argo data are in phase with peak salinities in February - March and the freshest water in September. Modeled salinities are overestimated by 0.1 between November - June. "*

p5, L26: “in many studies” is not a suitable substitute for citations
We have edited the manuscript with an eye on such statements and have reworded them on many occasions.

p6, L9: Where is “outside” the 2500m isobath? Toward greater depths or toward shal-lower depths?
“outside” has been changed to “inshore”

p6, L14-15: This statement should be supported by evidence if the authors plan to retain it in the manuscript.
We have referenced Figure 7 to support this statement. Figure 7 shows the seasonal composites of the EKE.

p6, L29-30: At various points the authors’ descriptions of the particles becomes confused by the fact that they are calculating back-trajectories, so e.g. it is difficult to tell what “the last time” a particle crosses the LS boundary actually means. In this example the ambiguity is between the first chronological crossing and the first crossing that occurs during backward time-integration.
We agree that this can be confusing, but have made sure that the entire manuscript is consistent in how the direction of the trajectories are described. We have also changed the paragraph referred to here to:

> **p.9 l.295:** *While the particles were released in the basin and tracked backwards, we will refer to there trajectories forward in time (e.g. particles enter the basin and end up at their release point). A particle is considered to have entered the basin if it crossed the 2500 m isobath from shallow into deeper water within the top 30 m of the water column. If a particle crosses the isobath multiple times, only the last crossing before reaching its release point is considered.*

p7, L2-3: This is an important methodological point that requires more explanation, and in fact I am concerned that this choice biases the author’s results toward wind control of particle crossings. The authors only deploy particles within the top 30m, (approximately within the Ekman layer) and only count particles as having “crossed” into the LS central basin if they do so within the top 30m. On p6, L22 the authors claim that “most freshwater is contained in the upper 30m”. First, how much is “most”? Second, storage depth does not necessarily equate to transport depth - it is quite plausible that freshwater could enter over a greater range of depths, but only accumulate in the upper 30m.
If the authors had deployed their particles over a greater depth range then they could defend their focus on the upper 30m, as they could compare freshwater inflow in the upper 30m against that occurring deeper than 30m. I consider this to be quite a serious caveat: this choice could potentially explain the apparent dominance of Ekman transport over eddies in controlling the diagnosed interannual variability in freshwater transport into the central LS, and the discrepancy between the relative magnitudes of authors’ diagnosed “pulses” of freshwater inflow and those reported in previous studies.
This is a good point. It is true that the method might be slightly bias towards Ekman transport, mainly because particles are only released in the Ekman layer. Because of this, we have addressed this issue in the discussion where we show that the surface 30 m make up 60% of the total freshwater flux over the top 100 m and that eddy fluxes become more important only when extending the calculation to 200 m.

Releasing particles over the entire water column would be crucial if attempting to close the freshwater budget of the Labrador Sea basin. This would be very interesting and it is true that eddies might be the dominant means of advecting freshwater to the basin. However, from ARGO floats and repeat hydrography sections by Yashyaev et al. we do not expect the deeper water to be fresh. Typically, below about 100 m the warm and very salty Irminger water dominates. Hence when trying to describe pathways of freshwater into the basin, we have opted to consider the surface layer, since the deeper water of the boundary current has been shown to be salty. This is a choice made throughout, and it does differ from other choices made to investigate the freshwater transport (models) or freshwater content (observations – e.g. Straneo 2006, Häkkinen 1999). While we agree that this choice highlights the freshwater transport by Ekman transport, this is also a meaningful way to distinguish between the layers in the Labrador Sea. Ekman transport is surface intensified, and while we so not attempt to determine the thickness of the Ekman depth, we expect that the top 30 m will capture the variability of the signal. Eddies would be likely to transport both the surface freshwater and the subsurface warm/salty water (Hatun et al 2007) which could actually decrease their role in freshwater transport into the Labrador Sea.

p7, L11-12: I am confused by this statement: don't the authors define "entering the basin" to mean that particles have crossed the 2500m isobath? Perhaps this relates to my earlier comment about the authors' vagueness in referring to "the basin".
The basin in this case is defined as the region offshore the 2500 m isobaths. This definition does exist earlier in the manuscript, where we define the particles that are considered to have crossed the 2500 m isobaths.
Hence the manuscript states that *"Of the remaining 323,084 trajectories that are not categorized as crossings according to the above criteria [...]"* In this category fall particles that enter the basin from the south, hence the North Atlantic but have never been in shallower water.

p7, L19-23: The criteria listed here are not mutually exclusive: do any particles satisfy multiple criteria? If so, is the determination of their origin performed following the logic indicated in these sentences?
Yes, the criteria where chosen such that no particle satisfies multiple criteria.

p7, L30-31: Difficult to parse because "end of their lifetime" actually refers to the chronological starting position of the particles - see earlier comment on the clarity of the authors' description of the particle trajectories.
When referring to "end of their lifetime" in the manuscript, we always refer to the end of their one year runtime. This is consistent with Sections 2.2 and 2.3.

p8, L24-25: I found the authors' geographical descriptions confusing because "south-east" actually refers to the eastern side of the LS region in which particles are deployed, while "northeast" actually refers to the northern tip of this region. I suspect other readers might similarly be misled by this terminology, and recommend changing to something more intuitive.
We believe that the naming of our sections is consistent with their location. The southeast refers to the southern part of the eastern side of the Labrador Sea basin, the northeast refers to the northern part of the eastern side of the Labrador Sea. While we could have named the northeast the 'north' it would have been more difficult to describe the more gradually sloping north to the northwest region in the Labrador Sea. While it would have been simpler if the central axis of the Labrador Sea were meridional, we did consider this choice extensively, and opted for the one used in the manuscript as the most generic.

p9, L24-31 (but also at various other points in the manuscript): The authors mischaracterize the probabilities that the calculate as e.g. the “probability of particles ... to enter the basin” (note that here the grammatical oddities are the authors’). The authors calculate the probability of particles having originated from a given region, given that their back-trajectories crossed the LS perimeter. This is different from the probability of waters originating in, e.g., the EGC inshore region crossing into the central LS - to calculate this the authors would need to compute forward trajectories for particles initialized throughout the EGC inshore region. Strictly speaking, the probability that the authors’ particles enter the basin is 100% because their trajectories all end in the central LS. The authors should rewrite all sections of the manuscript that discuss these probabilities to accurately characterize the results. E.g. on p10, L1-2, “inshore water is about twice as likely as offshore water to enter” might be more accurately written as “entering water is twice as likely to have originated from inshore as to have originated from offshore”.
We have revisited the manuscript keeping this comment in mind. The reviewer is correct that the probability of particles entering the basin is 100% because all particles were released in the basin. While it is true that all particles end up in the basin, here the probabilities refer to the percentage of those particles that did so crossing through a certain region or in a certain time period. This is described in Section 2.5.

p11, L18-19: The authors describe the correlation as “significant”, but do not define the criterion for statistical significance.
The reference for the method with which the correlation was calculated is given in:

> ***P.17 l.498:*** *The timeseries for EKE and Ekman transport are correlated with the probability anomaly using the Pearson method (Thompson and Emery, 2014).*

p13, L30-32: Here the authors explicitly decline to address the mechanism via which EGC offshore water is transported into the basin. I do not think this is acceptable in a manuscript that explicitly aims to quantify the relative roles of different mechanisms of freshwater transport into the LS. This point should be addressed in detail in a revised manuscript.
Unfortunately, addressing all mechanisms of freshwater transport into the Labrador Sea is beyond the scoop of this paper. Here, we have focused on diagnosing the regions of freshwater transport into the basin, and used the additional eddy and Ekman analysis to add insight to those central results. Eddies are the canonical view, while wind-driven transport became the unexpected major player in the study following the interannual analysis, after we discovered that eddy and Ekman transport could not be distinguished based on the seasonal cycles alone. However, we do agree that this is an intriguing question and that it would be great to study not only the impact of wind, but also the impact of other mechanisms on the freshwater transport. As the reviewer addressed earlier, for this particles should be released throughout the entire water column to avoid a bias towards wind driven exchange between the shelves and basin.

p14, L4-5: This calculation is likely to be sensitive to the choice of the reference salinity, and may be producing a misleading estimate of the Ekman freshwater flux. The authors calculate the mean and eddy components of the freshwater flux across the “northeast” and “southeast” sections of the LS boundary - a useful complement to the Lagrangian analysis that serves as the focus of the paper. That is they integrate the boundary-normal components of <u><S-Sref> and <u’(S-Sref)’> along the boundary, where angle frackers < > denotes a time average. Now, the eddy component is insensitive to Sref because <u’>=<S’>=0 by definition, so <u’(S-Sref)’> = <u’S’> + <u’Sref> = <u’S’> - <u’>Sref = <u’S’>. However, the mean component is <u><S-Sref> =

<u><S> - <u><Sref>. If the boundary integral of the boundary-normal component of <u> is non-zero (which seems very probable given the short lengths of the "northeast" and "southeast" boundary segments, and the prevailing northwesterly winds), then changing Sref will change the computed freshwater flux. Given that the choice of Sref is arbitrary, this renders the authors' estimate of the Ekman freshwater flux arbitrary. A solution is to integrate both the eddy and mean components over the full ocean depth, and to perform the integral along a contour of the time-mean depth-integrated streamfunction - this guarantees that the along-contour integral of <u> is zero, and therefore removes the arbitrariness introduced by Sref.
We agree that the calculation is sensitive to the choice of reference salinity. However, the choice of reference salinity is not arbitrary but was instead defined as the average salinity in the surface layer of the basin. In this way, it is used to determine whether the particular transport of water has a net freshening or a net salinifying effect. Unfortunately, this was not clear in the writing, for which we apologize. We have added a sentence at the beginning of Section 4.

> ***p.13 l.415:*** *To quantify if water is fresh or salty we will refer to a reference salinity of 34.95 - the average salinity of the top 30 m of the basin between 1990 -- 2009.*

p14, L6: The authors equate the mean freshwater transport with the Ekman transport, but the mean flow need not be entirely Ekman - are the authors sure that other contributions to the cross-boundary mean flow are small?
Actually, here we do not conclude that the mean freshwater transport is equal to Ekman transport. We find here that the mean freshwater flux due to eddy fluxes is a magnitude smaller than the mean freshwater flux due to Ekman transport, which is the only comparison we made as other mechanisms are beyond the scope of the investigation.

p14, L9-10: I think this sentence is a reasonable take-home message from the study, in contrast to the abstract, which I suspect rather over-states the strength of the authors' conclusions (see other comments above on the methodology).
The abstract has been changed to better represent our conclusion.

Fig. 2: How did the authors select this particular pattern of particle deployment? I am struggling to discern the rationale behind the particular pattern shown here.
The red dots in Figure 2 show the particle release locations. The locations were chosen to be a regular grid covering the entire central basin while remaining away from the mean boundary currents.

Fig. 4: I initially thought that the authors had chosen to rename "Greenland" as "Salt", before realizing their intent. Perhaps they could move this label to the left of the figure?
Label has been removed

Fig. 4: Please provide a scale for the probabilities associated with the sizes of the circles.
A scale has been added

Fig. 6: A legend would improve the clarity of this figure.
A legend is already part of the figure (panel c), but has been made larger for clarity

Fig. 8: The authors use EKE as a proxy for the freshwater transport by eddies in their consideration of seasonal and interannual variability. However, EKE alone does not dictate the eddy transport - a better proxy would be something like the square root of EKE multiplied by the

salinity difference across the LS boundary. How much seasonal/interannual variability is there in this gradient?
That is a great suggestion. For now we decided to use EKE as a proxy for potential eddy activity. While it does not dictate eddy transport, it does show variability which in turn is a good indicator for shedding of eddies. As with the freshwater calculation initially used (see response to comment on p1, 10-12), we anticipate that a true freshwater calculation based on the offline Lagrangian trajectories would be difficult to defend.

Fig. 10: This figure does not distinguish between waters originating from the EGC inshore and EGC offshore regions. Given that it appears to be the EGC inshore waters that are primarily responsible for the freshwater transport, it would be prudent to make this distinction, particularly given the potential impact on the correlation between winds/EKE and particle crossings.
It is true that this Figure only distinguishes between the water originating from the southeast, and northeast and not between water from inshore or offshore EGC. After much debating, we decided to not add the offshore and onshore water to the figure since it makes the figure really busy and hard to understand. However, Table 2 shows the correlations between the EKE and Ekman transport and the inshore and offshore components in the southeast and northeast.

Fig. 10: Why does the Ekman transport estimate only go back as far as 1992?
This has been fixed.

Fig. 10: The authors should highlight the differing axis ranges between the panels, as this might mislead readers - in fact I would argue that the axis ranges should be identical for this reason.
We have highlighted the different axis ranges in the caption. In the end, we opted for distinct ranges as otherwise it would be difficult to see any variability in the left panel (smaller range), if a reader were interested in the southeast region in particular.

Fig. 10: How strong are the computed correlations if annual, rather than three-month, averages are used? Much of the correlation might simply be due to the strong seasonal cycles present in the time series.
The correlations are still strong when considering only the annual average since, as stated in **p.16 l.496:** *"To consider variations beyond the seasonal cycle, the mean seasonal cycle for 1990 – 2009 is removed and the resulting anomalies are shown in Figure 10 […]"*.

Fig. 10: Plotting the probability anomaly over time may actually produce misleading results, because this only measures the number of particle crossings relative to the numbers of crossings in other sections of the LS perimeter. That is, a probability anomaly could arise due to more/fewer particles crossing the northeast section, or it could arise due to fewer/more particles crossing elsewhere. I would recommend switching to a measure of the absolute number of particles crossing to remove this ambiguity
We have considered this and analyzed the figure using both the absolute number as well as the probability anomalies of crossings. The results remain the same and we decided to show probabilities rather than absolute numbers, since this is a measure used throughout the entire paper.

# Wind-driven transport of fresh shelf water into the Labrador Sea

Lena M. Schulze*and Eleanor Frajka-Williams †

*Corresponding author: Lena Schulze, Geophysical Fluid Dynamics Institute, Florida State University, FL, USA (lschulze@fsu.edu)

†University of Southampton, National Oceanography Center, Southampton, UK

**Abstract**

The Labrador Sea is one of a small number of deep convection sites in the North Atlantic, that contribute to the meridional overturning circulation. Buoyancy is lost from surface waters during winter, allowing the formation of dense deep water. ~~In the recent~~ During the last few decades, mass loss from the Greenland ice sheet has accelerated, releasing freshwater into the high latitude North Atlantic. This and the enhanced Arctic freshwater export in ~~the~~ recent years have the potential to add buoyancy to ~~the~~ surface waters, slowing or suppressing convection in the Labrador Sea. However, the impact of freshwater on convection is dependent on whether or not it can escape the shallow, topographically-trapped boundary currents ~~around Greenland and Labrador~~ encircling the Labrador Sea. Previous studies have estimated the transport of freshwater into the central Labrador Sea by focusing on the role of eddies. Here, we use a Lagrangian approach, tracking particles in a global, eddy-permitting (1/12°) ocean model, to examine where and when freshwater ~~enters the Labrador Sea basin~~ in the surface 30 m enters the Labrador Sea basin. We find that ~~most freshwater enters in the east (near the west coast of Greenland), consistent with previous expectations. Seasonally two peaks of freshening are observed. The first peak occurs in the spring and results from a large number of shelf water particles. The second peak, occurring in~~ 60% of the total freshwater in the ~~fall, is due to the low salinity of the West Greenland current at this time of the year. We find that in these simulations surface~~ top 100 m enters the basin in the top 30 m along the eastern side. The year-to-year variability in freshwater transport from the shelves to the central Labrador Sea is dominated by wind-driven Ekman transport, rather than eddies, ~~are responsible for the larger year-to-year variability in freshwater transport from the shelves to the central Labrador Sea~~transporting freshwater into the basin along the northeast.

# 1 Introduction

In the Labrador Sea ~~, intense winter heat loss removes surface buoyancy, allowing~~ deep mixing and the formation of deep dense water are possible due to intense winter heat loss that removes surface buoyancy (Lazier, 1973; Clarke and Gascard, 1984; Pickart *et*

The so-formed Labrador Sea Water (LSW) joins the deep western boundary current (DWBC) and is transported south as part of the Atlantic meridional overturning circulation (AMOC) (Pickart and Smethie, 1998; Rhein *et al.*, 2002; Talley and McCartney, 198 Overall, the upper Labrador Sea is characterized by relatively salty Atlantic water offshore and cold, ~~fresh water~~ freshwater in the boundary currents over the shelves. ~~In the~~ Offshore of the boundary currents, in the salty basin, less cooling is required to cause static instabilities in winter~~that result in convection~~, making the Labrador Sea one of the prime regions for deep convection (Lazier and Wright, 1993; Marshall and Schott, 199

Freshening of the Labrador Sea surface water, in combination with weaker air-sea fluxes, could reduce or eliminate convection due to the increase in surface buoyancy. In fact, freshening periods of varying intensity are not uncommon in the Labrador Sea ~~(e.g. Houghton and Visbeck (2002))~~ (Houghton and Visbeck, 2002) due to its proximity to the fresh Arctic outflow ~~as well as~~ and melt from the Greenland ice sheet. An example of a complete shutdown of deep water formation due to ~~additional~~ anomalous surface buoyancy and weak air-sea fluxes was observed during the Great Salinity Anomaly (GSA) in the 1970s (Dickson *et al.*, 1988; Gelderloos *et al.*, 2012). Convection later resumed due to ~~a strong~~ increasing air-sea fluxes as well as advection of saltier water ~~(~~(Gelderloos *et al.*, 2012). Increased freshwater input in the North Atlantic ~~, as observed in the last decades (Bamber *et al.*, 2012), may increase the amount of freshwater entering the Labrador Sea while decreasing the~~ over the last few decades (Bamber *et al.*, 2012) could result in a similar situation and again decrease the deep water formation rate. Model simulations indicate that predicted rates of freshening in the ~~region~~ North Atlantic will cause a 20% change in the strength of AMOC (Häkkinen, 1999; Manabe and Stouffer, 1995; Jahn and Holland, 2013; Robson *et al.*, 2014).
Until 2005 ~~, increased freshwater was not detectable as a persistent freshening signal~~ a freshening signal was not detectable in the upper Labrador Sea (Yashayaev, 2007). However, more recent studies, using ocean observations ~~such as~~ from Argo floats and ship-based hydrography, show that the surface layer of the North Atlantic, including the Labrador Sea, has freshened~~. Simultaneously,~~ , while deep densities have decreased ~~over the last decade which has possible impacts for the Atlantic overturning circulation (Yashayaev, 2007; Robson *et al.*, 2014; ?).~~

~~Despite the reduction in salinity, recent years (2014 – 2016) showed the return of~~ (Yashayaev *et al.*, 2015; Robson *et al.*, 2014). Despite this trend in reduced salinity, deep convection and the formation of a new LSW class was observed in 2014 – 2016 (Yashayaev and Loder, 2016).

Early ~~, so-called~~ 'hosing experiments'~~,~~ were performed in coarse resolution numerical models to simulate large amounts of freshwater released during paleoclimate events. These simulations showed that freshwater ~~added to the Arctic~~ spread uniformly across the entire North Atlantic ~~, including the Labrador Sea (e. g. Weaver *et al.* (1994)).~~ and Labrador Sea (Weaver *et al.*, 1994). Higher resolution models suggest, however, that additional freshwater in the Labrador Sea may be confined to the shelf region ~~(Myers, 2005)~~ (Myers, 2005) where it would have less influence on the properties of the convection region. ~~In a comparison between three different models (with resolutions~~ While model resolution is crucial in the Labrador Sea (Myers, 2005; Chanut *et al.*, 2008; Gelderloos *et al.*, 2012), some features seem to be present regardless of the resolution. An increase of freshwater in the convection region was observed in models with resolution of 1/2°, 1/4°, and 1/12° ~~), an increase of fresh melt water from Greenland was found in the central Labrador Sea in all models (Dukhovskoy *et al.*, 2015). The freshwater entered mainly from Baffin Bay and the south,~~ Dukhovskoy *et al.* (2015). The pathways of freshwater into the region of deep convection were similar in the three models - entering the region of convection mainly from the north and the east - but the amount ~~of freshwater that reaches the region of convection differs~~ differed between the models. Additionally, the study suggests that ~~any freshwater signal reaching the Labrador Sea would~~ freshwater signals would likely be obscured by the increased salinity of the Atlantic Water entering the region at the same time~~(Dukhovskoy *et al.*, 2015)~~.

On seasonal timescales, freshwater is observed to ~~enters~~ enter the basin in a small pulse in the spring and a second, larger pulse in the fall (Schmidt and Send, 2007). ~~These authors attribute the freshwater of the first peak~~ The first freshwater peak is attributed to the Labrador Current and the second, larger peak to the West Greenland Current. This is consistent with Lilly *et al.* (2003) who ~~also~~ identify the

West Greenland Current as the primary source of ~~the~~ freshening in the Labrador Sea basin. Additional freshwater ~~joins the Labrador Current~~ enters the Labrador Sea from Davis Strait and Hudson Strait ~~. Evidence has been brought forward pointing~~ and joins the Labrador Current. Some evidence points to instabilities in the Labrador Current that could lead to advection of freshwater into the basin (LeBlond, 1982; Cooke *et al.*, 2014). ~~In fact~~Using a 1/4° model, Cooke *et al.* (2014) argue that ~~this indicates~~ the instabilities could indicate a direct connection between the Labrador Current and central basin salinities. Such a connection would further support the idea of a Labrador Current source to the fall freshening in the central Labrador Sea, but the dynamics are not further discussed and the coarse model allows freshwater to leave the Labrador Current more easily than might be the case in the real ocean.

In the past, studies have concentrated on eddies as the main mechanism by which heat and freshwater are imported into the basin. Eddies originating at the boundary current can carry warm and buoyant water ~~((Lilly *et al.*, 2003; ?)~~ (Lilly *et al.*, 2003; Jong have been associated with seasonal freshening ~~(Chanut *et al.*, 2008; Katsman *et al.*, 2004)~~(Chanut *e* Eddies with a core of Irminger Sea Water, termed Irminger Rings, are shed from the boundary current near the northeast corner of the basin (around 64°N, 54°W) (Lilly *et al.*, 2003; Gelderloos *et al.*, 2012). When assuming that 30 eddies are shed from the boundary current each year (as ~~observed~~ suggested by Lilly *et al.* (2003)), up to 50 – 80% of the wintertime heat loss to the atmosphere can be balanced by eddies advecting heat ~~(Lilly *et al.*, 2003; Katsman *et al.*, 2004). However, eddy advection can only account for~~ ((Lilly *et al.*, 2003; Katsman *et al.*, 2004). This accounts for only about 50% of the ~~freshwater that is needed to explain the~~ seasonal freshening in the basin (Lilly *et al.*, 2003; Hátún *et al.*, 2007; Straneo, 2001). Hence, there is an unresolved discrepancy between the advection of freshwater by eddies and that required to explain the annual freshwater gain in the basin. Observational studies may underestimate the number of eddies due to the coarse resolution of altimetry data relative to eddy size, while models are likely to misrepresent the advection due to eddies because of problems with mixed layer depths and grid size. In fact, an eddy-resolving ice-ocean model that, according to the authors, performed better in the Labrador Sea than previous models, found that near surface freshwater advection into the Labrador Sea basin increased (Kawasakim and Hasumi, 2014). However, this as well as previous studies failed to explain all of the seasonal freshwater fluxes by eddies alone. To explain the missing seasonal freshwater fluxes, other dynamics, for example Ekman transport, might also have to be considered. ~~Additionally, other dynamics might also be important in allowing freshwater to enter the basin. Here, we consider whether or not surface Ekman transportmay be important in this process.~~

Every year, substantial buoyancy is lost from the Labrador Sea basin during the wintertime convection. This buoyancy is replenished by surface heat fluxes and lateral buoyancy fluxes (Straneo, 2001) ~~, that~~ which have both a time-varying and a mean component. Here we focus on these aspects using a numerical model to better understand the ~~changing processes involved in the freshwater fluxes~~ role Ekman transport might have in advecting freshwater into the Labrador Sea ~~. This includes time-varying eddy fluxes and wind-driven Ekman fluxes.~~

basin. In this study we ~~will~~ use Lagrangian trajectories in a high resolution (1/12$^{o}$) numerical model to investigate how, when, and where surface freshwater from boundary currents enters the central Labrador Sea~~. In~~ , in particular, the relative importance of eddies versus wind in allowing freshwater to escape the shelves and enter the basin. In Section 2, we describe the model and methods. In Section 3, we outline the typical pattern of shelf-edge crossings, and their salinity and origin. In Section 4, we consider the variability of crossings and its ~~relationship~~ relations to eddy and ~~wind-activity~~ wind activity in the region. We conclude in Section 5 ~~and 6~~ with a summary and discussion.

## 2 Data and Methods

We use output from a 1/12$^{o}$ numerical model to compute offline Lagrangian trajectories of water particles~~to better understand where and how water crosses into the central Labrador Sea~~. Trajectories are ideally suited to identify the pathway and origins of water parcels with associated temperatures and salinities. The latter are key to our focus on processes driving the movement of water from the shelves to the central basin. In the following, we describe the numerical model and compare velocity and hydrography to observations (Section 2.1). We then give an overview of the particle-tracking software (ARIANE) and detail particle releases (Section 2.2 and 2.3), as well as explain the criteria for a ‘crossing’from shelf-to-basin ~~in the Labrador Sea (Section 2.3).Since a~~ (Section 2.4.) A large part of this work ~~will focus on where these particles originate,~~ focuses on the origin of particles and in Section 2.5 we define the ~~possible~~ regions of origin~~in (Section 2.4.~~

## 2.1 NEMO data

For this study, output from the high-resolution global ocean circulation model ~~NEMO ORCA V3.6 ORCA0083-N06 (~~Nucleus for European Model of the Ocean ~~,~~ ORCA V3.6 ORCA0083-N06 (NEMO N06 from here on) is utilized (Madec, 2008; Marzocchi *et al.*, 2015; Moat *et al.*, 2016). The model has a horizontal resolution of 1/12° with a tri-polar grid (~~with~~ one pole in Canada, one in Russia and one on the South Pole) to avoid numerical instability associated with convergence of the meridians at the geographic North Pole. Resolution is coarsest at the equator (9.26 km) and increases to about 4 km in the Labrador Sea. This allows the model to resolve some mesoscale eddies. Smaller features are parameterized.

The model has 75 vertical levels that are finer near the surface (about 1 m) and increase to 250 m at the bottom. The bottom topography is derived from the 1-minute resolution ETOPO bathymetry field of the National Geophysical Data Center (available at http://www.ngdc.noaa.gov/mgg/global/global.hmtl) and is merged with satellite-based bathymetry. Model output is produced every 5 days. Lateral mixing varies horizontally according to a ~~Bi-Laplacian~~ bi-Laplacian operator with a horizontal eddy viscosity of ~~500~~ $3 \times 10^{11}$ m$^4$/s. Vertical mixing at sub-grid scales was parameterized using a turbulent kinetic energy closure model (Madec, 2008). Background vertical eddy viscosity and diffusivity are $10^{-4}$m$^2$/s and $10^{-5}$m$^2$/s, respectively.

The model is forced by the Drakkar Surface Forcing data set V5.2. developed by the DRAKKAR consortium (http://www.~~drakkarocean~~drakkar-ocean.eu/) supplying air temperature, winds, humidity, surface radiative heat fluxes and precipitation. It is ~~integrated~~ used for the period 1958 – 2012, with a horizontal resolution of 1.125° (Dussin *et al.*, 2014; Brodeau *et al.*, 2010). Precipitation, downward shortwave and longwave radiation are taken from the CORE forcing data set (Large and Yeager, 2004) while wind, air humidity, and air temperature are derived from the ERA-Interim reanalysis fields. Surface momentum in the model is applied directly as a wind stress vector using daily mean wind stress. To prevent unrealistic salinity drifts in the model due to deficiencies in the freshwater forcing, the sea surface freshwater fluxes are relaxed toward climatologies by 33.3 mm/day/psu, corresponding to a relaxation timescale of 365 days. The subsequent analysis does not attempt to calculate any freshwater budgets or compare model salinities to observations. Instead we focus on pathways of fresh versus salty water into the basin as well as month-to-month and interannual changes in the freshwater that is transported to the basin within the model.

The sea ice module used is from the Louvain-la-Neuve sea ice model (LIM2) ~~, (Timmerman *et al.*, 2005).~~ (Timmerman *et al.*, 2005). For each model cell, the model uses the ice fraction to compute the ice-ocean fluxes combined with the air-sea fluxes to provide the surface ocean fluxes. No icebergs are implemented in this version.

No-slip conditions are implemented at the lateral boundaries~~.~~, except in the Labrador Sea where a region of partial slip is applied. This is done to favor the break up of the West Greenland Current into eddies (as observations have suggested). ~~For each model cell, the model uses the ice fraction to compute the ice-ocean fluxes combined with the air-sea fluxes to provide the surface ocean fluxes. No icebergs are implemented in this version. The absence of icebergs in our study is discussed in Section 5.~~

~~In the model , the ocean~~ The ocean in the model is bounded by complex coastlines, bottom topography and an air-sea interface~~at the surface~~. The major flux between the continental margins and the ocean is a mass exchange of freshwater through river runoff (taken from the 12-month climatological data of Dia and Trenberth (2002)), modifying the surface salinity. There are no fluxes of heat and salt across ~~solid~~ boundaries between solid earth and ocean, but the ocean exchanges momentum with the earth through frictional processes. Initial conditions for the model were taken from ~~(Levitus *et al.*, 1998)~~ Levitus et al. (1998)

with the exception of high latitudes and Mediterranean regions ~~. Here~~ where PHC2.1 (Steele *et al.*, 2001) and MEDATLAS (Jourdan *et al.*, 1998) are used, respectively. The model is run for the period of 1958 – 2012. Here we analyze the time period of 1990 – 2009, for which eddies and wave fields (Rossby waves) had ample time to spin up.

## 2.2 Model evaluation

~~We evaluate the model in terms of it being an acceptable tool to our scientific question. The NEMO simulation used in a variety of study involving the North Atlantic. For example, Moat *et al.* (2016) found that the model well represents the variability of heat transport at 26.5° N. Substantial changes have been incorporated to improve the representation of~~ To improve the NEMO 1/4° run, changes were incorporated in the N06 1/12° run to better represent boundary currents, interannual variability and depth of mixed layers~~compared to previous 1o and~~. These changes were: (1~~/4° runs. Changes implemented in the model were: 1~~) ~~the wind forcing was made more consistent~~ more consistent wind forcing reaching back to 1958 (more information at ~~www~~http://www.drakkar-ocean.~~drakkarocean.~~eu/forcing-the-ocean/the-making-of-the-drakkar-forcing-set-dfs5~~),~~, (2) ~~changes in topography and 4) the~~ steeper topography along the Greenland Coast and (3) use of a partial slip ~~condition~~ along western Greenland (Quartly *et al.*, 2013). ~~Together with the~~ The changes in topography ~~,~~ together with the partial slip condition promotes the formation of eddies in this region ~~and results in an improved pattern of salinity field and velocities~~ resulting in improved salinity and velocity fields (Chanut *et al.*, 2008), (Figure 1). The N06 simulation was previously used in other studies of the North Atlantic, one of which found that the model is able to represents the variability of heat transport at 26.5°N (Moat *et al.*, 2016).

~~The~~ In the NEMO N06 model, the deepest winter mixed ~~layer~~ layers in the Labrador Sea basin ~~seen in the N06 model~~ are located in the western basin, consistent with observations (Pickart *et al.*, 2002; Våge *et al.*, 2008; Schulze *et al.*, 2016), (Figure 1). The ~~correct location and magnitude of~~ model tends to over-estimate the mixed layers ~~shows that NEMO N06 well represents the boundary currents~~ in the Labrador Sea basin (Courtois *et al.*, 2017), but the agreement of the mixed layer depths and location indicates that the boundary current, and advection of freshwater and heat into the basin, are represented well. Without this representation ~~,~~ the basin stratification would be weaker and mixing would be stronger~~, resulting in mixed layers~~. This in turn would result in mixed layers in the wrong location that are much deeper ~~then~~ than in the observations. The relationship between fresh shelf water and mixed layers in the basin can be seen in a previous model study (McGeehan and Maslowski, 2011). That studie failed to represent the low salinity water along the western coast of Greenland, and produced drastically developing and unrealistic deep convection in the wrong area of the Labrador Sea.

The mean NEMO N06 surface salinities in the Labrador Sea are shown in Figure 1 together with data from Argo floats in the region (see www.argo.com for information about ~~this~~ these data). Argo data are generally not available on the shelves where water is shallower than 1000 m (with some exceptions) but the deep basin properties are ~~reasonably~~ well observed. Both the surface salinities in NEMO and from Argo data show freshest water (below 34.8) in the coastal regions. At Cape Farewell (southern tip of Greenland), salinities are high, 34.9 in NEMO and above 34.99 in the Argo data. The salinity of the basin is 34.85 in NEMO with a saltier region in the northwest (34.875 – 34.9) and a fresher region in the northeast (34.8 – 34.5). A similar salinity distribution can ~~also~~ be found in the Argo data. The saltiest region is in the western basin with salinities around 34.9. The freshwater in the northeast ~~extents~~ extends further into the basin but with salinities around 34.5 – 34.8. While there are some differences, both ~~,~~ the model and observations show increased salinities in the western Labrador Sea, as well as a band of slightly lower salinities extending across the Labrador Sea. This band joins the high salinities in the southeastern Labrador Sea. Seasonal cycles of the basin-averaged salinities in NEMO and from Argo data are in phase with peak salinities in February – March and the ~~freshes~~ freshest water in September (not shown). Modeled salinities are overestimated by around 0.1 between November ~~–~~ and June.

The NEMO N06 model shows a strong ~~WGC~~ West Greenland Current (WGC) and Labrador Current (LC), as well as flow from Baffin Bay and Hudson Strait (Figure 1). The region around 62°N and 52°W, described as the region of high ~~EKE (Eddy kinetic energy~~ eddy kinetic energy (EKE) in many studies, is characterized in NEMO N06 by an energetic WGC and the formation of eddies. Along the coast of the Labrador ~~peninsula~~Peninsula, the flow is separated into two currents~~;~~, a coastal flow ~~,~~ and the main branch of the Labrador Current. The coastal current is mainly fed by outflow from Hudson Strait and is separated from the Labrador Sea ~~Basin~~ basin ((Han *et al.*, 2008). The flux between the Labrador Sea and Baffin Bay experiences a strong seasonal cycle in NEMO that is consistent with hydrographic observations in this region (Myers, 2005; Curry *et al.*, 2014; Rykova *et al.*, 2015).

Along the east coast of Greenland, the EGC is also split into a coastal ~~branch and the~~ and main branch. Such coastal flow ~~has also been observed in the past by e. g. Sutherland and Pickart (2008). Luo *et al.* (2016)~~ is consistent with observations (Sutherland and Pickart, 2008). (Luo *et al.*, 2016) show a similar flow pattern in their model study, with current speeds of the WGC and LC of up to 1 m/s ~~in the WGC and LC. However,~~ but their data show very little eddy activity in the northeast~~, and a strong outflow from Baffin Bay, but no outflow from Hudson Strait. It is harder to compare the velocities to the higher resolution model used in Böning *et al.* (2016), since in their model , ice covers Baffin Bay, Hudson Strait and much of the Labrador Shelf. However, they also see~~. A 1/32° model agrees with our N06 model and shows a strong and steady WGC that becomes unstable around 62°N and 52°W (Böning *et al.*, 2016).

The region of high EKE in the northeast corner of the Labrador Sea basin has been described in many studies. ~~Using~~ For example, using merged along-track TOPEX/Poseidon and ERS data for 1997 – 2001, Brandt *et al.* (2004) ~~find~~ found the region of largest EKE ~~in the WGC~~ at 62°N, ~~in water shallower than~~ inshore the 2500 m ~~. Maximum values are found to be~~ isobath, with maximum values as high as 700 cm$^2$/s$^2$. ~~This differs from the gridded AVISO data, where the maximum EKE is located further offshore and does not exceed 100 cm$^2$/s$^2$. Their EKE reaches~~ The EKE reached values of 300 cm$^2$/s$^2$ inside the basin (offshore the 2500 m isobath) close to the northeast corner, consistent ~~also with Chanut et al. (2008), Katsman et al. (2004), and Lilly et al. (2003).~~ with Chanut *et al.* (2008); Katsman *et al.* (2004); Lilly *et al.* (200 The EKE calculated from the NEMO data has very similar values with ~~the~~ maximum EKE in the same ~~locations shown by Brandt et al. (2004).~~ location as shown by Brandt *et al.* (2004). In particular, the region of the highest EKE is located ~~outside~~ inshore the 2500 m isobath at around 62°N, with values ~~that reach~~ of up to 600 cm$^2$/s$^2$. Inside the basin, the northeast is characterized by EKE values of up to 200 cm$^2$/s$^2$. The highest values of EKE in the model used by ~~Luo et al. (2016)~~ Luo *et al.* (2016) are consistent with the location of the highest EKE values in NEMO. Altimetry data on the other hand, ~~does not have~~ did not show elevated EKE inside the basin ~~(Brandt et al. , 2004). Brandt et al. (2004) further observe~~ (Brandt *et al.*, 2004). Brandt *et al.* (2004) further observed that the EKE in the WGC is on average more than 300 cm$^2$/s$^2$ higher than in the central LS, and that the minimum/maximum EKE in the WGC and the basin occurs in September/January. ~~Both are~~ This is also true for the NEMO ~~data with EKE timing and values that compare well to satellite data~~N06 data.

### 2.3 ARIANE and experiment setup

The off-line Lagrangian tool ARIANE is used to track particles using velocity fields output from the NEMO model. ARIANE is available at http://www.univ-brest.fr/lpo/ariane and described in detail by Blanke and Raynaud (1997) and Blanke *et al.* (1999). For each 5 day timestep of the model the trajectories are analytically solved, respecting the mass conservation of the model within each grid cell.

For this study, particles were released every 10 days ~~over the period of 1990 – 2009~~ at 264 points in the Labrador Sea basin ~~(Figure 2). Most freshwater is contained in the upper 30 m and we place our release points were place~~ over the 20-year period 1990 – 2009 (**Figure 2**). To determine the impact of wind vs. eddies on surface freshwater fluxes into the Labrador Sea, we released particles at three different depths (0 m, 15 m, and 30 m). This ~~results~~ resulted in 28,512 particle releases each year, for a total of 570,240 particles over the 20 ~~year period~~

~~of 1990 – 2009.~~ years. Each particle is tracked backwards for one year. These particles provide a statistical description of water pathways in the Labrador Sea.

~~Each particle is tracked backwards for one year.~~

## 2.4 Particles crossing into the basin

We refer to the Labrador Sea basin as the region that is offshore of the 2500 m isobath. This ~~region~~ basin is encircled by the boundary currents ~~which are usually~~ that on average are centered at this isobath (Figure 1c). While the particles were released in the basin and tracked backwards, we will refer to their trajectories forward in time (i.e., particles enter the basin to end up at their release point). A particle is considered to have entered the basin if it crossed the 2500 m isobath from shallow into deeper water within the top 30 m of the water column. If a particle ~~crosses~~ crossed the isobath multiple times, only the last time before reaching its release point ~~(integrated backwards in time) is~~ was considered. In addition, the particle has to ~~move~~ be at least 50 km away from the 2500 m isobath to be considered as within the basin. This ~~criteria~~ criterion ensures that the particle has left the boundary current completely. The 50 km threshold was determined by averaging the velocities of the basin as a function of distance from the 2500 m isobath (not shown). Average velocities exceed 0.25 m/s within 20 km of the 2500 m isobath but decrease to 0.1 m/s at a distance of 50 km. There is little to no influence of the boundary currents beyond this distance and velocities remain constant at 0.1 m/s.

Note, particles are only considered ~~in this study~~ if they crossed into the basin within the top 30 m. ~~Between~~ From 1990 ~~–~~ to 2009, a total of 570,240 particles were released, of which 230,147 (40%) entered the basin within the top 30 m ~~during their lifetime of one year~~ (Table 1~~, second line: Crossing <30 m~~). Additionally, we ~~will consider~~ only considered crossings that occur within 7 ~~month~~ months of the particle release~~(i. e., particles that crossed from the shelves to the Labrador basin within the 7 month prior to when they were initialized in the central Labrador Sea).~~ . This is the case for a total of 205,929 particles. A randomly chosen ensemble of ~~trajectories of particles~~ particle trajectories in this category is shown in Figure

3. The 7-month cut-off allows the seasonal cycle to be resolved, but the results presented below are not strongly sensitive to the choice of a cut-off time. Of the remaining 323,084 trajectories that are not categorized as crossings according to the above criteria, 1657 crossed below 30 m and 15,352 were initialized in the basin and remained there during their one year lifetime (Table 1). The largest number of particles (56%) ~~enters~~ entered the basin from the south but never ~~crosses~~ crossed the 2500 m isobath.

## 2.5 Regions and Water Sources

The ~~2500 m isobath, which we consider to be the~~ boundary between shelf and basin ~~, -~~ the 2500 m isobath - is split into three areas: Southeast, Northeast and West (Figure 2). Particles crossing into the basin via ~~three sections is traced to its~~ these three sections are traced to their source. We consider five sources: Hudson Strait, Baffin Bay, East Greenland Current (EGC) inshore, ~~and EGC offshore~~EGC offshore, and water from other sources in the North Atlantic (also referred to as North Atlantic water~~), (~~, Figure 2). The EGC inshore and offshore sources at the east Greenland coast are separated by the 1000 m isobath. This isobath coincides with a strong surface salinity gradient of 0.6 ~~psu~~ between the fresh inshore water and saltier offshore water (not shown). If a particle passed through either the EGC inshore or offshore regions at any point during its lifetime it is considered to have its origin in the EGC. A particle is considered to originate from Hudson Bay if at any point it was located west of 65°W. Similarly, every particle that passed through the region west of Greenland and north of ~~65oN~~ 65°N has its origin in ~~the~~ Baffin Bay. All other particles must originate elsewhere and are of North Atlantic origin.

~~The majority~~ Eighty percent of the particles ~~entering~~ that entered the Labrador Sea basin ~~(80%)~~ originate in the EGC (both ~~,~~ inshore and offshore~~portions of the current~~, Figure 2). Specifically, 95,810 (46.5%) of the 205,929 particles originated in the offshore section of the EGC; 69,028 (33.5%) ~~originate~~ originated in the inshore EGC (hence from the shelf). A much smaller number (29,406 or 14%) entered the Labrador Sea basin from elsewhere in the North Atlantic. During the

20 years considered here, only 153 particles (~~much smaller than~~ 1%) originated in Baffin Bay and four in Hudson Bay. Because of this small number (compared to the number of crossings from the other sources), Baffin Bay and Hudson Bay ~~will not be~~ are not considered in the results from here on. Due to the one-year lifetime ~~30~~ of the particles, 5.5% (11,528) of particles that crossed into the basin did not originate in ~~one~~ any of these five regions. Hence, at the end of their lifetime they were located outside the basin but had not left the Labrador Sea.

## 2.6 Probability of crossings

Below we ~~will~~ present the number of crossings as a probability of particles ~~enter~~ entering the basin in a certain region ~~and~~ or during a specific time period (e.g., monthly or yearly). The probability is calculated by dividing the number of crossings in a certain region or within a certain time period ~~(monthly or yearly)~~ by the total number of crossings.

## 2.7 Ekman Transport

To calculate the expected Ekman transport for a homogeneous ocean into the basin we use the ERA-Interim reanalysis 10-meter wind product for 1990 – 2009. Daily winds are interpolated onto the southeast ~~, northeast and west sections~~ and northeast (Figure 2) and the along and across velocity components projected onto the respective section to be along ($\tau_{\parallel}$) and across the section ($\tau_{\perp}$). In this way, the Ekman transport across the section is given by

$$V_{\perp,ek} = \frac{\tau_{\parallel}}{f\rho} \qquad (1)$$

where $\tau$ is the mean wind stress along the section (calculated following Large and Pond (1980)), $f$ the Coriolis force, and $\rho$ the mean water density.

## 2.8 Error Analysis

Errors on the number of crossings and salinity are calculated using a Monte-Carlo approach. For the calculation of the error, a 90% subset of the variable (number of crossings and salinity) is selected randomly with replacement, and the mean of the variable across the subset is calculated. The process is repeated 5000 times, after which the distribution of the estimated mean can be used to determine 95% confidence intervals. ~~In this way, we can estimate how confident we are in the calculated mean of the variable.~~ The error evaluates the robustness of our estimates using a reduced number of particles but does not address any uncertainties associated with model shortcomings in salinity or velocity fields.

# 3 Geography of Crossings

In this section, we discuss the geography of crossings identified by the ARIANE particles in the NEMO N06 1/12° model run. In general, the highest probability of particles crossing into the basin occurs in the southeast and northeast of the Labrador Sea (Figure 4). In the west, the probability ~~of crossings~~ is about four times smaller~~compared to the east~~. It is worth noting ~~, however,~~ that the probability is slightly elevated south of 57°N (~~section IV ,~~ sections IV and V in Figure 5). The southeast has the highest probability of particles entering the basin (~~section I ,~~ sections I and II) with average salinities of 34.98. That is 0.04 ~~psu~~ higher than the average salinities of particles crossing in the northeast (34.94). Low salinity water ~~crossing~~ crosses in the northeast (~~section~~ sections II and III). This combined with the high probability of crossings results in a ~~large~~ high likelihood of freshwater entering the basin ~~at these locations~~here. Crossings in the southeast, on the other hand, do not supply any freshwater to the basin overall, due to the high salinities of the crossing particles~~here~~. Hence, the model output shows two distinct pathways of water into the basin; salty water enters in the southeast and freshwater in the northeast.

## 3.1 Crossings by water sources

To analyze the origin of the water (fresh and salty~~water that enters~~) that entered the basin in the north- and southeast, we consider water originating in the EGC (inshore and offshore) as well as water from other regions in the North Atlantic separately. Water from the offshore EGC source is most likely to enter the basin in the southeast, a short distance downstream from Cape Farewell (Figure 5). These particles are salty with an average of 34.97~~psu~~. The main pathway of EGC inshore water into the basin is about 200 km ~~further~~ farther north along the boundary. Compared to the EGC offshore water, the water here is much fresher with salinities as low as 34.91~~psu~~. Water with origin elsewhere in the North Atlantic primarily enters the basin a short distance from Cape Farewell, via the southeast (section I). The water is about 0.04 ~~psu~~ fresher than the EGC offshore water that also crosses the boundary primarily at this location. ~~Further~~ Farther along the 2500 m isobath, the salinities of the water from all three sources are comparable and the probability of crossings decreases to close to zero (~~section~~ sections III – VI). For all three water sources, the speed at which particles cross into the basin is comparable (not shown).

In summary, ~~the~~ a large amount of EGC offshore water ~~crossing~~ crosses into the basin in the southeast and results in an influx of relatively salty water to the basin. The EGC inshore water ~~, on the other hand,~~ enters farther north and brings ~~much~~ fresher water to the basin. Compared to the high probability that water enters along the eastern side of the basin, the crossings along the western side are negligible. Additionally, in our study the contribution to freshwater fluxes from the water of other North Atlantic sources is small ~~compared to the contributions of the inshore and offshore EGC water~~as well. Therefore, we focus on water originating in the EGC ~~and~~ inshore and offshore and entering the Labrador Sea basin along the eastern side.

# 4 Variability of crossings

In the following section, we identify the seasonal and interannual variability of particle crossings in the 1/12° model run. To quantify if water is fresh or salty we will refer to a reference salinity of 34.95 the average salinity of the top 30 m of the basin from 1990 to 2009.

## 4.1 Seasonality of crossings

We divide the crossing particles according to their origin (EGC inshore or offshore) and the location at which they enter the basin (southeast or northeast) to investigate ~~the seasonalityof water entering the basin.~~their seasonality.

In the southeast, the probability of particles of EGC ~~inshore and offshore origin to enter~~ origin entering the basin is ~~largest~~ greatest in March (Figure 6). However, the probability of EGC offshore water ~~entering the basin~~ crossing is twice as high as the probability of inshore water crossing (10.8% ± 0.2% and 4.6% ± 0.1%, respectively). In addition to the high probabilities in March, ~~there is also a high probability~~ probabilities of inshore water crossing are high in January (4.2% ± 0.1%). In summer the crossing probability is about half that of the one in March for both inshore and offshore water. During the minimum in July, offshore water crosses with a likelihood of 3.8% ± 0.1% and inshore water with a probability of 0.1% ± 0.02%.

In the northeast, the ~~crossing probabilities~~ probability of EGC offshore water ~~is low in the northeast with probabilities~~ crossing into the basin is low, varying from 1.3% in February to 3.2% in October. The seasonal cycle of the inshore crossings, however, is similar (in timing and magnitude) to the southeast region, with maximum probabilities in January and March and a minimum in the summer. Inshore water is about twice as likely as offshore water to enter during the time of convection ~~in~~ (November – April~~(~~), 5% ± 0.2% versus 1.8% ± 0.1%, respectively~~)~~. In the summer, ~~the inshore~~ inshore water crossings drop to almost zero while offshore water keeps entering the basin with ~~probabilities~~ a probability of 3.5% ± 0.1%.

In the southeast, EGC inshore and offshore water entering the basin is saltier than 34.95~~except during May and December. In the northeast, on the other hand, the EGC inshore water brings fresh water into the basin year-round~~ , with the exception of ~~July, August, and November. In other words~~May and December. In the northeast, the seasonal cycle of inshore water ~~entering the basin in the northeast~~ crossings is characterized by two pulses of ~~fresh water~~freshwater, one in December – April and a second, shorter pulse in September. The EGC offshore water also freshens during these two periods ~~,~~ but this freshening is much weaker and salinities remain close to the reference salinities. The high probability of inshore, freshwater entering the basin in the spring is balanced by the high probability of high salinity water entering along the southeast section and results in the fall freshening peak being stronger than the spring peak.

### 4.1.1 Seasonal role of winds and eddies

Three-monthly composites of EKE and wind speeds show that the northeast portion of the Labrador Sea experiences ~~high EKE~~ EKE of 500 $cm^2/s^2$ in the spring and ~~weak EKE in the~~ winter, 400 $cm^2/s^2$ in the summer and 200 $cm^2/s^2$ in the fall. Winds are predominantly northwesterly ~~,~~ (Figure 7) ~~. Northwesterly winds will~~ and result in a southwestward Ekman transport, which, for the Greenland side of the Labrador Sea, ~~will be~~ is in the offshore direction. ~~This effect is largest~~ The Ekman transport is highest in the winter, ~~followed by~~ lower in the spring, ~~with nearly zero average transport~~ and nearly zero in the summer.

~~There is only weak seasonality~~ The seasonal cycle of EKE near the southeast section is weak, with values around 80 $cm^2/s^2$ all year (Figure 8). In the northeast, on the other hand, EKE values are much higher, with an average of nearly 300 $cm^2/s^2$ and ~~an~~ a seasonal amplitude of 200 $cm^2/s^2$. The maximum EKE is observed in February – March. Ekman transport into the basin is strongest in the southeast, with peak values of around 4 mSv in March and a minimum of -1 mSv (transport out of the basin) in June. (Note that this is the overall water transport due to the winds, not the freshwater transport.)

In the southeast, the peak of EGC inshore and offshore crossings coincides with the peak of the Ekman transport. In the northeast, ~~on the other hand~~however, the peak of EKE and Ekman transport coincides only with the peak of inshore crossings. Due to the similar timing of the seasonal ~~maxima in EKE and winds~~EKE and wind cycles, we cannot use the ~~seasonal cycles~~ timing to distinguish between their potential roles in transporting water from the shelves into the basin. In order to ~~further~~ separate their effects~~further~~, the interannual variability of the number of crossings, EKE, and Ekman transport are evaluated~~below~~.

## 4.2 Interannual variability of crossings

The annual ~~averages of the~~ average probability of crossings and their average salinities are determined for the southeast and northeast sections (Figure 9). Throughout the entire ~~period of study~~20 years, offshore water is twice as likely to enter the basin via the southeast compared to inshore water. The inshore water crossings ~~are relatively constant throughout the 20 year period, with~~ show little variability and no apparent long term trend ~~. However, there seems to be~~ throughout the 20-year period, while there is a decrease in the amount of offshore water that enters the basin. In the northeast, the probability of EGC inshore and offshore water ~~have the same probability of~~ entering the basin ~~.~~ are comparable.
In both regions, the offshore water transports mainly salty water (relative to the reference salinity) ~~. The~~ while the inshore water is relatively salty in the southeast and fresher in the northeast. ~~The salinities~~ Salinities during 1993 – 1995 are ~~anomalous in both regions. During these years the inshore water was much fresher~~ anomalously low along the entire eastern boundary~~than during other years~~. Other periods of elevated freshwater fluxes ~~would have~~ occurred in 1999, 2004, and 2007 – 2009 when salinities of the inshore water fell below the reference salinity.

~~For all of the~~

During the entire 20 years, the EGC offshore water ~~is~~ was the main source of salty water ~~entering~~ and entered in the southeast. Due to the low number of crossings, the EGC inshore water did not contribute significantly to fresh or salty water ~~entering the basin in the southeast~~in the basin. In the northeast, where both sources ~~are~~ were equally likely to enter the basin, EGC inshore water ~~cause~~ caused large freshwater fluxes in ~~certain years (~~1993 – 1995, 1999, 2004, and 2007 – 2009 ~~),~~ due to its ~~much lower~~ low salinities.

### 4.2.1 Interannual role of winds and eddies

We ~~now~~ compare the interannual crossing probabilities to the anomalies of the Ekman transport and EKE. In particular, three-month averaged timeseries of EKE, Ekman transport, and probability of crossings in the southeast and northeast are constructed. To consider variations beyond the seasonal cycle, the mean seasonal cycle for 1990 – 2009 is removed and the resulting anomalies are ~~shown in Figure 10, together with~~ compared to the crossing probabilities (Figure 10). The time-series for EKE and Ekman transport are correlated with the probability anomaly using the Pearson method (Thompson and Emery, 2014).

~~As mentioned above, previous~~

Previous studies have investigated eddies as the main mechanism through which water enters the basin from the shelf. Here, we find that anomalies of the crossing probabilities in the southeast are not significantly correlated with the EKE anomaly in this region (Table 2). The crossing probabilities do, however, have a low but significant correlation with the Ekman transport (r = 0.43~~, Table 2~~). This relationship is more pronounced in the northeast ~~,~~ where the variability of the crossings is ~~highly~~ strongly correlated to the variability in the Ekman transport (r = 0.73). In other words, in the northeast the variability in ~~Ekman transport can explain~~ the Ekman transport explains the majority of ~~the~~ variability in the number of crossing particles. In the NEMO model used here, EKE, and hence eddies, do not play a role in ~~the variability of crossings~~ this relationship (correlation of r = 0.05). One possible exception to this may be in the northeast, during the period 1998 – 2002, where there appears to be a period of transient correlation between crossing probability and EKE.

When repeating this calculation separately for the inshore and offshore ~~crossing probabilities~~crossings, only the probability of the inshore water crossing is significantly correlated to the Ekman transport (not shown). Furthermore, the correlation between EGC inshore water and the Ekman transport is stronger in the northeast (r = 0.72) ~~,~~ than the southeast (r = 0.54), though both are significant.

For a spatial view of the different conditions during times with high versus low crossings, maps of EKE and Ekman transport and ~~the~~ mean salinity of the Labrador Sea are calculated (Figure 11). In particular, the maps are comprised of months when the probability of crossings in the southeast and northeast is outside of a two standard deviation envelope. At times when crossing probabilities are high, the EKE in the northeast is weak and the Ekman transport across the eastern side of the basin is stronger, compared to times with anomalously low crossings. Additionally, the surface salinities on the Greenland shelves and the central Labrador Sea basin are 0.2 ~~psu~~ fresher when the probability of crossings is high. The ~~West Greenland Current~~ WGC at Cape Farewell is also fresher in this scenario.

The following pattern emerges: During times with anomalously high crossings, the EKE in the northeast, just ~~onshore~~ inshore and adjacent to the 2500 m isobath~~was~~ , is on average 100 $cm^2/s^2$ lower than during ~~the months with the fewest~~ months with a low amount of crossings. The northeast region just inside the 2500 m isobath, on the other hand, has similar EKE values for both scenarios. Much larger differences are found in the Ekman transport. During times of anomalously low transport, winds force water into the basin along the northern boundary, but the Ekman transport is parallel to the eastern boundary and ~~hence~~ results in weak cross-shelf Ekman transport here. This is accompanied by higher than average salinities on the shelves. When the number of crossings is high, however, the Ekman transport is strong and perpendicular to the eastern boundary, allowing the water to spread away from the shelf ~~region into the Labrador Sea~~ into the basin. This leads to an overall freshening of the basin.

# 5 Discussion

We use the ocean model NEMO and the Lagrangian particle tracking tool ARIANE to assess the major routes and mechanisms of freshwater in the Labrador Sea basin~~that are important to understand how the~~ . This is important in understanding how freshwater released from the Greenland ice sheet or Arctic may influence the region of deep convection in the Labrador Sea. ~~The model used here is 1/12° which is eddy permitting but not eddy-resolving at these latitudes. By determining the relative likelihood and associated salinities, we can evaluate the cause of freshwater changes in the basin. In addition, by investigating the~~ Investigating the temporal variability of the cross-shelf ~~movements of water , we can determine likely forcing mechanisms of~~ movement of water demonstrates the importance of Ekman transport to the cross-shelf transport. In particular, we ~~have~~ considered the role of Ekman transport and eddy fluxes (~~given~~ approximated by eddy kinetic energy) for the exchange between the boundary and basin in the upper 30 m.

Lagrangian trajectories suggest that in this configuration of the NEMO model, with the given forcing, 80% of ~~the~~ water entering the basin ~~each year~~ in the top 30 m each year originates in the ~~East Greenland Current~~EGC. It reaches the Labrador Sea via the ~~West Greenland Current~~ WGC before crossing into the basin along the eastern boundary. In comparison, water originating from other regions such as Baffin Bay and Hudson ~~Straight are negligible. While there are some~~ Strait is negligible. There are possible shortcomings in how the circulation in these regions is represented in the model ~~, our findings are consistent with previous studies that anticipate water entering the region in the east (Myers, 2005), coincident with freshening near Greenland (Schmidt and Send, 2007) and near the location of high EKE (Lilly *et al.*, 2003). Here,~~ and it would be worth verifying with observational data that there is no additional pathway for freshwater from these sources to the Labrador Sea basin. We find the dominant pathway of water particles from the boundary to the central basin ~~is found~~ to be in the northeast. ~~There is a significant role of~~ The wind-driven transport ~~which seems to force~~ plays an important role in forcing the interannual, and possibly the seasonal, variability of cross-shelf exchange in the model. ~~These results show that Ekman transport may also play an important role in the cross-shelf transport, and offer some guidance on likely regions where the cross-shelf transport may occur. While the Hudson Strait and Baffin Bay waters played little role in the freshwater transport in this model, due to their extremely low salinities, it would be worth verifying with observational data that there is no additional pathway for freshwater from these sources to the Labrador basin. In addition, higher resolution models might be able to resolve~~ Higher resolution models that better resolve the eddies in the Labrador Sea ~~much better. This might~~ will be needed to ~~really~~ fully understand the role eddies play in transporting freshwater to the basin in this region.

Seasonally, the largest number of crossings is observed in the spring, but fluxes into the basin continue at a lower rate throughout the year. This is consistent with previous observationally-based estimates using a budget framework ~~that also showed~~ showing continuous fluxes of water into the basin (Straneo, 2001). Freshwater is advected into the basin in two pulses, in the spring and in the fall, as was also observed by ~~previous studies (Schmidt and Send, 2007; Straneo, 2001)~~Schmidt and Send (2007) and Straneo (2001). Due to the different methods applied in the studies (e.g. deeper surface layers and different reference salinities) and the saltier model used here, the absolute magnitudes of the freshening pulses are not explicitly compared. However, the results are consistent in the timing of the freshening and their relative magnitudes, with the second pulse about three times stronger than the first pulse.

One of the unique benefits of a Lagrangian approach is the ability to determine the statistical source of the water entering the basin. We investigate the origin of the freshwater that enters the basin, finding that the water ~~originating in~~ from the inshore region of the ~~East Greenland Current and entering~~ EGC enters the Labrador Sea in the northeast. This water is responsible for the first (March – April) freshening pulse. ~~This water alone is able to flux large amounts of freshwater into the basin. However, at the~~ At the same time, large amounts of salty EGC offshore water enter the basin in the southeast. This counteracts and weakens the ~~freshening in the spring~~ spring freshening pulse. The large fall pulse (September – October), on the other hand, is the result of a combination of relatively low salinity water from the EGC offshore source and very fresh EGC inshore water. The two water masses enter the basin in two different regions, the EGC offshore water in the southeast and the EGC inshore water in the northeast.

Our results show that ~~the interannual probability of freshwater entering the basin was highest~~ water entering the Labrador Sea basin was freshest in the mid-1990s, with other maxima in 1999, the early 2000s and the mid-2000. The freshening in the mid-1990s is likely to be related to the freshening observed by Häkkinen (1999), with the freshest waters located on the shelves. Several other years stand out as well~~in terms of large probabilities of freshwater fluxes~~, such as 1999, 2003 – 2004 and 2007 – 2008. The water responsible for these freshening periods ~~originated~~ originates in the inshore part of the EGC~~, while the EGC offshore water did not contribute. A freshening in the late-1990s was observed by Häkkinen (1999), with fresh anomalies located mainly on the shelves~~. A surface freshening signal in 2007 – 2008 was found in observations, as well as the model.

This is ~~consistent with the model where such a freshening period took place due to the fresh EGC inshore water.~~ also the year in which deep convection was observed again after a long period of absence (Våge *et al.*, 2008). It is not clear what exactly caused the freshening periods since the NAO is neither strongly positive nor strongly negative and there is no obvious increase in Greenland runoff at these times.

Due to the remarkably high correlation between the Ekman transport and crossing probability, we suggest that wind forcing plays the primary role in the variability of freshwater transport near the surface, and ~~in allowing~~ allows fresh shelf water to enter the basin. This conclusion is consistent with model results presented by Luo *et al.* (2016). In summary~~: As~~ , as water rounds Cape Farewell and enters the Labrador Sea~~a large amount~~ , large amounts of the offshore water crosses into the basin. The inshore water ~~on the other hand~~ spreads away from the coast, off the shelf and towards the basin, due to Ekman transport. The offshore water enters the basin due to other mechanisms (not addressed in this study) and hence the number of crossings of this water is not significantly correlated to the Ekman transport.

While the Lagrangian approach ~~us to investigate into~~ is useful in investigating the timing, relative numbers of crossings and salinities of ~~these crossings, they~~ crossings, it cannot be directly related to a net transport across a section. For a quick comparison, we calculate the freshwater fluxes due to Ekman transport directly from the model data by using wind and mean model salinities of the top 30 m across ~~eastern sections. This shows that~~ the eastern sections: The Ekman transport is responsible for a mean inflow of 1.5 mSv of freshwater. To estimate eddy fluxes across the same sections, we consider ~~$v = \bar{v} + \tilde{v}$~~ $v = \bar{v} + v'$ where $v$ is the total volume flow, $\bar{v}$ the time-mean, and ~~$\tilde{v}$~~ $v'$ a deviation from the time-mean and hence the volume flux due to eddy fluxes. This is done for the southeast and northeast sections and multiplied by the freshwater relative to the reference salinity ~~$S_{ref}$ =~~ $S_{ref} =$ 34.95. The mean freshwater flux due to the eddy fluxes is 0.2 mSv. This is an order of magnitude lower than the freshwater fluxes due to Ekman transport. Repeating this calculation for the upper

100 m (a more common choice of the surface layer in the Labrador Sea, ~~e.g. Straneo (2001); Schmidt and Send (2007); Schulze *et al.* (2016)~~ (Straneo, 2001; Schmidt and Send, we find that the combined freshwater transport to the basin due to Ekman and eddy fluxes is 2.4 mSv. This means that the freshwater flux in the top 30 m makes up 60% of the total freshwater flux over the top 100 m. Of this, more than half is due to Ekman transport. When dividing the freshwater flux of the top 100 m into Ekman transport and eddy fluxes, the Ekman transport alone ~~still~~ accounts for more than 60% of the total 2.4 mSv. Eddy fluxes become more important only when extending the calculation to 200 m.

Two novel results emerge from this study. Firstly, the two seasonally-occurring freshwater pulses identified in the model can be traced to the EGC. The inshore water is the main source of freshening in the basin, seasonally as well as inter-annually. This means that Arctic meltwater and runoff from Greenland have the largest influence on the freshwater input to the central Labrador basin. In light of the changing climate, this could ~~mean a reduction in the~~ reduce formation of LSW with the potential for further reduction in the overturning circulation (Robson *et al.*, 2014). Secondly, we show that Ekman transport plays a significant role in the advection of water to the basin. Previous studies concentrated on determining how large a role eddies play in the restratification of the Labrador Sea, but in a region where the freshest ~~waters are~~ water is concentrated at the surface and winds are strong, the surface Ekman transport cannot be neglected.

*Acknowledgments.* This work was supported by the University of Southampton Graduate School.

# References

Bamber, J., M. van den Boreke, J. Etterna, and J. Lenaerts. 2012. Recent large increase in freshwater fluxes from greenland into the north atlantic. *39*, L19501.

Blanke, B. and S. Raynaud. 1997. Kinematics of the pacific equatorial undercurrent: An eulerian and lagrangian approach from cm results. J. Phys. Oceanogr., *27*, 1038–1053.

Blanke, B., M. Arhan, G. Madec, and S. Roche. 1999. Warm water paths in the equatorial atlantic as diagnosed with a general circulation model. J. Phys. Oceanogr., *29*, 2753–2768.

Böning, C., E. Behrens, A. Biastoch, K. Getzlaff, and J. Bamber. 2016. Emerging impact of greenland meltwater on deepwater formation in the north atlantic ocean. Nature, *9*, 523–527.

Brandt, P., A. Schott, A. Funk, and C. Martins. 2004. Seasonal to interannual variability of the eddy field in the labrador sea from satellite altimetry. J. Geophys. Res., *109*, C02028.

Brodeau, L., B. Barnier, A. Treguier, T. Penduff, and S. Gulev. 2010. An era40-based atmospheric forcing for global ocean circulation models. Ocean Modelling, *31*, 88–104.

Chanut, J., B. Barnier, W. Large, L. Debreu, T. Penduff, J. Molines, and P. Mathiot. 2008. Mesoscale eddies in the labrador sea and their contribution to convection and restratification. J. Phys. Oceanogr., *38*, 1617–1643.

Clarke, R. and J.-C. Gascard. 1984. The formation of labrador sea water. part i: Large-scale processes. J. Phys. Oceanogr., *13*, 1764–1778.

Cooke, M., E. Demirov, and J. Zhu. 2014. A model study of the relationship between sea-ice variability and surface and intermediate water mass properties in the labrador sea. Atmosphere Ocean, *52*, 142–154.

Courtois, P., X. Hu, C. Pennelly, P. Spence, and P. Myers. 2017. Mixed layer depth calculation in deep convection regions in ocean numerical models. Ocean Modelling, *120*, 60–78.

Curry, B., C. Lee, B. Petrie, R. Moritz, and R. Kwok. 2014. Multiyear volume, liquid freshwater, and sea ice transports through davis strait. J. Phys. Oceanogr., *44*, 1244–1266.

Dia, A. and K. Trenberth. 2002. Estimates of freshwater discharge from continents: Latitudinal and seasonal variations. J. Hydrometeor., *3*, 660–687.

Dickson, R., J. Meincke, S. Malmberg, and A. J. Lee. 1988. The great salinity anomaly in the northern north atlantic 1968–1982. Progr. Oceanogr., *20*, 103–151.

Dukhovskoy, D., P. Myers, G. Platov, M.-L. Timmerman, A. P. B. Curry, J. Bamber, E. Chassignet, X. Hu, C. Lee, and R. Somaville. 2015. Greenland freshwater pathways in the sub-arctic seas from model experiments with passive tracers. J. Geophys. Res., *121*, 877–907.

Dussin, R., B. Barnier, and L. Brodeau. 2014. The making of drakkar forcing set dfs5. DRAKKAR/MyOcean Rep. 05-10-14, LGGE, Grenoble, France.

Gelderloos, R., F. Straneo, and C. Katsman. 2012. The mechanism behind the temporary shutdown of deep convection in the labrador sea: Lessons from the great salinity anomaly year 1968–71. J. Climate, *25*, 6743–6755.

Häkkinen, S. 1999. A simulation of thermohaline effects of a great salinity anomaly. J. Climate, *12*, 1781–1795.

Han, G., Z. Lu, Z. Wang, J. Helbig, N. Chen, and B. de Young. 2008. Seasonal variability of the labrador current and shelf circulation of newfoundland. J. Geophys. Res., *113*, C10013.

Hátún, H., C. Eriksen, and P. B. Rhines. 2007. Buoyant eddies entering the labrador sea observed with gliders and altimetry. J. Phys. Oceanogr., *37*, 2838–2854.

Houghton, R. and M. Visbeck. 2002. Quasi-decadal salinity fluctuations in the labrador sea. J. Phys. Oceanogr., *32*, 687–701.

Jahn, A. and M. Holland. 2013. Implications of arctic sea ice changes for north atlantic deep convection and the meridional overturning circulation in ccsm4-cmip5 simulations. Geophys. Res. Let., *40*, 1206–1211.

Jong, M. D., A. Bower, and H. Furey. 2014. Two years of observations of warm-core anticyclones in the labrador sea and their seasonal cycle in heat and salt stratification. J. Phys. Oceanogr., *44*, 427–444.

Jourdan, D., E. Balopoulos, M. Garcia-Fernandez, and C. Maillard. 1998. Objective analysis of temperature and salinity historical data set over the mediterranean basin. OCEANS'98 82–87.

Katsman, C., M. Spall, and P. Pickart. 2004. Boundary current eddies and their role in the restratification of the labrador sea. J. Phys. Oceanogr., *34*, 1967–1983.

Kawasakim, T. and H. Hasumi. 2014. Effect of freshwater from the west greenland current on the winter deep convection in the labrador sea.

Large, W. and S. Pond. 1980. Open ocean momentum flux measurements in moderate to strong winds. J. Phys. Oceanogr., *11*, 324–336.

Large, W. and S. Yeager. 2004. Diurnal to decadal global forcing for ocean and sea-ice models: The data set and flux climatologies. NCAR Technical Note, National Center for Atmospheric Research, *11*, 324–336.

Lazier, J. 1973. The renewal of labrador sea water. Deep-Sea Res., *20*, 341.

Lazier, J. and D. Wright. 1993. Annual velocity variations in the labrador current. J. Phys. Oceanogr., *23*, 659678.

LeBlond, P. 1982. Satellite observations of the labrador current undulations. Atmosphere Ocean, *20*, 129–142.

Levitus, S., M. Conkright, T. Boyer, T. OBrian, J. Antonov, C. Stephens, L. Johnson, and R. Gelfeld. 1998. World ocean database 1998. Tech. Rep. NOAA Atlas NESDIS U.S. Gov. Printing Office, Washington, D.C., *18*.

Lilly, J., P. Rhines, F. Schott, K. Lavender, J. Lazier, U. Send, and E. D'Asaro. 2003. Observations of the labrador sea eddy field. Progr. Oceanogr., *59*, 75–176.

Luo, H., R. Castelao, A. K. Rennermalm, M. Tedesco, A. Bracco, P. Yager, and T. L. Mote. 2016. Oceanic transport of surface meltwater from the southern greenland ice sheet. Nature, *9*, 528–533.

Madec. 2008. Nemo ocean engine. Note du Pole de Modelisation, Inst. Pierre-Simon Laplace (IOSL), France., *27*, 209.

Manabe, S. and R. Stouffer. 1995. Simulation of abrupt climate change induced by freshwater input to the north atlantic ocean. Lett. Nature, *378*, 165–167.

Marshall, J. and F. Schott. 1999. Open-ocean convection: Observations, theory, and models. Rev. Geophys., *37*, 1–64.

Marzocchi, A., J.-M. Hirschi, N. Holiday, S. Cunningham, A. Blaker, and A. Coward. 2015. The north atlantic subpolar circulation in an eddy-resolving global ocean model. J. Mar. Sys., *142*, 126–143.

McGeehan, T. and W. Maslowski. 2011. Impact of shelf-basin freshwater transport on deep convection in the western labrador sea. J. Phys. Oceanogr., *41*. doi: doi.org/10.1175/JPO-D-11-01.1.

Moat, B., S. Josey, B. Sinha, A. Blaker, D. Smeed, G. McCarthy, W. Johns, J.-M. Hirshi, E. Frajka-Williams, D. Rayner, A. Ducjez, and A. Coward. 2016. Major variations in subtropical north atlantic heat transport at short (5 day) timescales and their causes. J. Geophys. Res., *121*, 3237–3249.

Myers, P. 2005. Impact of freshwater from the canadian arctic archipelago on labrador sea Geophys. Res. Let., *32*, L06605.

Pickart, R. and W. Smethie. 1998. Temporal evolution of the deep western boundary current where it enters the sub-tropical domain: Evidence from tracer data. Deep-Sea Res., *45*, 1053–1083.

Pickart, R., D. Torres, and R. Clarke. 2002. Hydrography of the labrador sea during active convection. J. Phys. Oceanogr., *32*, 428–457.

Quartly, G., B. de Cuevas, and A. Coward. 2013. Mozambique channel eddies in gcms: A question of resolution and slippage. Ocean Modelling, *63*, 56–67.

Rhein, M., J. Fischer, W. Smethie, D. Smythe-Wright, R. Weiss, C. Mertens, D.-H. Min, U. Fleischmann, and A. Putzka. 2002. Labrador sea water: Pathways, cfc inventory and formation rates. J. Phys. Oceanogr., *32*, 648–665.

Robson, J., D. Hodson, E. Hawkins, and R. Sutton. 2014. Atlantic overturning in decline? Nature, *7*, 2–3.

Rykova, T., F. Straneo, and A. Bower. 2015. Seasonal and interannual variability of the west greenland current system in the labrador sea in 1993 – 2008. J. Geophys. Res., *120*, 1318–1332.

Schmidt, S. and U. Send. 2007. Origin and composition of seasonal labrador sea freshwater. J. Phys. Oceanogr., *37*, 1445–1454.

Schulze, L., R. Pickart, and G. Moore. 2016. Atmospheric forcing during active convection in the labrador sea and its impact on mixedlayer depth. J. Geophys. Res., *121*, 6978–6992.

Steele, M., R. Morley, and W. Ermold. 2001. Phc: A global ocean hydrography with a high quality arctic ocean. J. Climate, *14*, 2079–2087.

Straneo, F. 2001. Heat and freshwater transport through the central labrador sea. J. Phys. Oceanogr., *36*, 606–628.

Sutherland, D. and R. Pickart. 2008. The east greenland coastal current: Structure, variability and forcing. Progr. Oceanogr., *78*, 58–77.

Talley, L. and M. McCartney. 1982. Distribution and circulation of labrador sea water. J. Phys. Oceanogr., *12*, 1189–1205.

Thompson, R. and W. Emery. 2014. Data analysis methods in physical oceanography. Newnes.

Timmerman, A., H. Goossee, G. Madec, T. Fichefet, C. Ethe, and V. Dulire. 2005. On the representation of high latitude processes in the orca-lim global coupled sea-ice ocean model. Ocean Modelling, *8*, 175–201.

Våge, K., R. Pickart, V. Thierry, G. Reverdin, C. Lee, B. Petrie, T. Agnew, A. Wong, and M. Ribergaard. 2008. Surprising return of deep convection to the subpolar north atlantic ocean in winter 2007-2008. Nature, *2*, 67–72.

Weaver, A., S. Aura, and P. Myers. 1994. Interdecadal variability in an idealized model of the north atlantic. J. Geophys. Res., *99*, 12423–12441.

Yashayaev, I. 2007. Hydrographic changes in the labrador sea, 1960 – 2005. Progr. Oceanogr., *99*, 242–276.

Yashayaev, I. and J. Loder. 2016. Further intensification of deep convection in the labrador sea in 2016. Geophys. Res. Let., *36*, L01606.

Yashayaev, I., D. Seidovb, and E. Demirovc. 2015. A new collective view of oceanography of the arctic and north atlantic basins. Progr. Oceanogr., *132*, 1–21.

**Table 1:** Number of trajectories with different criteria

| | | Count | % of total |
|---|---|---|---|
| Total | | 570,240 | |
| Crossings <30 m | | 230,147 | 40% |
| | Crossing within 7 mth | 205,929 | |
| | • <30 m | 176,790 | |
| | • >30 m | 29,139 | |
| | Crossing after 7 mth | 24,218 | |
| | • <30 m | 20,585 | |
| | • >30 m | 3633 | |
| Crossings >30 m | | 1657 | <1% |
| Enter in south | | 323,084 | 56 % |
| | • <30 m | 96,926 | |
| | • >30 m | 226,158 | |
| Stay in basin | | 15,352 | 3% |
| | • <30 m | 1453 | |
| | • >30 m | 13,899 | |

**Table 2:** Correlation of the number of crossings in the southeast/northeast and the EKE and Ekman transport in the same region. The table shows the r-value of each correlation, printed in **bold** if the correlation is significant within 99 % confident levels.

| **SOUTHEAST** | **Ekman** | **EKE** |
|---|---|---|
| Number of crossings | **0.45** | 0.25 |
| Number of inshore crossings | **0.54** | 0.11 |
| Number of offshore crossings | 0.2 | 0.26 |
| **NORTHEAST** | | |
| Number of crossings | **0.72** | 0.05 |
| Number of inshore crossings | **0.72** | 0.21 |
| Number of offshore crossings | 0.11 | 0.29 |

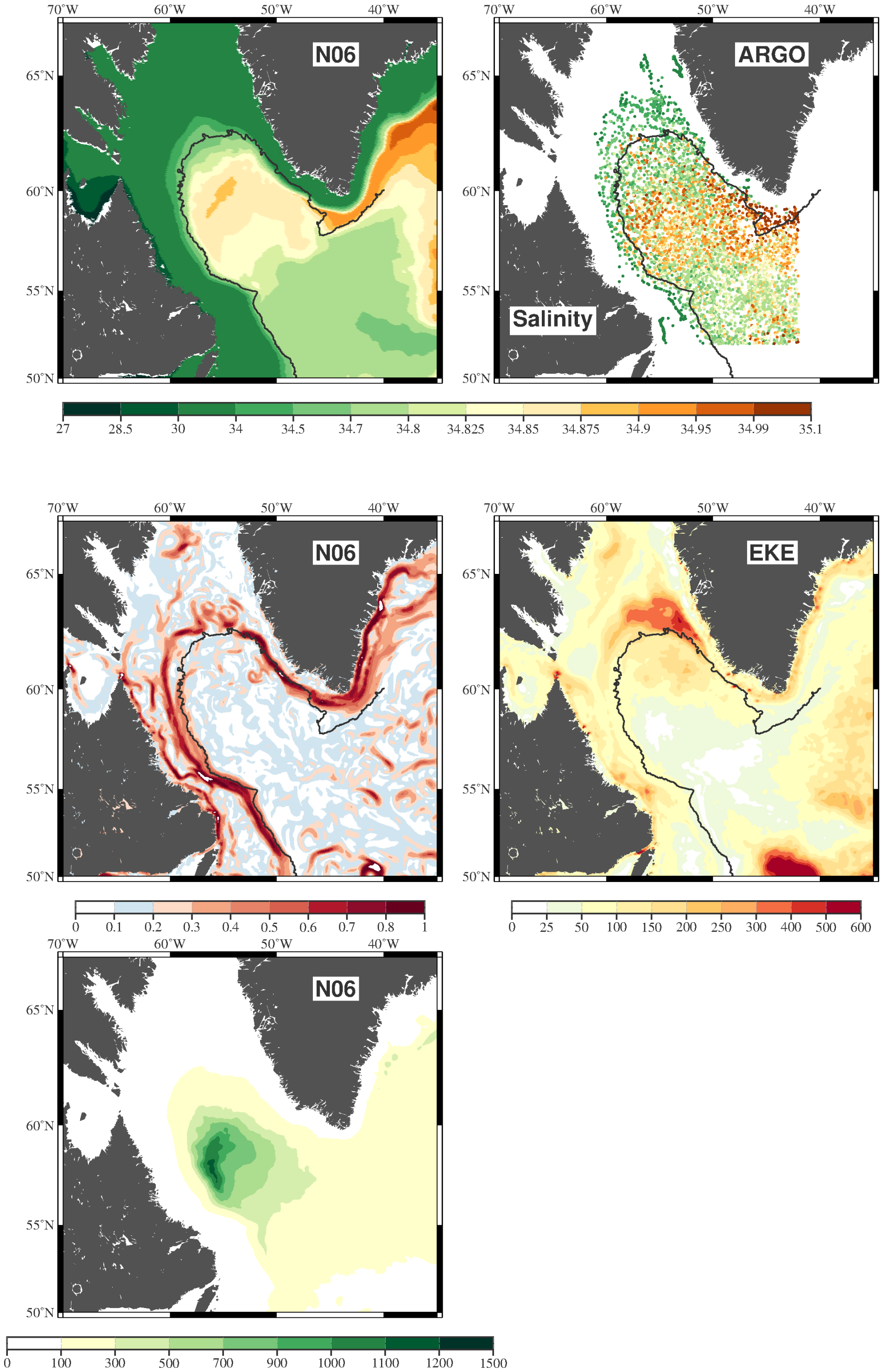


**Figure 1:** a): Mean salinity in the top 100 m from NEMO-N06 b): same as a) but from ARGO data. c): Speed [cm/s] and d): mean EKE [cm$^2$/s$^2$] derived from the NEMO-N06 model of the top 100 m. e): Mean winter time (Dec – Mar) mixed layer depths [m] from NEMO-N06. All means are calculated for the period of 2002 – 2009

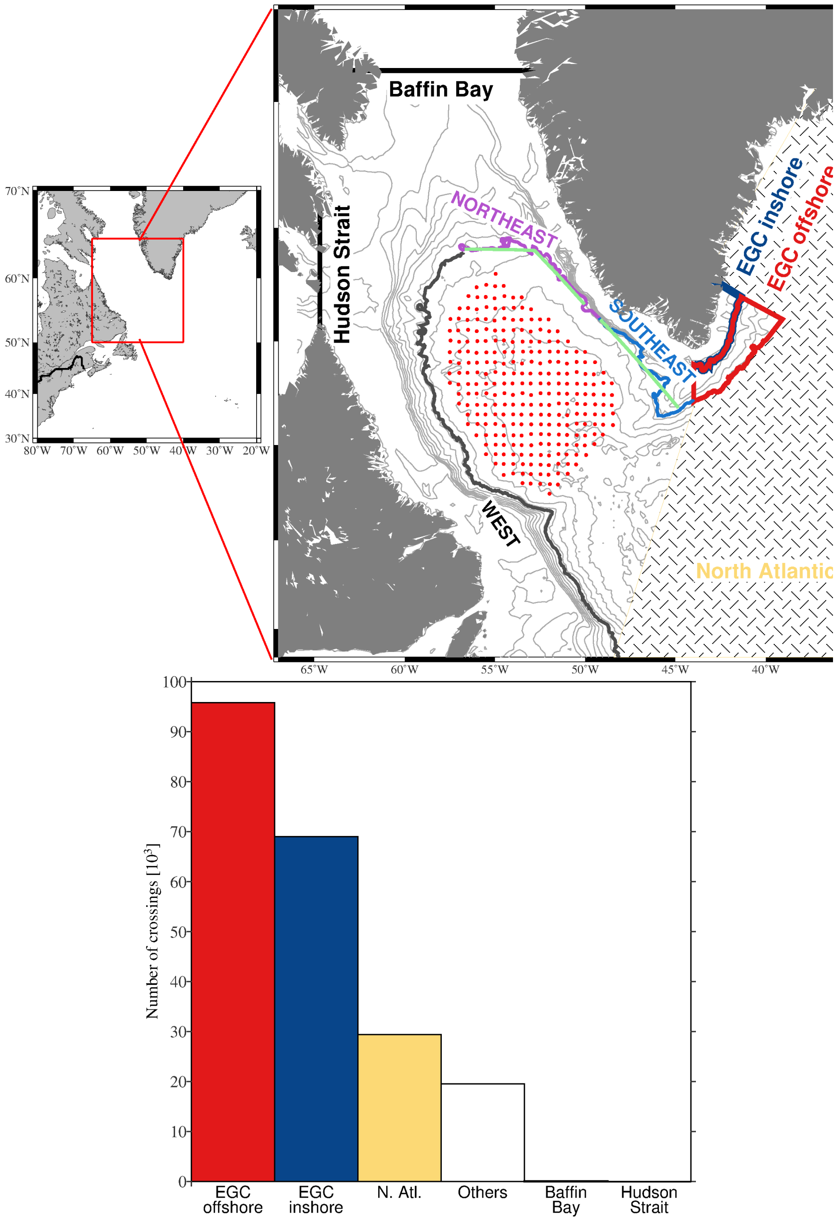


**Figure 2:** Top: The location of the Labrador Sea (left) and a zoomed in view of the Labrador Sea on the right. The topography is shown in gray contours, spaced in 500 m intervals. The thick contour shows the 2500 m isobath and is referred to as the boundary between shelf and basin in the text. The areas referred to in the study as southeast and northeast are shown in blue and purple, respectively. Red dots denote the release positions of the particles in this study. The five regions referred to as the origin of water are also shown here. The East Greenland Current (EGC) inshore and offshore region are shown as the blue and red box, respectively. Baffin Bay and Hudson Strait are shown as black sections and the North Atlantic region as the yellow line and structures region. Bottom: The number of crossings per origin. East Greenland offshore (red), East Greenland inshore (blue), other regions in the North Atlantic (yellow), unidentified origins (no color), Baffin Bay and Hudson Strait (black). The light green sections show the sections across which Ekman transport is calculated.

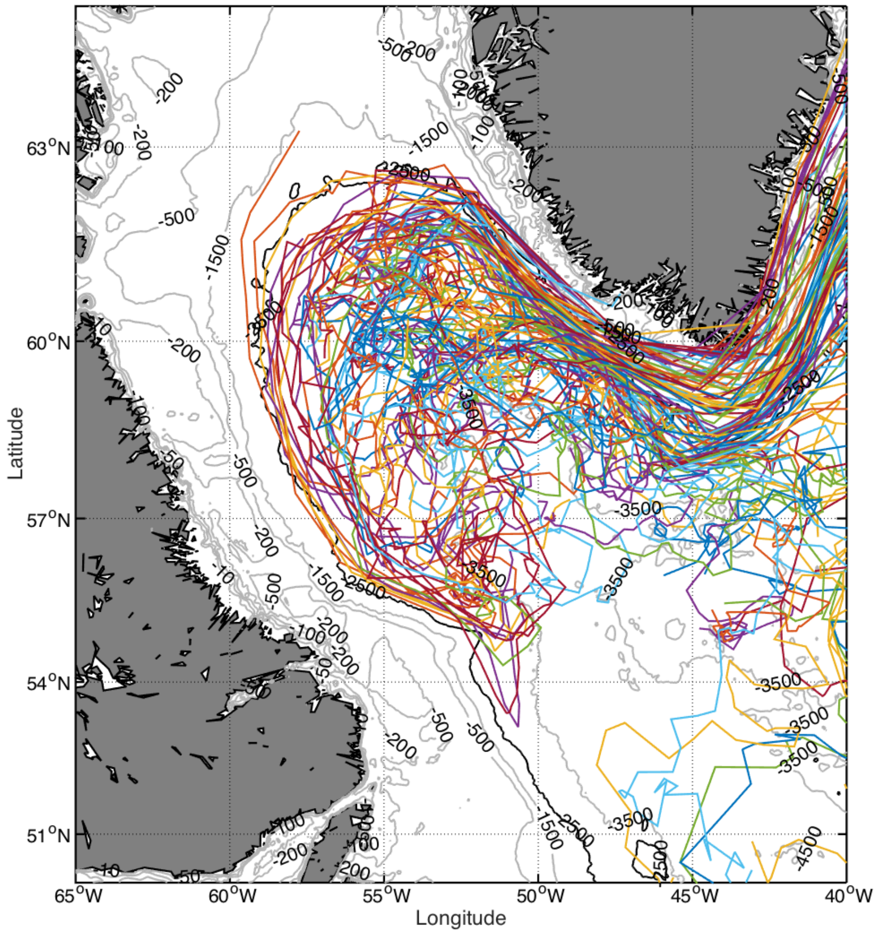


**Figure 3:** Trajectories of 0.01% of the 205,929 trajectories that entered the basin. The trajectories were chosen randomly and are shown in a different color each. Bathymetry is contoured in gray at 500 m intervals with the 2500 m isobaths in black

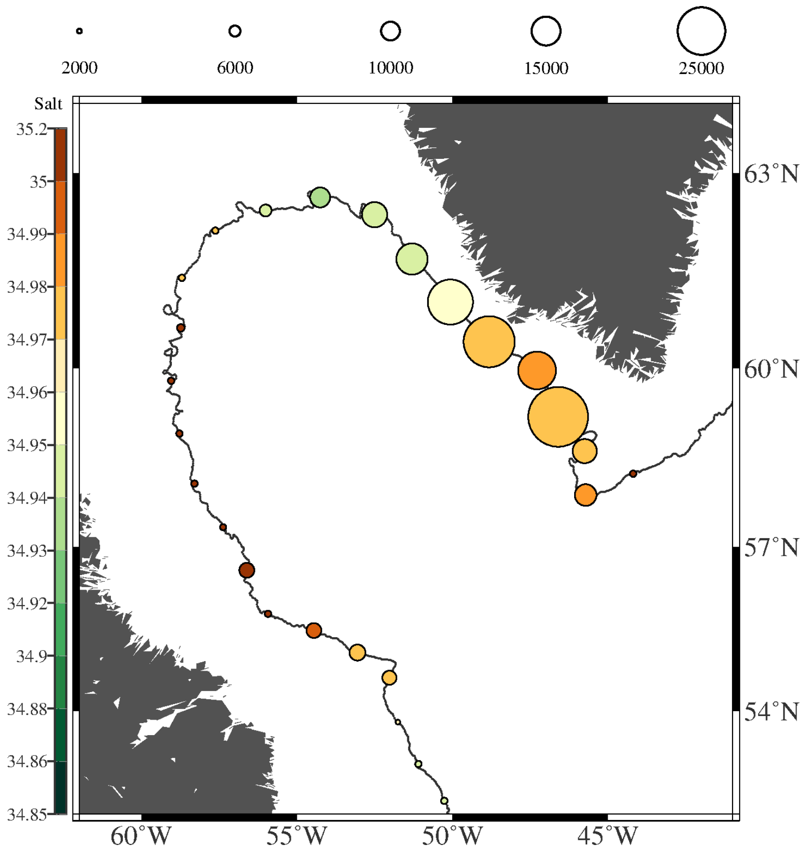


**Figure 4:** The probability of crossings per 100 km along the boundary is indicated by the size of the circles, with larger circles indicating a larger probability. The color shows the mean salinity of the crossings at each section.

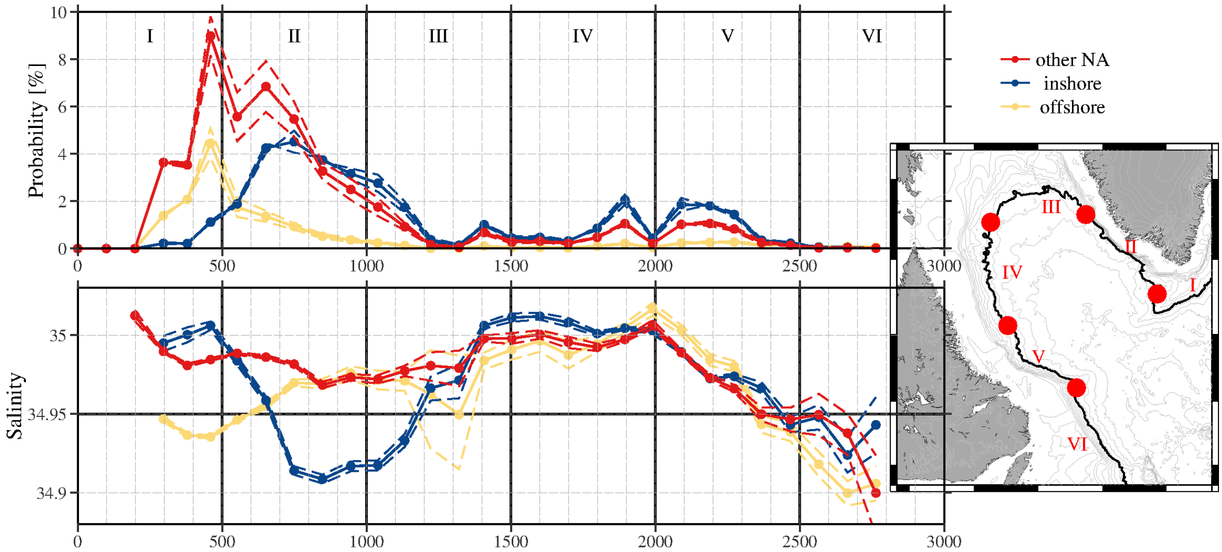


**Figure 5:** a): The probability of crossings per 100 km section (solid line) and the estimated error (dashed line). b): The average salinity of the crossings particles at each 100 km section (solid line) and the associated error (dashed lines). The black horizontal line shows the reference salinity of 34.95 that is used to calculate the freshwater flux. In both panels the vertical lines correspond to the location of the red circles on the map to help orient the reader geographically. Red lines show the EGC offshore water, blue the EGC inshore water and yellow the water from other regions of the North Atlantic.

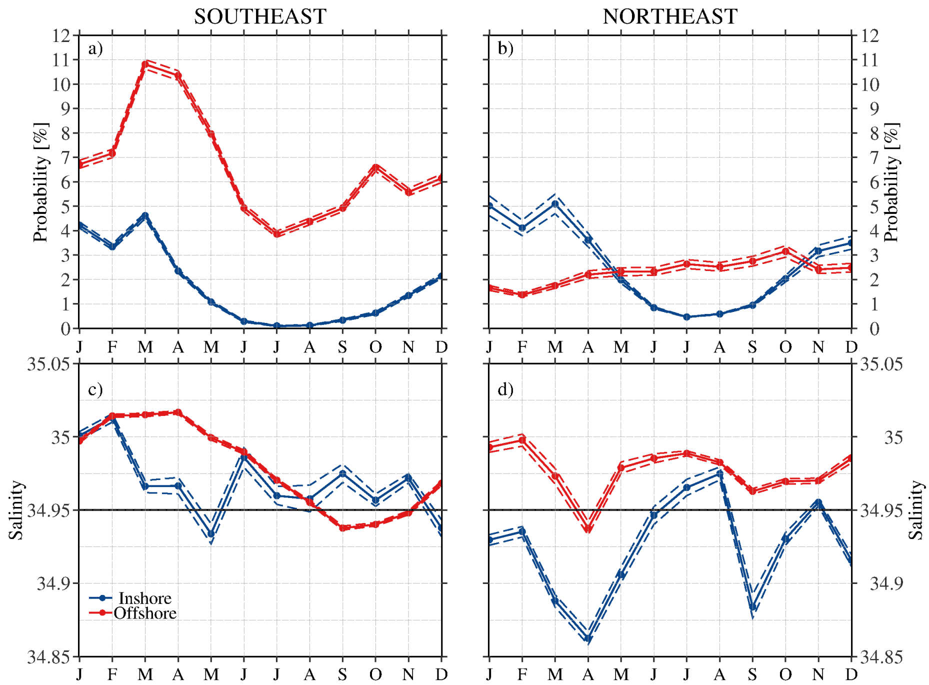


**Figure 6:** a) Seasonal cycle of the probability of particles entering the basin in the southeast and b) northeast, (see Figure 2 for the location of the regions). Seasonal cycle of salinity for particles crossing in the c): southeast and d) northeast. In all panels, the colors show the sources of the water: Blue lines shows water from the EGC inshore region and red the water from the EGC offshore region. The dashed lines show the associated errors.

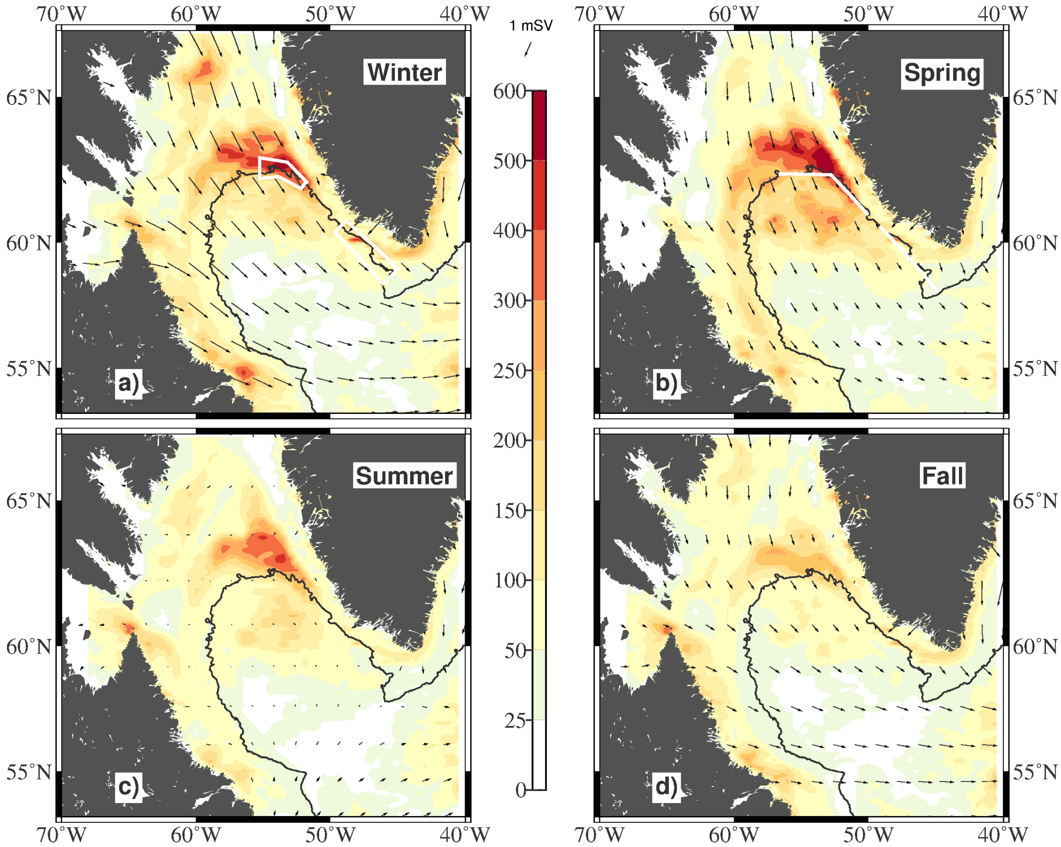


**Figure 7:** Three monthly mean of eddy kinetic energy (color [$cm^2/s^2$]) and wind (vectors [m/s]) in the Labrador Sea, 1990 – 2009, for a), Dec – Feb), b), Mar – May), c), Jun – Aug), and d), Sep – Nov). The white boxes in a) show the regions over which EKE is averaged in **Figure 8**. The white lines in b) show the sections across which Ekman transport is calculated.

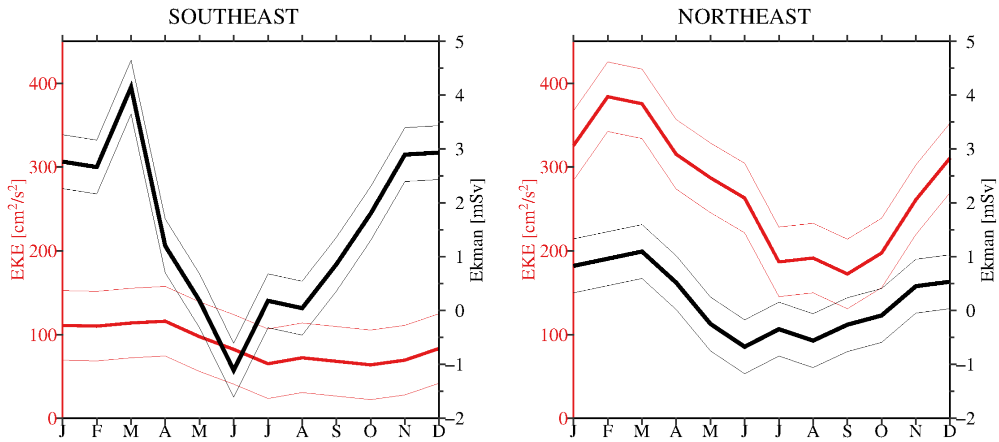


**Figure 8:** Left: The seasonal cycle of EKE (red line) and Ekman transport (black line) (1990 – 2009) in the southeast (See white box and section in **Figure 7**). The thin lines show the associated standard deviation. Right: Same but for the northeast.

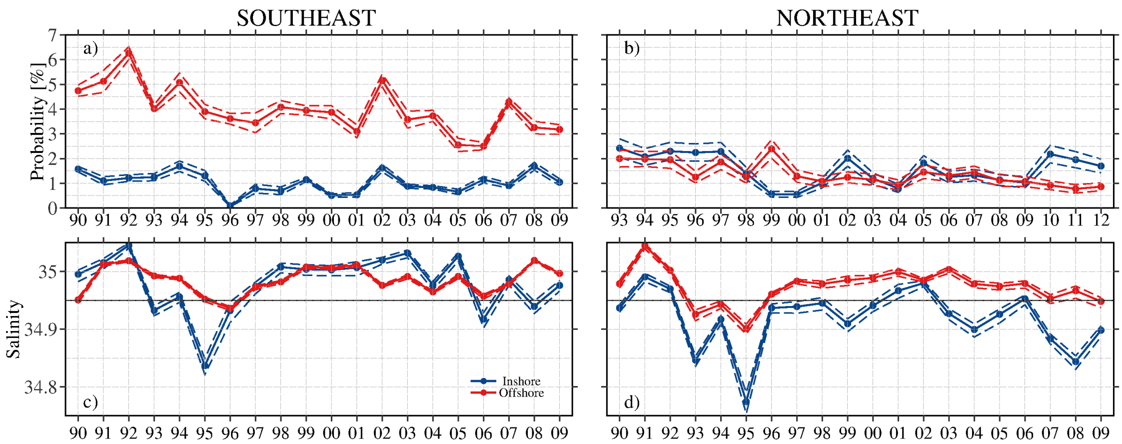


**Figure 9:** The probability of water entering the basin in the a): northeast and b): southeast. The salinities of particles crossing in c): the northeast and d): the southeast. The colors refer to the water's origin: blue shows the EGC inshore water, red the EGC offshore water. The doted lines show the estimated errors.

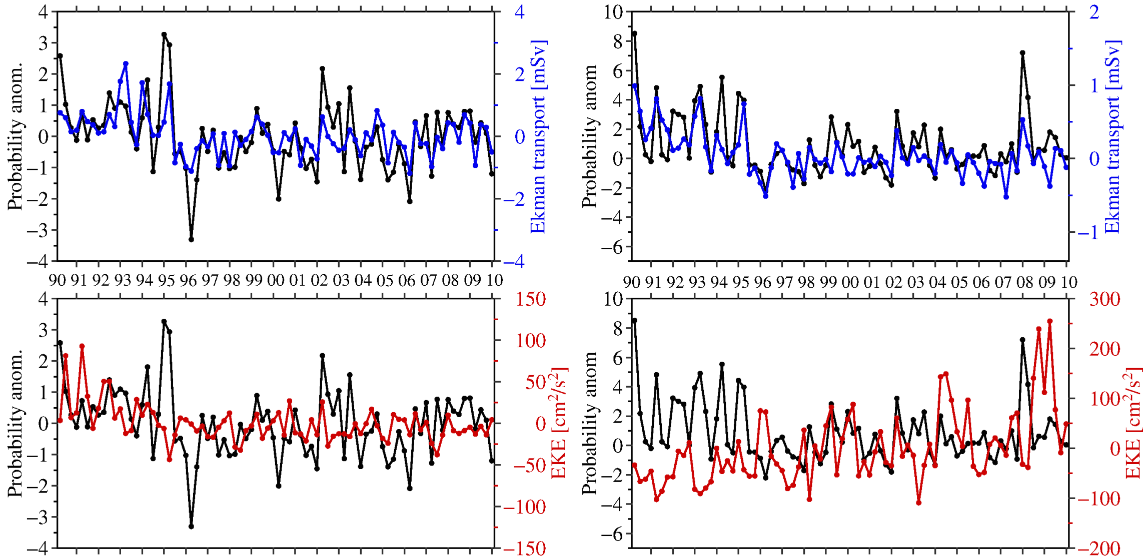


**Figure 10:** Top panels: Three-monthly anomaly of the crossing probability in the southeast (left) and northeast (right), (black lines) and the Ekman transport anomaly in the same regions (blue). Bottom panels: Same as above but for the crossing anomaly (black lines) and EKE anomaly (red). Note that axis ranges change for the different regions.

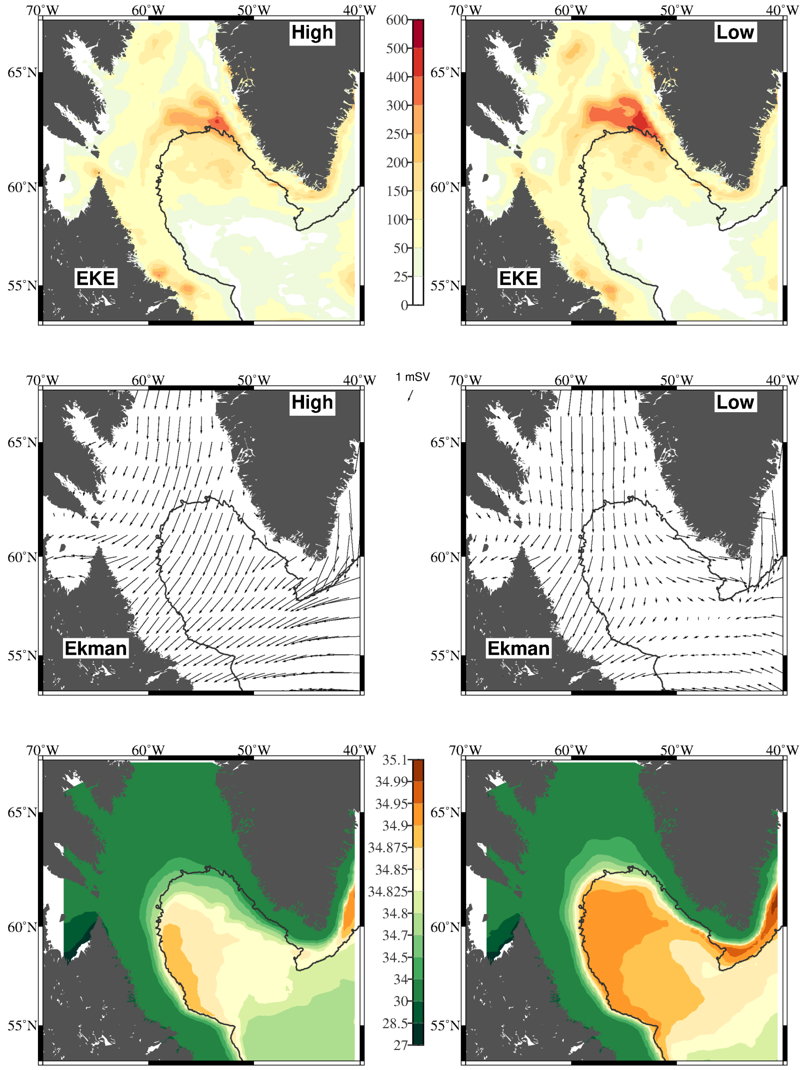


**Figure 11:** Top: The mean surface EKE [$cm^2/s^2$] during months with anomalously high (left) and low (right) number of crossings. Middle: Same as the top row but for the Ekman transport, Bottom: Same as top but for the model salinities of the top 30 m.