Uncovering a hidden oceanic pathway using numerical particle tracking experiments

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Abstract

Over a period of 10 weeks in the summer of 2018, I gained competence in the use of the analytic particle tracking software Ariane. Using the velocity field output of an Ocean General Circulation Model, hosted on the JASMIN servers. Using the 1/4 degree resolution velocity fields of the ORCA025-N401 data, I ran particle tracking experiments for up to 25 years to study various pathways in the North Atlantic and explore sources of a synthetic tracer signal discovered at 24N. I explored the level to which the fields model observations in the ocean and other well oceanographic models. I assessed the uses of Ariane by computationally replicating tracer release experiments carried out in the North Atlantic, for direct comparison to measurements. Finally, I explored the Greenland Sea Tracer Experiment as a source of the synthetic tracer, and the extent to which a new pathway, hypothesised by Marie-Jose, might contribute to the signal.

1 Introduction

In February 2018, Marie-Jose gave a presentation on an unexpectedly high measurement of a synthetic tracer (SF_6) along 24 North, that she found in 2010. She believed that this signal may have come from the 1996 Greenland Sea Tracer Experiment (GSTE) [7], suggesting that there must be a previously unconsidered pathway that transported the tracer there. The aim of my project is to use Global Oceanographic Circulation Models (OGCM) and particle tracking software to quantify the likelihood of each of the major release experiments as a source of the signal. As well as observing the potential pathways that the particles took to get there.

After a quick literature review, which got me familiar with oceanographic processes and measurement techniques, I went to the Laboratoire d'Océanographie Physique et Spatiale in Ifremer to learn how to use the Ariane particle tracking software under Nicolas Grima [3]. By the end of the week I was competent enough to conduct my own experiments with the program using the ORCA NEMO velocity fields on Jasmin [2]. Ariane can be run in one of two main modes, quantitative and qualitative, and I will briefly explain what I learnt about these modes and their potential uses in my project.

Quantitative:
In the quantitative mode, before you start the experiment you set up a domain, closed by land or 'sections' - transects through the ocean. Particles are initialized along one of the 'sections', and then integrated forwards or backwards deterministically using the model velocity fields. Once a particle intercepts a section, it leaves the domain and is removed

from the experiment, with it's properties recorded. If in the total integration time a particle does not leave the domain, the particle is lost along with it's properties. This mode has a relatively low memory usage so it is possible to conduct experiments with millions of particles with ease.

In my experiments I want to source particles in a cubic region in the middle of my domain, which means that my domain is not simply connected (it has a hole in it). This causes issues when plotting the stream function, but the main issue it causes is that the seeding regions have a high level of recirculation. So a very high percentage (30-60%) of the initialized particles re-enter the seeding section. These are called 'meanders'. As explained above these particles, once incident on the section, are then removed from the experiment, and so no longer meaningfully contribute to the statistics. Furthermore, the domains I am considering are large. Thus, of the particles that do not meander, the majority of the particles do not make it to the edges of the domain and are lost. As a result, in my preliminary experiments a typical number of particles that provided useful data was on the order of 0.05%. It is possible to conduct statistical analysis of this subset of particles (i.e. in *Section 4*), however it is important to remember that a lot of particles lost to meanders may potentially have contributed as well if they hadn't been removed (as demonstrated in *Section 2.3*).

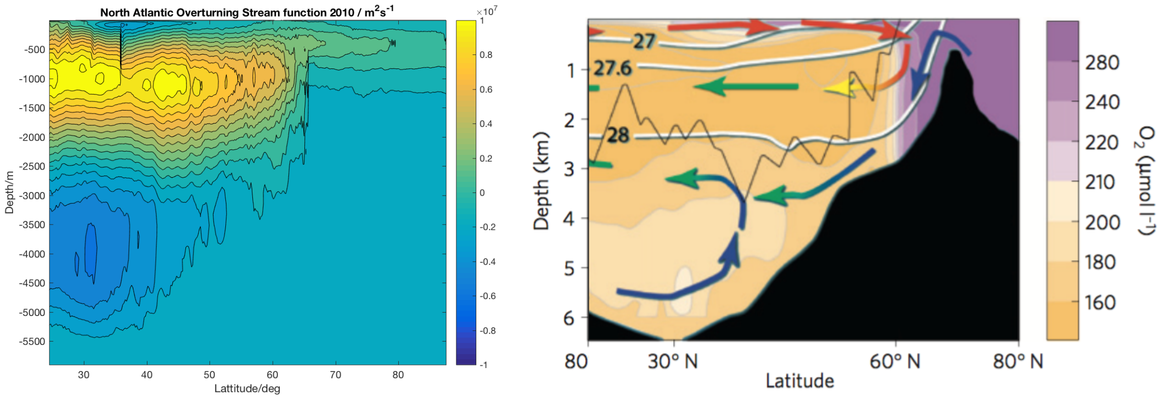
It is possible to try and mitigate this meandering issue by seeding particles over an extended time period, so that the particles lost to meanders are 'regenerated' and can continue to remain in the experiment. The issue I have with this method is that it is equivalent to saying the tracer is continually dumped in the ocean over an extended region of time. This is not an accurate statement, but the technique may be a useful method in exploring the spreading of particles nonetheless.

Qualitative:
In this mode, you seed the particles at specific positions (spacial and temporal) defined by you. A MATLAB script is necessary to generate a sizeable number ($O(10^3)$) of particles in the required region [4]. These particles are then integrated forward in the same way as the quantitative mode, except that the properties (position/temp/salinity/etc.) are recorded for each time step. Therefore, you are able to plot and analyse the trajectories of the particles and their properties. In this mode none of the particles are lost and, unless a restricted domain is imposed, no particles are removed. However, this mode requires a much higher amount of memory, and so I have been restricted to seeding only thousands of particles to avoid the program terminating with an 'Out of Memory' error.

In general I feel more comfortable statistically analysing the results of the qualitative method when sourcing particles in the middle of my domain, due to the meandering issue. That being said, in *Section 5* I do a quantitative mode experiment where the particles are seeded at the edge of the domain in a region where there is much less recirculation and this provides some really nice results. So I do think that there is good merit in use of this Ariane function.

The rest of my report will be structured as followed. *Section 2* will explain a few of the experiments conducted to assess the validity of using the model data and the Ariane tool. An exploration of the various tracer release experiments is conducted in *Section 3* followed by a reverse integration aimed to further explore how each of the sites may have contributed to the signal in *Section 4*. A forward release experiment along a 60N transect is explained in *Section 5*. Finally a discussion of the results, errors and potential further action is done in *Section 6* and the report is concluded in *Section 7*.

I have saved all of the scripts that I created throughout this process in a GitHub repository [1]. I have also taken all of the data collected off of my home directory on Jasmin and placed it on SciHub, it can be located in $/data/expose/gste\_rep/Jasmin\_data/$.



(a) (b)

Figure 1: *(a) Meridional Overturning circulation stream function of the North Atlantic Basin. The North Atlantic basin was masked off, then the meridional velocities were averaged zonally and integrated vertically to generate the stream function (10Sv). All the basic expected features are visible as can be compared to (b) from Marshall and Speer [6]*

2 Model validation

2.1 Meridional Overturning Circulation (MOC)

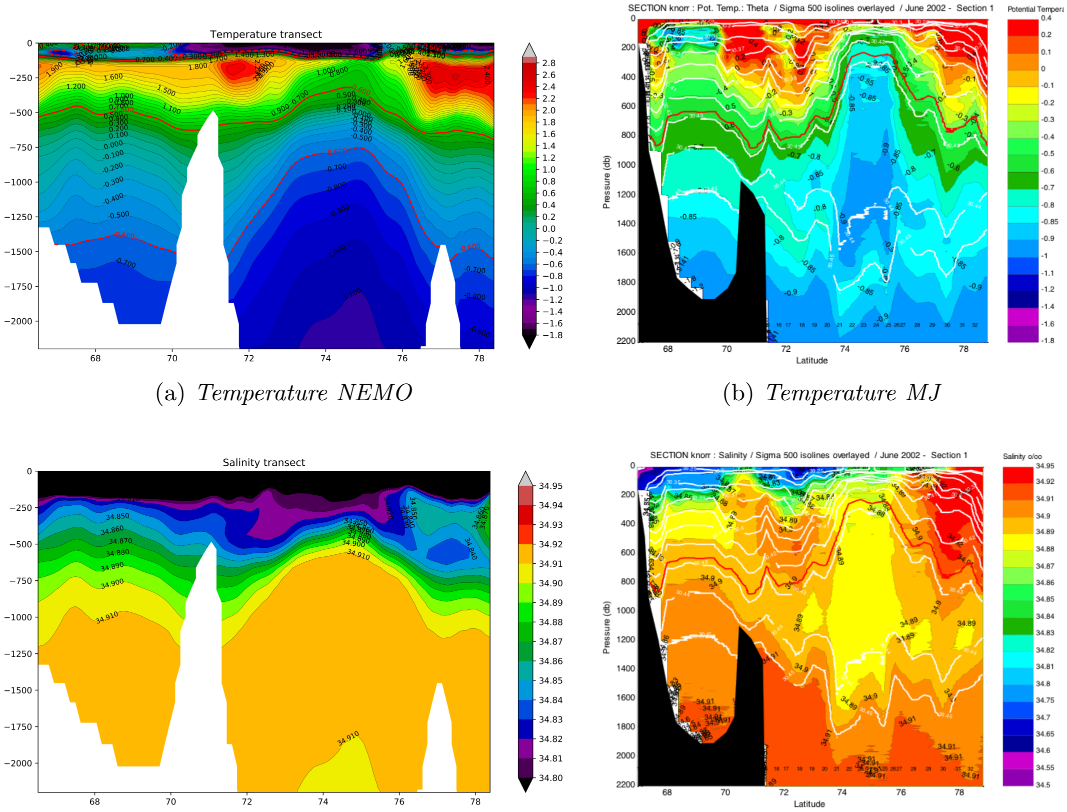
In order to get an idea of how well the NEMO output data models large scale oceanographic features, I generated a plot of a Meridional Overturning Circulation for the North Atlantic and Nordic basins of interest. Using a yearly mean global data file, I took the meridional velocity field and applied a custom mask to select out the Basins of interest. I then averaged the velocity fields zonally, before generating the stream function by integrating this average from the sea floor to the surface and contoured the result (*Figure 1*).

It can be seen that, in the regions of interest of my experiments, the model produces a reasonable overturning circulation with the following features displayed:

- The upper clockwise cell of warm surface water travelling North due to the Ekman current, and down welling in the North due cooling and brine rejection of ice formation. This dense water then travels south due to mass conservation. This has a maximum of 9Sv at a depth of about 1000m, and continues down to about 2200m in depth. It extends to about 65N.
- The lower anticlockwise cell, with deep cold Antarctic bottom water travelling north, and upwelling (due to the unstable water column generated by the shallow dense water formation in the north) before converging with the upper cell's lower (south bound) limb. It has a maximum of 4Sv at a depth of about 4000m. This cell extends only to about 50N.

2.2 Greenland Sea transect

Another method of assessment was to compare some model transects to the real data that was collected in the years following the GSTE. One of such measurements was a transect through the Greenland Sea, from the tip of Iceland through the release site. I was able to produce an approximately similar transect using some of the NEMO model data. Using python, I then produced contour plots of the temperature and salinity along those transects for direct comparison to the real data (*Figure 2*). I also highlighted the contour corresponding to the



(a) *Temperature NEMO*

(b) *Temperature MJ*

(c) *Salinity NEMO*

(d) *Salinity MJ*

Figure 2: *Depth vs Latitude plots along a meridional transect from the tip of Iceland into the Greenland Sea Gyre from the NEMO model, where color represents temperature (deg C) (a) and salinity (psu) (c) . These can be directly compared to the similar plots, (b) and (d), produced by measurements along a similar transect. The dashed red isotherm (-0.06 deg C) is the closest isotherm to the target density isopycnal, it can be seen that this is about 700m deeper in the NEMO data than in reality. The solid red isotherm (0.06 deg C) passes through the release depth.*

isotherm which follows the target release density the closest (-0.06 deg C) of the GSTE. The colour bars were adjusted such that the important information was clearly displayed, which resulted in some less aesthetically appealing sections.

2.2.1 Greenland Sea Comparisons

It is apparent that the general large scale features of the transects are the same, with a 'bump' in the isotherms peaking at 75 N. We can also see that the highlighted isotherm follows a similar downwards vertical trend away from the preak towards lower latitudes. However, it should be observed that in the model at the release site this isotherm corresponds to a depth of 700m instead of the target 300m release site. The isotherm that goes through this depth (0.6 deg C) does not show anywhere near as much of a vertical plunge southwards, sinking only to depths of about 500m as it goes over the sills (*Figure 2a*).

2.3 Greenland Sea Tracer Experiment (GSTE)

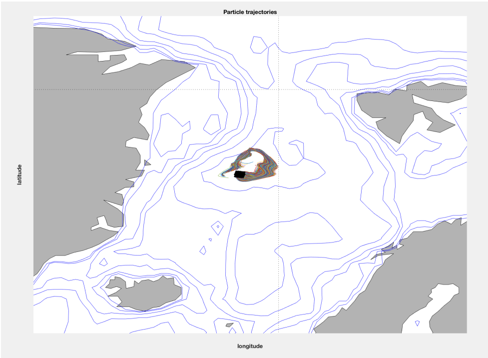
The third method of validation was to see how well the model data and the Ariane software was able to recreate the spreading of particles in the GSTE. The particles were release in a $10km^2$ box at the target depth of 300m, and then integrated through time using the Ariane software for varying lengths of time. These trajectories were then plotted in MATALB and compared to the real data recorded [7]. It can be observed that the software quite nicely replicated the spreading shape and pattern of the real data (*Figure 2*). However, the time scales over which it did this varied greatly from the observations. By the end of the observation period of 6 years the virtual particles had struggles to leave the Greenland sea gyre, whereas in reality they'd well reached the Western Boundary current and the sills. It took an extra 4 years of particle integration for the particles in Ariane to spread into the North Atlantic. I also plotted the trajectories over a time period of 22 years, as this was the scope of the data available, where you can see that the particles still haven't made it down to 24N. This was consistent with a couple of quick preliminary Ariane runs that took 25 years before anything was detected at 24N.

2.4 Validation Conclusions

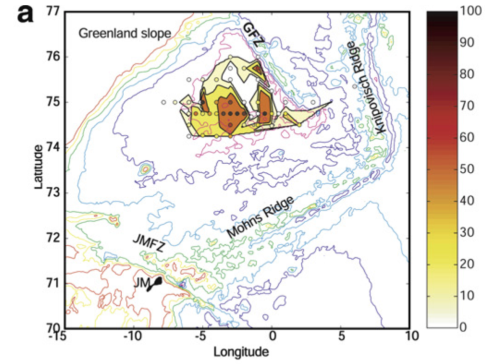
From the MOC (*Section 2.1*) we can see that the hight of overturning cells is better than in the ECCO model previously considered to analyse the spread of particles in the GSTE [8]. However there are some issues with the vertical advection properties in the Nordic sea. Namely that, due to discrepancies in the heights of isopycnals, it will struggle to get particles deep enough, so they flow over the sills and enter the deep Iceland Scotland overflow water (ISOW). As it has been observed that this is indeed what they did [7]. This may also contribute to the fact that there a massive time discrepancy observed with particles leaving the Greenland sea gyre and thus contribute to the lag time of the model. We thought about potentially changing the release site of the particles to 700m so that the properties of the particles (as opposed to the depth) of the release is closer to the target. However, as these tracer values are passive in the Ariane integration, this may not greatly improve the simulation and may introduce new sources of error. One issue that this might cause is that particles go too deep, and without any good up welling mechanism built into the model, will get trapped behind the sills and not overflow into the North Atlantic whatsoever. A solution to this, that will be described in *Section 5*, is to assume that there is a good mechanism for getting particles over the sills and into the deep waters, as these pathways have been observed experimentally. Thus, we can conduct some Ariane experiments with particles seeded along a transect below the sills at 60N and a depth below that 1500m and see where the model will take them. This could help to identify new pathways from the overflows to the detection site and provide some insight into the complete pathway.

3 Replication of tracer release experiments

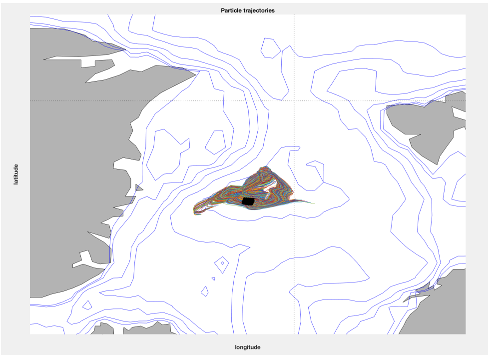
There have been numerous SF_6 tracer releases in the last few decades, any of which could potentially contribute to the highly concentrated signal at 24N. In this section I used Ariane's forward integration qualitative mode with a 5 day mean data series, similarly to the GSTE validation in *Section 2*, to explore the spread of particles from the various release sites. The aim being to identify which of these sites is the most likely source of the tracer, by quantifying their contributions. I ran these experiments, releasing 3600 particles in a $10km^2$ box, from their true release date until the 2010 detection date. I then used a MATLAB tool to extract the particles who's trajectories passed through the target region. It is hard to quantify how the sluggishness of the model might affect the validity of these results, as it will likely be a



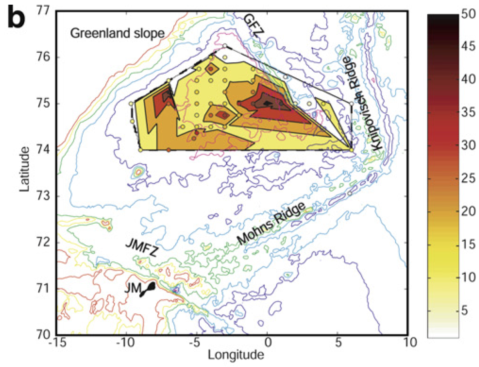
(a) 1.5 yrs



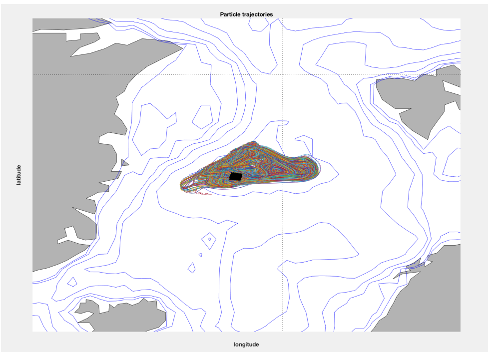
(b) 3 months



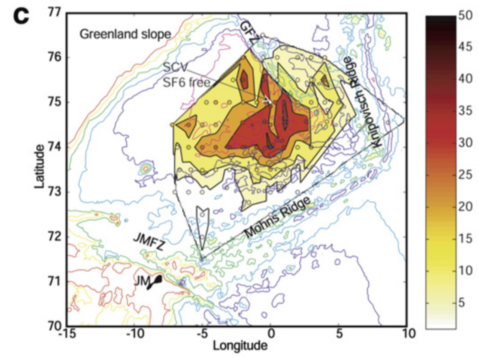
(c) 2 yrs



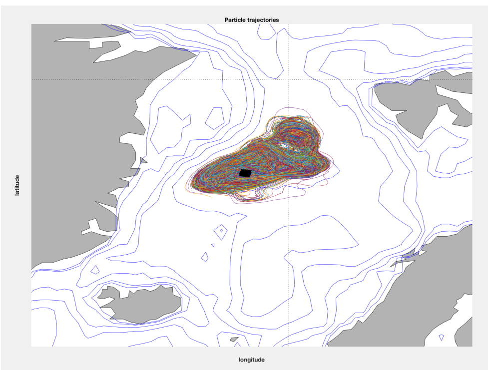
(d) 7 months



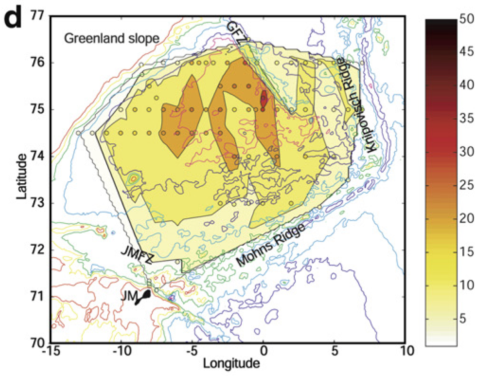
(e) 3 yrs



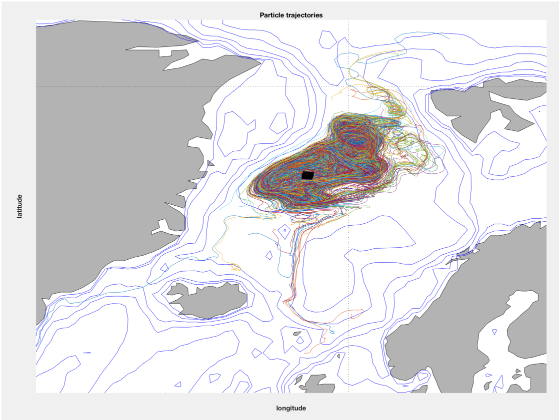
(f) 9 months



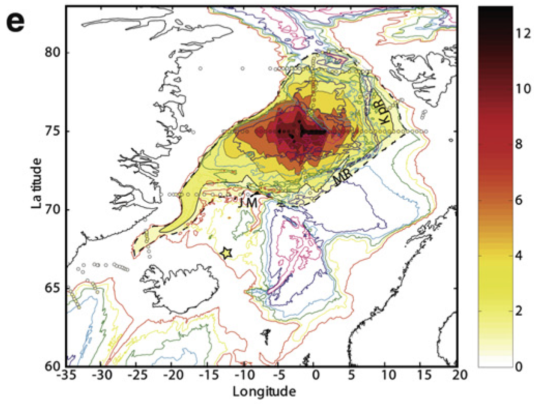
(g) 6 yrs



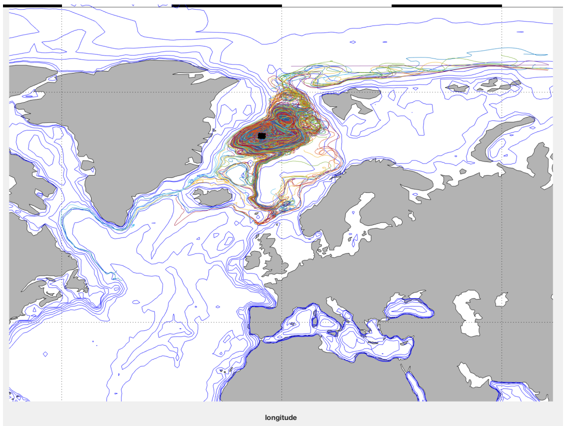
(h) 1.5 yrs



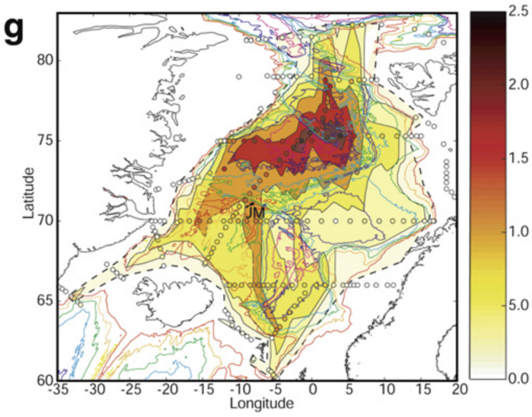
(i) 8 yrs



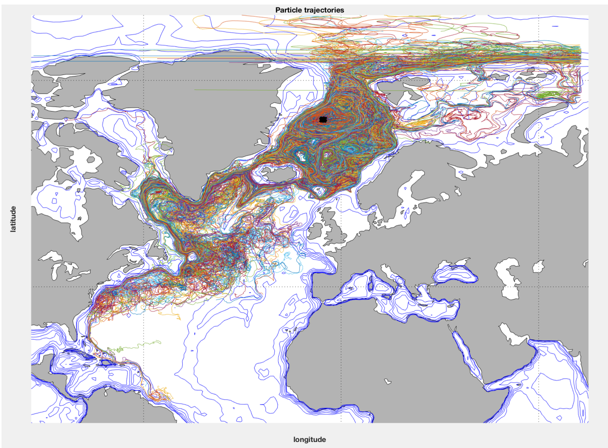
(j) 2 yrs



(k) 10 yrs



(l) 6 yrs



(m) 22 yrs

Figure 2: *Comparing the spread of a simulated GSTE in Ariane (left) with the recorded data from the various cruises (right). The integration times (ie runtimes) are below the figures so that you can compare the time discrepancies of the model to reality. (m) is a full trajectory for a 22 year integration time, to show that even in this time scale particles do not make it down to 24N*

complicated function of position and time. Hence, I decided to stay consistent and run them for the amount of time they ran in real life.

From here onwards there are several scatter plots, of mainly temperature vs salinity (TS) diagrams, that by construction may provide some misleading information (*Section 6.1*). The data points that are plotted later in the plotting process are placed over top of the previous points and thus mask their data. This is especially an issue in the densely populated regions near the release site, and so these plots should be examined with caution.

3.1 Brazil Basin Tracer Release Experiment (BBTRE)

Released at at depth of 4000m in the Brazil basin, this experiment was run for 14 years from 1996 to 2010 [10]. In this time you can clearly observe that the particles did not get advected very far at all, with a spread of only about 30 degrees meridionally. Most of the spreading was completely isopycnal as can be clearly seen in the TS diagrams (*Figures 4*), with the Eastern branch mixing slightly to lighter densities. It can be observed in Marie-Jose's figures (*Figures 3*) that this is indeed the sort of mixing that was observed in reality, with the bathymetry forcing some vertical mixing to the east [9]. This is some positive reinforcement for the reliability of these runs, and even with the sluggishness of the model, it is hard to see that these particles will be advected to 24N any time soon.

3.2 Salt Fingers Tracer Release Experiment (SFTRE)

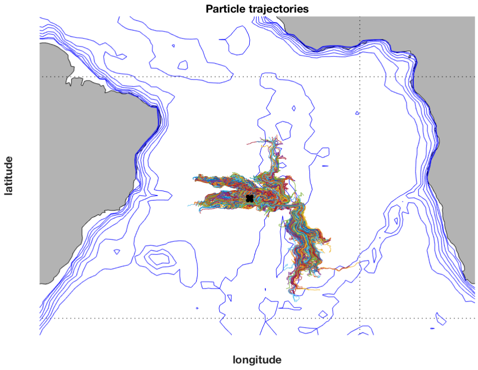
The particles were released at the target depth of 300m and integrated forward for 9 years from 2001 to 2010 [11]. Most of the particles appear to have entered the shallow warm gulf stream and been advected north at great speed (*Figures 5*). In doing so, there was also little vertical mixing until much later on in the experiment. This means that even the particles that look like they were heading towards 24N, were doing so at far too shallow a depth to have contributed to the observed signal. Now this could be another fault of the model, similar to the issue of a lack of downwards advection observed in the Greenland sea. However, due to time constraints, we did not compare the models properties to any measured data in these regions, and therefore cannot specify the extent of this. Especially as the release location had a completely different current structure to the release in the Greenland Sea gyre. It is worth noting that in many of the experiments released close to the surface (less than 500m deep) displayed similarly surface contained trajectories, an aspect that could potentially be improved in a coarser resolution model.

3.3 North Atlantic Tracer Release Experiment (NATRE)

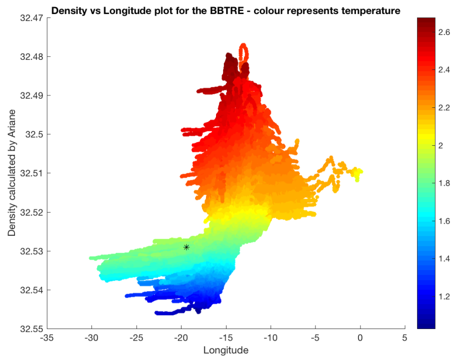
Again, the particles were released at the target depth of 300m and integrated forward for 18 years from 1992 to 2010 [12]. The particles appear to traverse the North Atlantic in it's entirety (*Figures 7*), however when the depths are observed it is clear that they do this while in the surface layers of the ocean, with lots of isopycnal spreading as well as diapycnal mixing - mainly to lighter densities (*Figures 8*). So once again none of the particles went through the target box, or got anywhere near the 1500m depth range.

3.4 Conclusions of the release experiments

Initial assessment of the TS diagrams may be misleading due to the way they were generated. Seeing as none of the experiments managed to get any particles to the desired location, it is not worth analysing them much deeper here, as we didn't have time to explore the extent to which the model matched measured data. In future these TS diagrams could be modified to point density plots to prevent data masking, although it would remove the colour information.

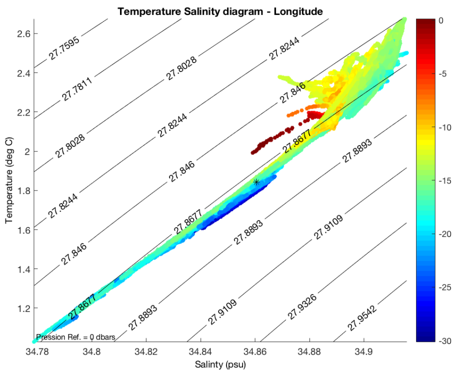


(a) *Trajectories for BBTRE*

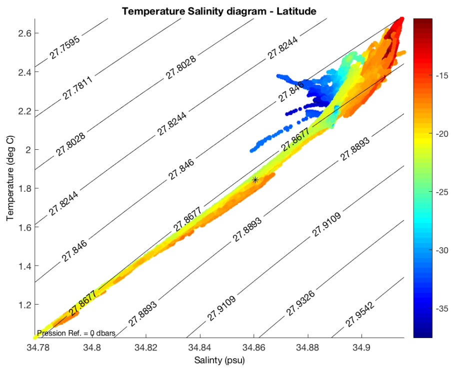


(b) *Density - longitude for BBTRE*

Figure 3: *(a) shows the trajectories of the the BBTRE experiment run with Ariane from 1996 to 2010. (b) shows the corresponding density vs longitude plot, with colour representing temperature for all of the points in the trajectories. The asterisk defines the release properties.*



(a)



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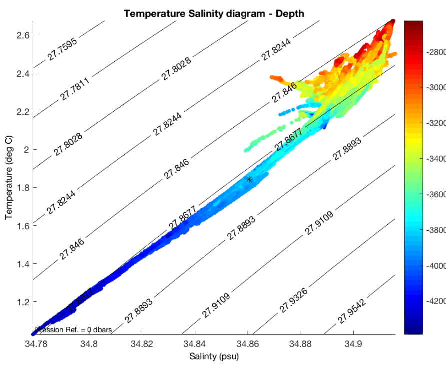

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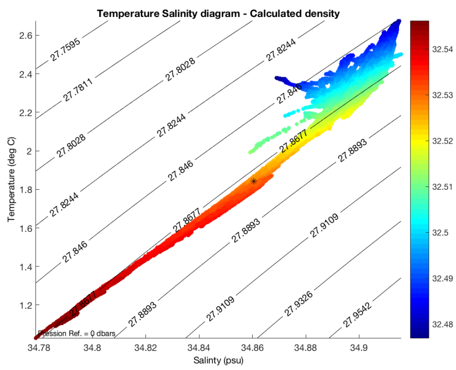
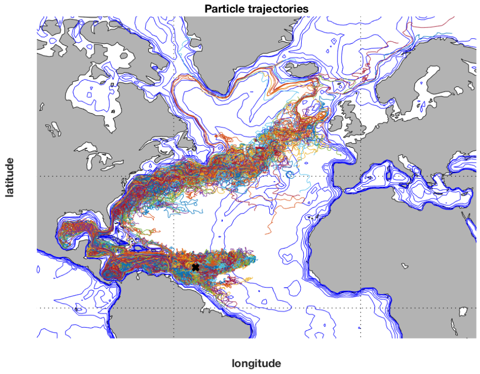
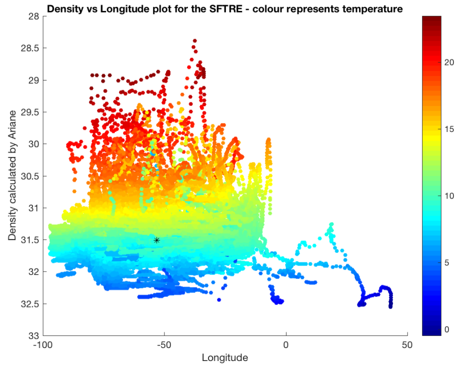


(d)

Figure 4: *TS diagrams for the BBTRE, with isopycnals reference to 0 bar plotted in the background and the asterisk is the release properties. For the various plots the colours correspond to (a) Longitude (deg E), (b) Latitude (deg N), (c) Depth (m), (d) Calculated neutral density by Ariane (psu)*

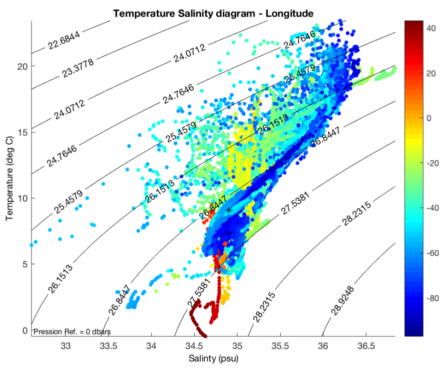


(a) *Trajectories for SFTRE*

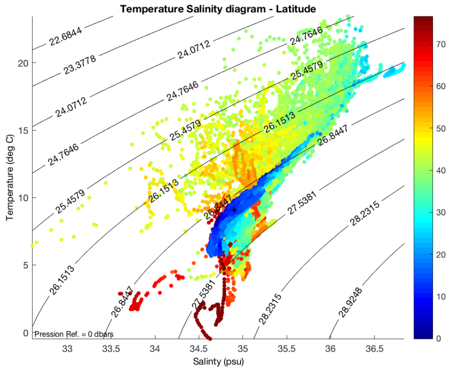


(b) *Density - longitude for SFTRE*

Figure 5: *(a) shows the trajectories of the the SFTRE experiment run with Ariane from 2001 to 2010. (b) shows the corresponding density vs longitude plot, with colour representing temperature for all of the points in the trajectories. The asterisk defines the release properties.*



(a)



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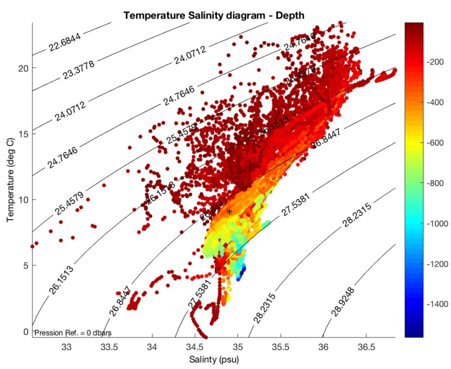

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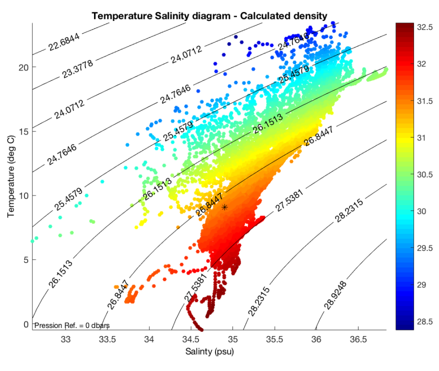
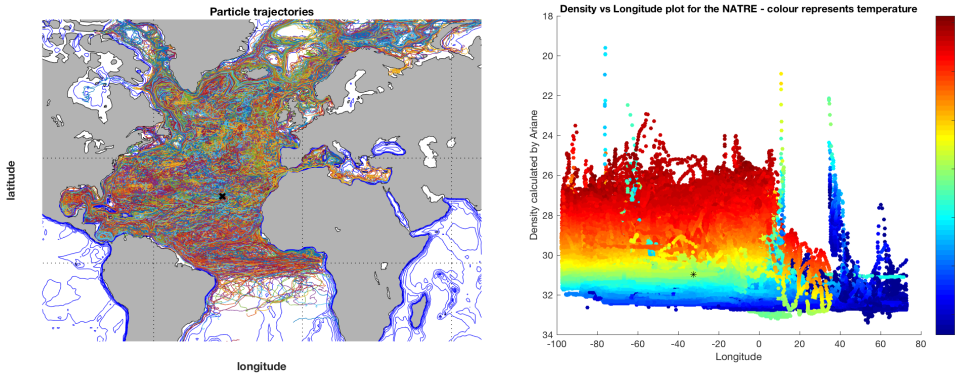


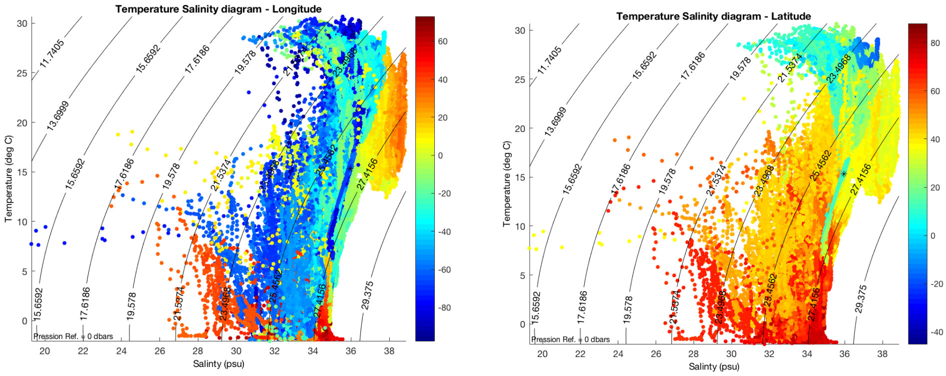
(d)

Figure 6: *TS diagrams for the SFTRE, with isopycnals reference to 0 bar plotted in the background and the asterisk is the release properties. For the various plots the colours correspond to (a) Longitude (deg E), (b) Latitude (deg N), (c) Depth (m), (d) Calculated neutral density by Ariane (psu)*

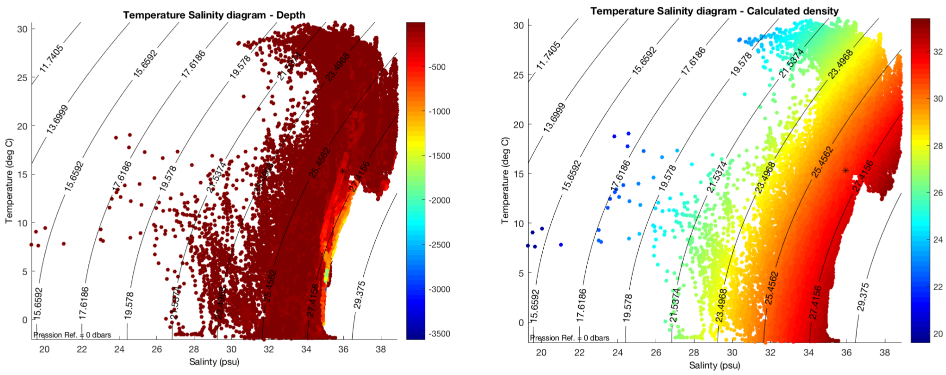


(a) *Trajectories for NATRE* (b) *Density - longitude for NATRE*

Figure 7: *(a) shows the trajectories of the the NATRE experiment run with Ariane from 2001 to 2010. (b) shows the corresponding density vs longitude plot, with colour representing temperature for all of the points in the trajectories. The asterisk defines the release properties.*



(a) (b)



(c) (d)

Figure 8: *TS diagrams for the NATRE, with isopycnals reference to 0 bar plotted in the background and the asterisk is the release properties. For the various plots the colours correspond to (a) Longitude (deg E), (b) Latitude (deg N), (c) Depth (m), (d) Calculated neutral density by Ariane (psu)*

Using the MATLAB tool to extract particles that passed though the 24N detection site (a box of appropriate size, depth and location), none of the release experiments got any particles to 24N. This could be due to a sluggishness of the model (BBTRE and GSTE) or potentially due to a lack in its ability to vertically mix/advect the particle to the correct depth (SFTRE and NATRE). Having said that, perhaps the model is not at fault and in fact the signals are just not likely to come from these releases, this would require further exploration of the velocity fields compared to measured data.

This experiment has been largely inconclusive and so the effectiveness of this forwards integration method may be brought into question. I think that with longer integration periods we might be able to find some routes for the particles to get to the detection site, but this may not be useful in answering the question of 'where did the signal come from?'. If it would require 100's of years to get particles there, then it is not likely the source of the signal. Perhaps increasing the number of particles seeded would help, however, if you required their trajectories to be calculated, this would require a lot of computing power and memory. As explained in the introduction, I do not believe that using the quantitative mode to seed millions of particles would be an appropriate replacement to this.

4 Reverse integration from 24 North

Another type of experiment that can be run with the Ariane software is a reverse integration. Here I source the particles at the 24N detection site, and run the simulation backwards through time to find out the possible origins of the particles in that region. In doing this, the hope is that we will be able to quantify the percentage contribution to the water mass at 24N from the various release sites that were explored earlier. The hope was that this would be consistent with the conclusions of *Section 3*, however due to the lack in successful results this is not likely. It is interesting to see the results of this complimentary experiment because, due to the analytical nature of Ariane, the trajectories should be exactly the same as the forward integration (to within machine precision).

I encountered many issues with this method throughout my testing. The main source of error being that, for a good enough sampling of data, a lot of particles would need to be introduced, which would exceed the memory limit of the servers I ran my experiments on. To get around this you can use the quantitative mode, and get the statistics from there. Again there are the issues outlined in *Section 1.* The 24N region where I source the particles has a lot of recirculating flow, and the experiment domain was large. As a result the percentage of the 2 million particles initiated that corresponded to useful data was insignificant (0.033%).

4.1 Reverse Integration Method

That being said a reverse experiment was conducted, with a particles initialized at 24N, 43W and a depth range of 1500m to 2500m, which is a decent approximation of the detected signal [9]. Then a domain of 30S to 60N was set up, such that an acceptable number of particles were detected leaving the experiment, while still recording data associated with the release sites of interest. The particles exceeding latitude of 60N were associated with the GSTE, the particles that went below 30S were taken as linked to the BBTRE and the particles that went through the gulf stream were connected to the SFTRE. Once this data was collected, the particles that made it to the North and South boundaries were then put as an input into a qualitative experiment and the trajectories were calculated using monthly data for 25 years. These trajectories are shown in *Figure 9.* It is important to remember that this is still a tiny fraction of the particles that were initialised in the experiment (0.033%), and that it is a reverse experiment. This means that the black cross is the final position

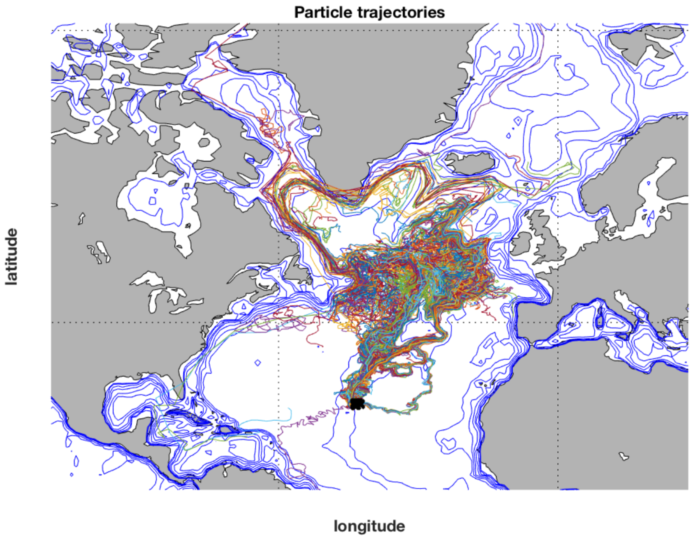
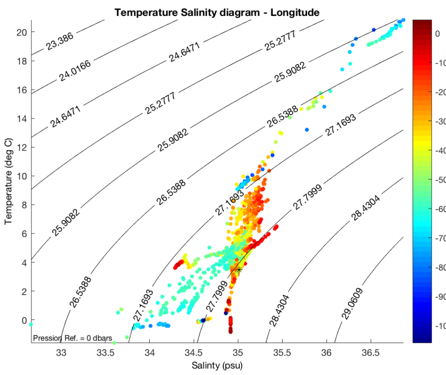
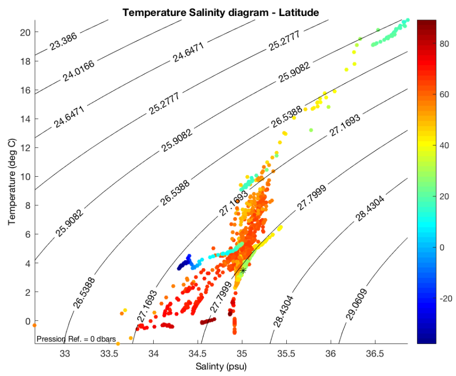


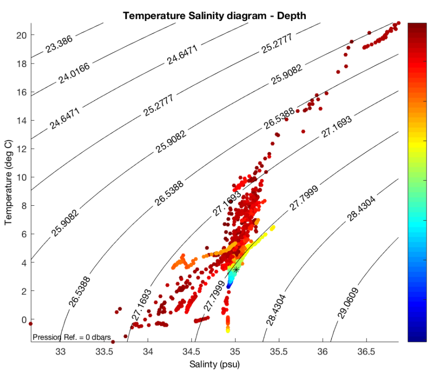
Figure 9: *Trajectories for a reverse experiment released from 24N with monthly data for 25 years. This is a plot of the particles that made it out of the domain of the quantitative experiment preceding it (ie omitting lost particles and meanders)*



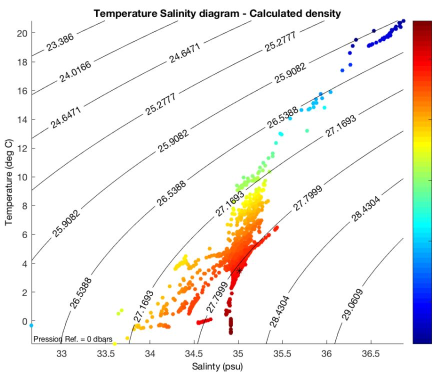
(a)



(b)



(c)



(d)

Figure 10: *TS diags for the reverse experiment, with isopycnals plotted in the background. For the various plots the colors correspond to (a) Longitude (deg E), (b) Latitude (deg N), (c) Depth (m), (d) Calculated Density by Ariane (psu). The asterisks corresponds to the properties at 24N where they were detected.*

at the 24N detection region and the particles trajectories converge here. After identifying two seemingly distinct pathways, I used a MATLAB tool [1] to extract the set of particles that passed through a box at about 38N 20W and separate the two pathways for further analysis. Once doing this I attempted a new type of plot; removing the colour information from the TS diagrams, gridding the TS space into bins, and creating a 3D histogram plot of the number of particles that lay in each cell, I was able to make a density plot of the initial and final positions of the particles *Figure 11*.

4.2 Reverse Integration Results

When we look at the trajectories we can identify two main routes from the sills to 24N. One that we will call the Eastern Pathway which can be seen as the band of trajectories that pass through 38N 20W on the eastern side of the basin. The other one we will call the Western Pathway, and constitutes of the rest of the particles, which appear to come from directly north. These two paths appear to be visible on the TS diagrams as well (*Figure 10*). Observing (c), where colour corresponds to depth, we can see that some of the particles decrease in density as they spread, increasing in temperature as they move to the surface (red). Also there is a very tight-nit group of points that remain close together and come from deeper and very slightly denser, waters (blue). This is likely to correspond to the very tight-nit set of trajectories following the deep bathymetry in the Eastern Pathway. Excitingly this is a very similar pathway to that hypothesised initially by Marie-Jose that inspired the summer project.

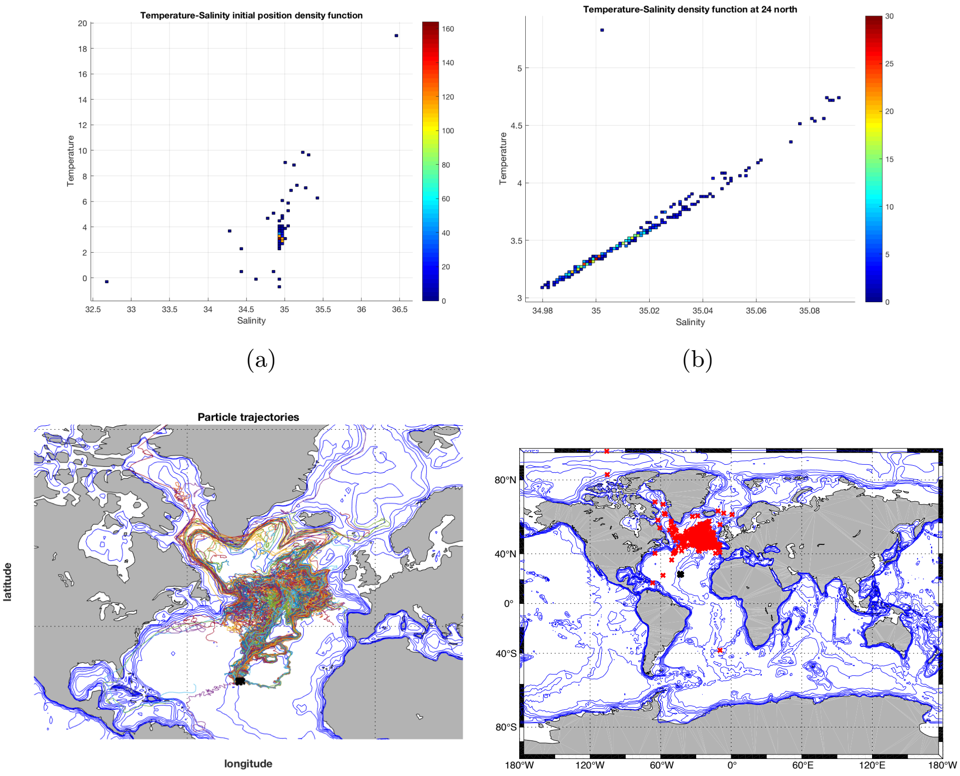
In order to consider these two pathways separately and in more detail, I then extracted these subsets of trajectories and re-analysed them.

4.2.1 Eastern Pathway

524 out of the total 676 trajectories; 78% (or 0.026% of the initial 2 million particles); occupied this pathway (*Figure 12*) which is surprising from just observing the full set of trajectories (*Figure 11*). As the particles are so coherent in this pathway, a lot of the trajectories are covered up, masking the strength of this flow. All of these particles were initially in the North Atlantic basin at about 60N in a strong region of recirculation in deep waters. They then flowed south, strongly hugging the bathymetry of the eastern side of the mid Atlantic ridge coherently. As these trajectories passed below 40N they split into two main routes, one following the mid-Atlantic ridge before crossing it along a fracture zone, and the other potentially entering a gyre and approaching 24N from the east. The initial properties of these particles were in mainly in the (34.92-34.99 psu) salinity range with a temperature range of (2.3-4.2 degrees C). However there is a very strong peak of particles at (34.94 psu, 3.15 deg C) as shown by a dark red colour representing point densities of 50 times the blue values *Figure 12*. This is promising because these are the properties of the ISOW which has come over the sills from the Nordic Sea, and so provides a pathway for waters that may contain some SF_6 tracer from the GSTE to get to 24N.

4.2.2 Western Pathway

The other 152 particles; 22% (or 0.0073% of the initial 2 million particles); took the 'Western Pathway' (*Figure 13*). These trajectories were much more dispersed and incoherent, with a lot of recirculation occurring in the northern part of the North Atlantic, however, unlike the Eastern Pathway, at slightly shallower depths. As can be seen a group of these particles came out of the western boundary current, where overflow water from the sills travelled around the Reykjanes ridge and then into the western boundary current. These may be the trajectories



(a) (b)

(c) (d)

Figure 11: *TS density function plots for the reverse release, where (a) shows the initial positions of the particles and (b) shows the attributes at the final position of 24N. The colors represent the number of particles that are within the discretised bins. A plot of the particles trajectories is given in (c) and it's* ***initial*** *and* ***final*** *positions in (d).*

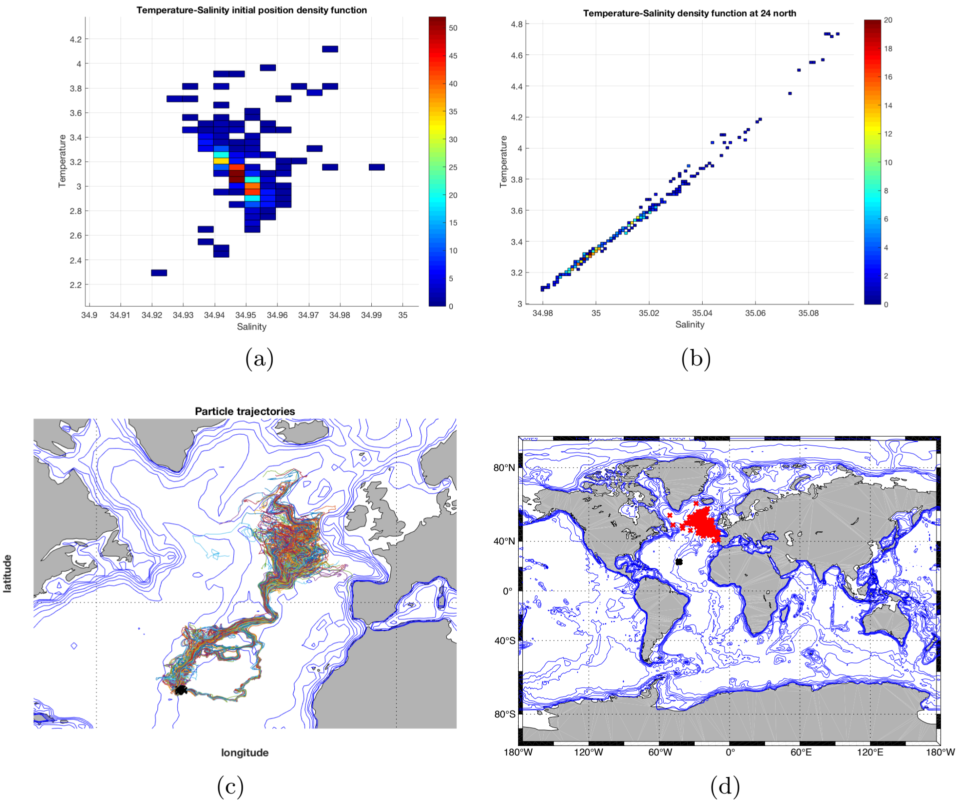
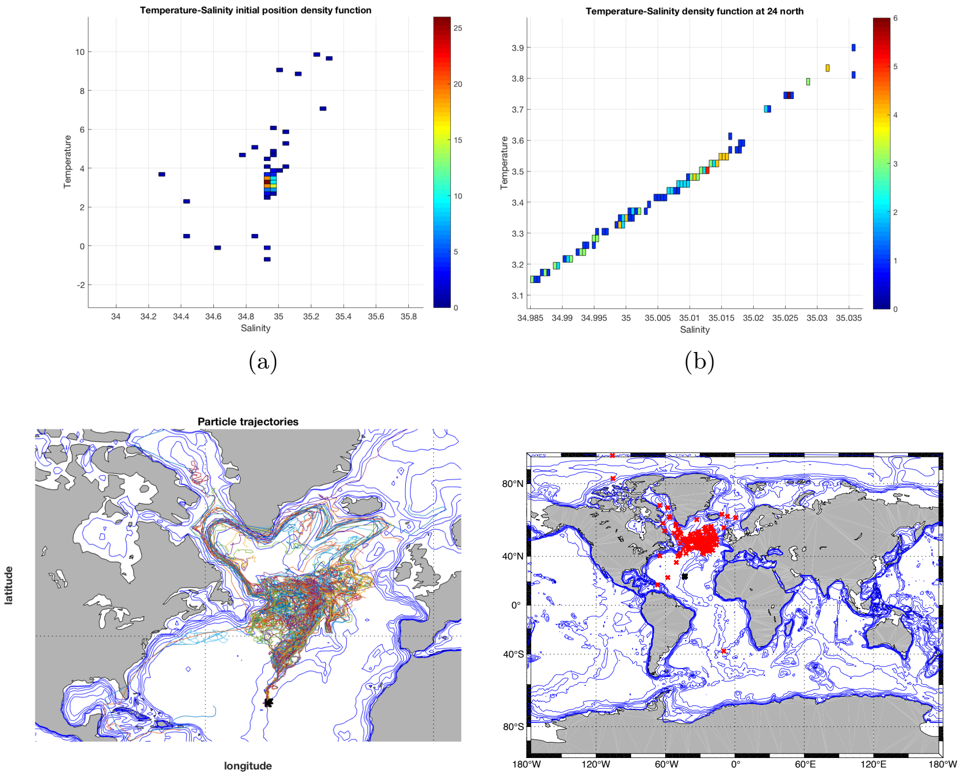


Figure 12: *TS density function plots for the Eastern Pathway of the reverse release, where (a) shows the initial positions of the particles and (b) shows the attributes at the final position of 24N. The colors represent the number of particles that are within the discretised bins. A plot of the particles trajectories is given in (c) and it's* ***initial*** *and* ***final*** *positions in (d).*



(a) (b) (c) (d)

Figure 13: *TS density function plots for the Western Pathway of the reverse release, where (a) shows the initial positions of the particles and (b) shows the attributes at the final position of 24N. The colors represent the number of particles that are within the discretised bins. A plot of the particles trajectories is given in (c) and it's* ***initial*** *and* ***final*** *positions in (d).*

that correspond to the 25 particles in the (34.94 psu, 3.2 deg C) peak of the TS diagrams, this is a set of properties that also is very similar to the ISOW seen above. So potentially this could suggest a second route for particles to get from the GSTE to 24N, albeit a sightly less strong path (1/4 the strength). Unlike the eastern route, the rest of the TS points are much more dispersed, as are the initial positions, perhaps due to lots of currents feeding into the region of recirculation.

4.3 Reverse Integration Conclusions

As can be seen in *Figure 9* the reverse integration struggles to get particles up and over the sills, perhaps in a similar fault of mechanism as described earlier, which provides motivation for *Section 5*. However this does provide some positive reinforcement of the effectiveness of these reverse integrations and how the qualitative trajectories can provide some quantitative output, even if the quantitative method doesn't. It also suggests two distinct pathways for water with properties that match the ISOW's to get from latitudes of 60N to the 24N detection site, however in the greater scheme of the experiment the percentage contribution to the water mass from these sources is 0.033%.

5 60N transect release experiment

As previously discussed, the forward integrations from the GSTE struggles to get particles over the sills into deep enough water to match the observed readings, and from *Section 4* we have observed a potential set of pathways for this overflow water to get to 24N. So to experiment more on this issue I conducted a forward integration with the particles seeded below 1500m along a '60N' transect. Due to the way the experiments are conducted in Ariane, and the bipolar mapping of the c-grid data I am using, it was easier for me to do a transect along the array coordinate around 60N. The array coordinates do not follow a Cartesian system, and thus the row doesn't correspond to 60N along the full length of the transect. However, the slope of the array row actually corresponds to a transects that is more perpendicular to the bulk flow of the major currents in that region. This will act in our favour for advecting particles south, increasing the number of particles seeded (which is proportional to the perpendicular volume flux) and reducing losses to meanders.

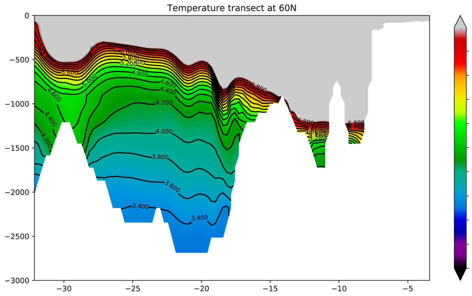
5.1 60N Release Results

I plotted some property transects along 60N to explore how the NEMO data modelled the ocean in this region (*Figure 14*), in a similar fashion to *Section 2.2.* We can see the different types of water; the cold dense ISOW at depths greater that 1500m; the warm salty northward flowing Mediterranean sea water along the east; and the flow around the Reykjanes ridge, southwards on the east and back north on the western side. However, we expected to observe a bulk of southward flowing water hugging the eastern side of the Reykjanes ridge, which is not displayed in the temperature or salinity properties model. This would mean that any overflow water that should've been entrained in that flow isn't, removing a potential pathway that was expected. It should also be noted that water shallower 1500m deep is moving northbound, this is good because I seeded the particles deeper than that, so fewer particles will immediately be lost to a meander.

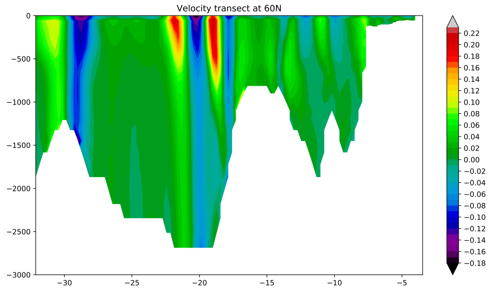
As can be seen in the stream function (*Figure 15*) there are several major pathways taken by the particles, as well as numerous recirculating paths. At 30W 60N to the far western side of the seeding section, there is a strong current around the Reykjanes ridge as expected from the transects above and observation. There is also a strong southward flow from the same section at about 20W (where all the numbers collide) which appears to flow down the eastern side of the basin and follow the bathymetry. This southward flow is also visible in the transects and is probably the deep dense bottom water in the middle of the basin following the trench, this also reasonably approximated the measured properties of the overflow water. This could be the same eastern pathway observed in *Section 4* as they're similar in structure and it appears that particles may be able to make it to the detection site. Above 48N and just further west than the Eastern Pathway we see a lot of recirculating currents. At about 38N we can also see a strong westerly current which carries a lot of particles into the western boundary current and then south.

5.2 60N Release Conclusions

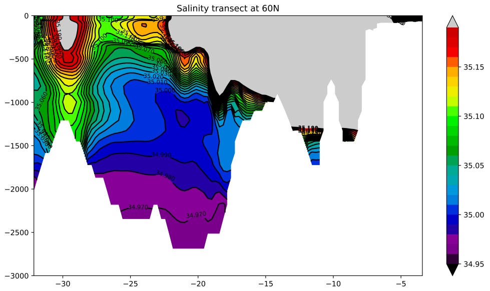
It seems that the pathway for deep Iceland Scotland overflow water down to 24 North is definitely possible using the Ariane model. The Eastern Pathway that can be observed in the 30 day mean reverse experiment is also visible in the 5 day mean forward integration, as is to be expected. This pathway can facilitate the transport of deep ISOW down to the 24N detection site, and so provides support to the hypothesis that there is a pathway for the SF_6 tracer to get south.



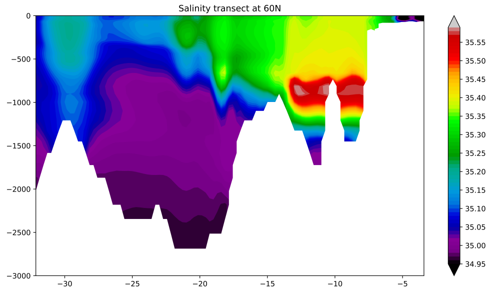
(a)



(b)



(c)



(d)

Figure 14: *A transect along the 60N release section of the Stream function (*Section 4*), where the color represents; temperature with contours every 0.2 deg C (a); meridional velocity (b); salinity with the colour bar is capped at 35.2 so the at regions of interest below 1500m are clearer and contours every 0.01 psu (c); and salinity with a full range of values (d)*

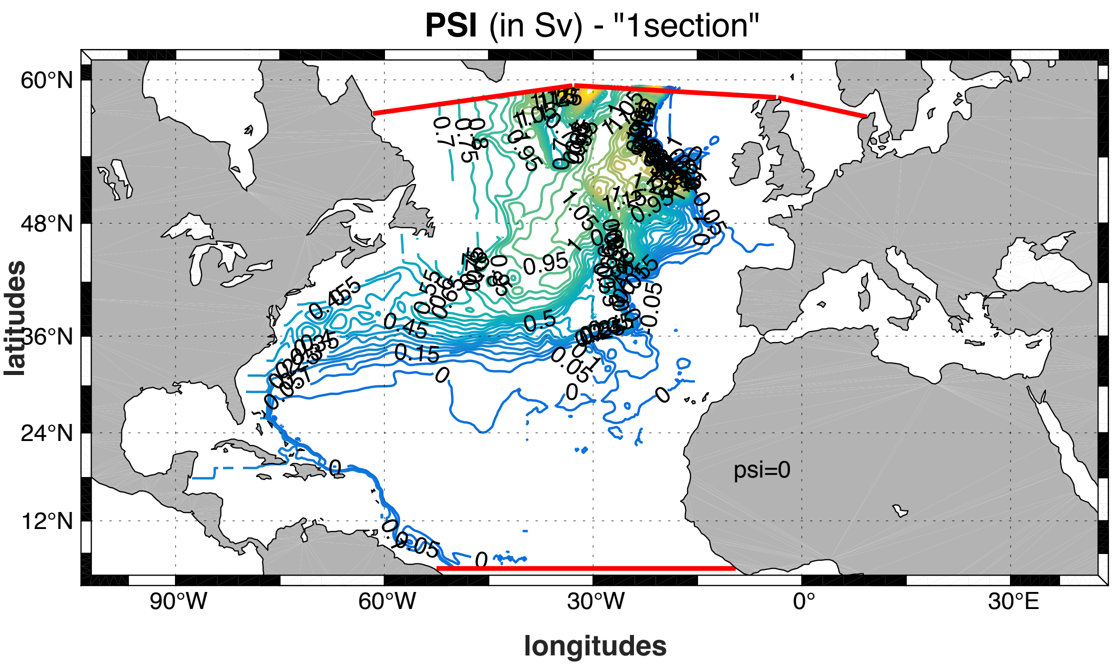


Figure 15: *Stream function produced by a quantitative particle release experiment, where particles were only seeded at depths greater than 1500m along the 60N transect. The integration was done forward in time with daily data for 25 years*

6 Discussion

6.1 Errors

Some of the errors in using the Ariane tool were discussed in the introduction as these were recognised in the preliminary use of the tool and the model, for example the evaluations of the output statistics. Any quantitative result will have to be considered within the context that they were created and appreciated such to avoid bias.

Another source of error is the resolution of the model data I was using. Due to computational restrictions I was not able to conduct any experiments using the 1/12th of a degree NEMO output data, and thus was using 1/4 degree. This means that only mesoscale eddies would feature in the model, and the particles are not affected by the vertical mixing parametrisation scheme, as far as we are aware. Ariane is only provided with the velocity field information.

We also identified in *Section 2.2* that the model doesn't properly replicate observed vertical advection in the Greenland sea, as the density properties occur at depths that differ significantly from observations. This could contribute to the feature that most of the particles remained at the surface 500m for longer periods than would be expected, and therefore may effect how the particles spread both spatially and temporally. There was not enough time to explore the other release experiments in the level of detail as we did the GSTE, therefore this should be considered as a large source of error. This may contribute significantly to the temporal discrepancies observed in *Section 2*

Due to the way the TS diagrams are created, the latter particles are plotted over the former particles, and thus a lot of information is hidden, especially in densely populated regions. This means that there is a lot of visual bias when looking at those plots. One good way of mitigating this was to just view the end and beginning situations and to generate a density plot, however this removes the previously assigned color information. Another issue is that when generating the isopycnal contours, I was unable to use the neutral density (like the densities calculated by Ariane), as the calculation doesn't work for particles over a range of positions, instead they're referencing a pressure of 0 bar. The errors that would be introduced trying to fix this would be comparable, and so potential density will do.

As previously mentioned, the method for defining the sections involves editing array coordinates which do not directly correspond to latitude and longitude. So attempting to construct transects along these lines would take way too long, hence there is an error in the definition of the transects. For example a transect across 60N is only going to approximate that latitude at one point, and the curvature of the line prevents it from being true across the whole transect, as seen in *Figure 15*. However, the property transect and release section are self consistent within my figures, just not necessarily with the observational data or grid references.

7 Conclusion

Use of the Ariane program has been insightful into how the properties and aspects of the NEMO model output data affect the trajectories of particles placed in it, and therefore where the model lacks and succeeds. It has revealed the sluggishness of the model, as well as how it struggles with vertical advection, but has shown how well it models particle spreading patterns and pathways. When used with careful consideration, the qualitative mode can be used to produce some meaningful statistics even in situations where the quantitative mode struggles. As far as achievement of the REP's aim. I struggled to assign meaningful quantitative results to the contributions of the 3 release sites, due to a mixture of the sluggishness of the trajectories and the potential issues in the properties of the velocity fields. The conclusions of my experiments suggest that none of them would contribute any water mass to the signal. A more detailed analysis of transects in the respective regions is needed to be able to assess if the trajectories are behaving how they are supposed to or if, like with *Section 5*, the trajectories need to be partitioned into sections for proper analysis. A potential new pathway between the GSTE and the 24N tracer detection site has been identified, that closely resembles that of the hypothesised route from the Faeroe Shetland overflow, along the North Atlantic ridge on the eastern side of the basin, and across a fracture zone to 24N . The initial properties of the particles that followed this route also suggest that it is indeed the overflow water that we predict it to be, increasing confidence further. However, the water mass percentage contribution to the signal is very small (0.033%).

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