The Timing of Global Change

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Abstract

Because of its responsiveness to changes in the marine environment, it has been suggested by Rose in 2005 that the capelin, a small pelagic fish that is key to the ecology and fisheries of the North Atlantic, could be seen as a "canary in the coalmine" to detect signals of changes in the Arctic and sub-Arctic Ocean. We describe the historical data that make possible a quantitative assessment of the geographical shift capelin migration-paths and spawning grounds undergo, with increasing temperature, and the time it takes to make these shifts long-lasting. Then we introduce recent data that make these quantitative measurements more accurate and predictive. Direct measurements made in the fall expeditions of Iceland's Marine and Freshwater Research Institute along the East Coast of Greenland, and the Copernicus database of the European Union, are used to examine the evolution of the returning Atlantic water (from Svalbard) that is forming a warmer and saltier boundary current under the colder and fresher East Greenland polar current. The returning Atlantic water has a temperature range (1 to 4 degrees Centigrade) suitable for feeding migrations of the capelin. This current is reaching further north along the coast of North East Greenland and we use simulated data from Copernicus to monitor this evolution. We calibrate the Copernicus data with the direct measurements made by the Marine and Freshwater Research Institute, in Iceland. A trend emerges, both in the direct measurements and in Copernicus data, showing that the returning Atlantic water boundary current may reach Greenland's major Northeastern glacier streams, draining the bulk of the Greenland Glacier in the relatively near future We use the capelin data to predict when this may happen.

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Arctic ecosystems face many challenges as the climate changes around them. Marine temperatures are changing, as are oceanic currents, salinity, and sea ice cover. For the health of these ecosystems, as well as the continuation of the human industries that depend on them, it is of the utmost importance to understand the impact of the changes that may occur. It is interesting to note that the changes which these ecosystems have already undergone may also be able to give us insight into the future of these environments. Here, we use historical data about the capelin in order to do exactly that.

Warm Ocean Currents Surrounding Greenland

We present a brief discussion of the currents around Greenland and in the sub-Arctic Seas that is necessary for understanding the present work. For a visual representation, refer to Figure 1. The Gulf Stream leaving the East Coast of the United States becomes the North Atlantic Current, bringing saline warm Atlantic water to the West Coast of Europe and into the sub-Arctic Seas [32]. The North Atlantic Current bifurcates in the far-north Atlantic: the Irminger Current (IC) heads towards Iceland and Greenland, while the other branch of the North Atlantic Current crosses between the Faroe Islands and Shetland Islands to become the Norwegian Current (NC). The IC then splits into a cyclonic branch in the Irminger Sea between Iceland and Greenland and the Icelandic Irminger Current flowing clockwise around Iceland. The cyclonic branch eventually rounds the southern tip of Greenland and becomes the West Greenland Current (WGC). It flows along the coast to Northwestern Greenland, beneath the fresh and cold coastal water, and some of it reaches all the way to the Nares Strait. Along the eastern coast of Greenland, a current of fresh cold polar water from the Arctic flows south through the western Fram Strait; we call this the East Greenland Polar Current (EGPC) to distinguish it from other branches of the East Greenland Current. This cold current then continues into the East Greenland Coastal Current (EGCC) along the Southern Coast of Greenland.

The NC flows towards the Arctic along the Norwegian Coast and then divides into two branches, one crossing the Barents Sea and the other flowing along the West Coast of Svalbard [32]. Water from each branch enters the Arctic, one through the Fram Strait west of Svalbard [29] and the other through the Santa Ana Trough [40] east of Franz Josef Land after traversing the Barents Sea. Although these currents are warmer than the surrounding water, they are saltier and sink into the Arctic ocean. There, they circulate, becoming colder and denser and returning as a current of Atlantic Arctic Water (AAW), below both the NC and the EGPC, south through the Fram Strait [29]. However, not all the water from the NC enters the Arctic, because the westerly branch bifurcates south of the Fram Strait. One branch of it, that we will call the Returning Atlantic Water (RAW) [32, 52, 25], flows west toward northern Greenland and then south along Greenland's Continental Shelf.

It has been understood for some time that the warmer oceans are causing accelerated melting of the Greenland Ice Sheet [41]. Both in Iceland and in Svalbard, the warmer and more voluminous ocean currents have caused a warming of the climate and greatly increased melting of glaciers [1, 6, 28, 7, 38, 22, 44]. The IC gained access to the glacier streams in Southeast Greenland between 1990 and 2009, and greatly increased melting was observed along the Southeast Coast [36, 2, 19, 35]. This was due to the increased volume and temperature of the branch of IC flowing south along the coast of Greenland and pushing itself under the EGCC along the Southeastern Coast of Greenland. The WGC has also warmed and grown at less than 200 meters depth along the coast of West Greenland. This has led to greatly increased melting of the glacier streams along the coast of Northwest Greenland, see [51], in recent years. Thus, the influence of the IC on the melting of the Greenland glacier is understood in some detail [41, 51].

The influence of the RAW is less appreciated, as is its ability to melt the glaciers in the northeast and central east coast of Greenland. We show in this paper that the RAW is beginning to access the Continental Shelf of Greenland. This water has already gained access to the fjords and glacier streams in Central Greenland. It is difficult to predict what changes to the currents the future will bring. However, these changes affect the ecology, in particular the migrations and spawning of the capelin. Here, we combine the observed changes in the currents and their influence on the

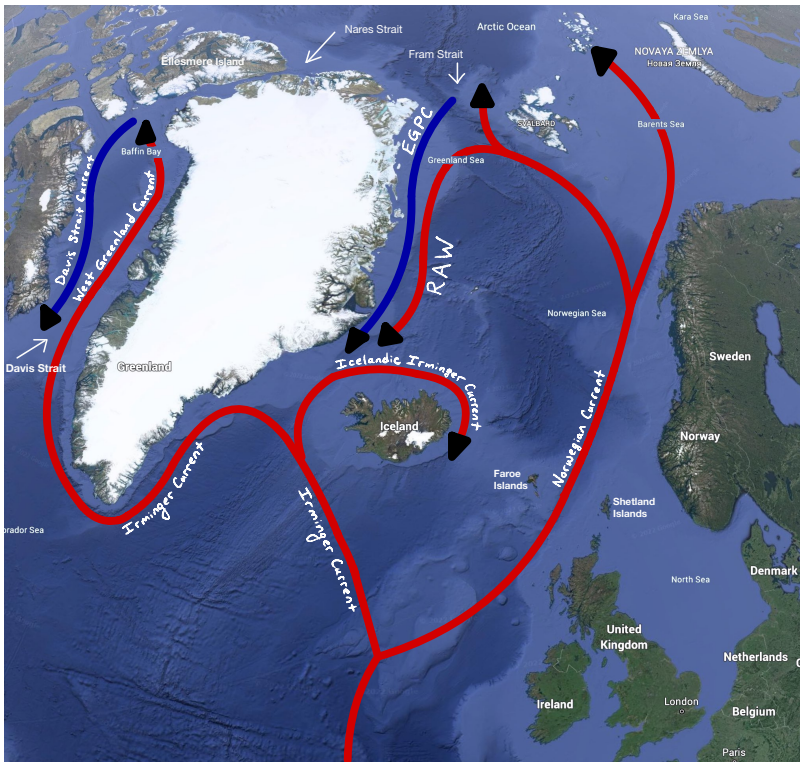

Figure 1: A cartoon of the currents in the Nordic Seas.The Atlantic Current (red, bottom) splits into the Irminger Current (IC) and the Norwegian Current (NC). The IC spits into a branch circling Iceland and another branch going south along the coast of Southeast Greenland. This branch continues north along the coast of West Greenland. The NC splits into a branch going through the Barents Sea and another going through the Fram Strait. The latter branch splits again sending the RAW (Returning Atlantic Water) south along the East Greenland Coast. The cold East Greenland Polar Current (EGPC) and Davis Strait currents are also shown (blue).

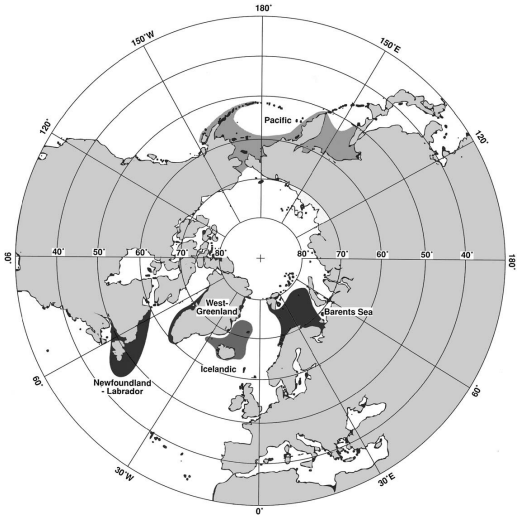

Figure 2: Map of current distribution of the major capelin stocks (*Mallotus villosus*), dark (Atlantic) and dark grey (Pacific), and their likely migration routes from the North Pacific to the North Atlantic. From Rose, 2005 (redrawn from Vilhjálmsson, 1994).

migrations of the capelin stocks, in the past, to predict how the currents may change in the future and influence the melting of the Greenland Icecap. In particular, we will assess when the RAW is likely to have pushed warm Atlantic Water onto the Continental Shelf of Northeastern Greenland under the EGPC (due to its greater salinity). When this happens, the currents of the warm Atlantic Waters will truly have the Greenland Glacier surrounded, and a much greater rate of melting may quickly result.

1 The Capelin

The ecosystem data centers on the capelin, a small planktivorous species of pelagic fish that plays an essential role in bringing the biomass from the Arctic marine environment south into the subarctic region. There are four major stocks of capelin globally: one in the seas around Iceland, one in the Barents Sea, one off the coast of Newfoundland and Labrador, and one in the Northern Pacific ocean between Alaska and Russia [48]. Two additional stocks of capelin are under management in Eastern Canadian waters but are generally smaller and therefore figure less prominently in this paper. For a map of the distribution of the major stocks, see Figure 2. The capelin occupies the tropic level of forage fish in the sub-Arctic Oceans, feeding on the zooplankton bloom that follows the phytoplankton bloom moving north in the Arctic spring. Because the capelin is essential as a feeder stock to the commercially valuable species in the Northern oceans, such as Cod, Herring, Haddock [4, 49, 43], and the general ground-fish tropic level [21, 17, 50], but is also commercially valuable itself, several of the stocks have been well-researched during the last five to seven decades [10, 11].

In his seminal 2005 paper, Rose characterized the changes in the feeding and spawning migrations and spawning location of the capelin due to changes in temperature [42]. He found a quantitative relationship between temperature change and the magnitude of the displacement (shift) of these migrations and locations. He also quantified the persis-

tence (in years) of the changes in terms of displacement distance, see Table 2 in [42]. Rose suggested that the changes are driven by temperature-induced changes in food availability and feeding areas, and this seems to be universally true for the three stocks (the Newfoundland, Iceland, and Barents Sea stocks) considered below. He also observed that changes in migrations precede changes in spawning areas.

In particular, the relationships that Rose found were a linear relationship between the logarithm of the distance of shifts and changes in temperature, and a linear relationship between the persistence time of these shifts and the logarithm of the distance of the shift [42]. Recently, these persistence periods are relatively short for both Iceland- and Greenlandic waters and the Barents Sea. Hence, we consider the changes to be persistent if they last more than three years; we consider the short "persistence time" to be the time it takes to change from one persistent state to another (Rose makes note of these different types of data in [42]). We carefully curate all data to distinguish between Rose's long-time persistence, which we leave aside, and the time it takes these shifts to become persistent for three or more years, see Supplementary Materials A. We use this same line of thinking for recent shifts in Canadian waters.

This allows us to elaborate on Rose's foundational relationships. Expanding on the relationships Rose found between the shift distance, the oceanic temperature, and the timing of the shift, we construct two functional relationships, the "Capelin Thermometer" and the "Capelin Clock," which enable us to predict the distance and timing of temperature induced changes along the coast of Greenland. We augment the historical data used by Rose with more accurate recent measurements from Iceland, Norway, and Newfoundland/Labrador. By using these recent measurements, we are also able to to validate and refine his data, see Supplementary Materials A.

1.1 The Capelin Clock and the Capelin Thermometer

We are able to augment the data from Rose [42] with data from more recent changes. The greatest changes for the capelin are currently taking place for the Icelandic stock. The acoustic observations are also the most extensive for this stock, with data going back to the 1960s [48]. In recent years, its feeding migration has reached higher and higher latitudes along the East Greenland Coast [10] and the longer feeding routes have resulted in distinct earlier and later spawning migrations taking place for different portions of the stock, see [5].

A careful examination of the catch data for the Icelandic stock [45] shows a significant shift toward the northwest of the averaged spawning migrations between the periods 1993-2002 and 2003-2018. Figure 3 shows the average temperature (left) and salinity (right) at the centroid of the second and third week fishery during the period of 1993-2002. On the two temperature plots, we see an increase of 0.650 degrees Centigrade between the two locations at depth 100 meters for the second week fishery. During that week, the migration has adjusted to the temperature of the spawning path but not yet sped up to optimize the time until spawning [18]. The figure shows the increase in the temperature at the old location, and we see a shift of 224.914 kilometers, see [45], between this new (blue) warmer temperature at the old location, and the new relatively cooler temperature (also blue) at the new location.

Shifts have also been observed in the other stocks. In the Barents Sea, a shift of spawning location has also been observed, see Figure 4, in this case towards the southwest, between the periods 1994-1998 and 1999-2020 with increasing averaged ocean temperature measured in the West Barents Sea [3]. Off Newfoundland and Labrador, a shift in centroids of fall trawl surveys conducted from 1983 to 2020 shows a shift towards the southwest, closer to shore, after 1995, while a shift is found in the opposite direction, farther from shore, towards the northeast, after 2005 [8]. In all three cases, these shifts in location can be interpreted as a response to increase in ocean temperature in the traditional location, shifting towards cooler temperatures. This adds credence to Rose's central thesis and is in accordance to the temperature preference of the capelin [5, 18].

We use these collated data points to find the correct coefficients for the Capelin Thermometer, see Figure 5. There, we show the Capelin Thermometer that we have constructed from this data (left) and the regression upon which it is based (right). To construct the Capelin Clock, we use the same method and omit points which belong to the persistence time, see Supplementary Materials A. In Figure 6, we show the Capelin Clock that we constructed from this collated

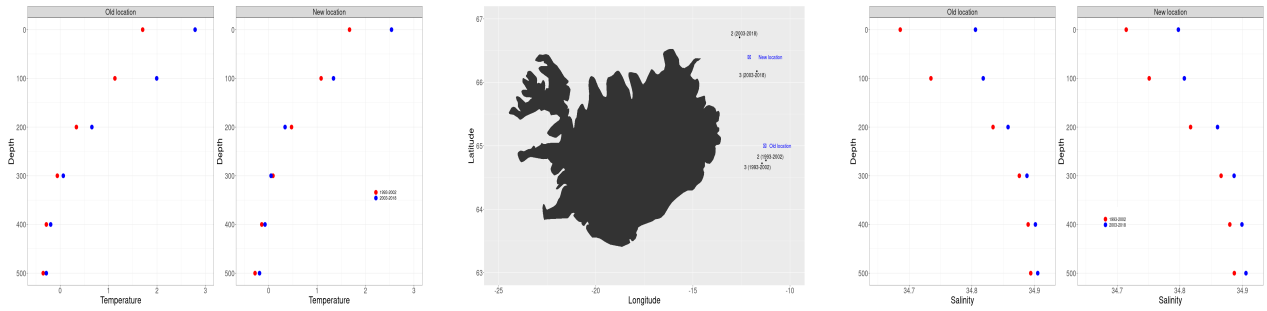

Figure 3: The average temperature and salinity, in Iceland, at the second and third week centroids (of capelin catches) from 1993-2002, labelled 2 and 3 on the map, for depths from 0 to 500 meters. For each centroid, the temperature and salinity measurements were taken at the same location; labelled the old location and the new location, (blue square) on the map in the center. The left figure shows the temperature and the right figure the salinity. The red dots are for the period 1993-2002 and the blue dots for the period 2003-2018. Notice the 0.650 ^{o}C difference in temperature at 100 meters, between the blue dots at the old and the new location. This causes a shift of 224.914 kilometers in centroid 2 and a shift of 162.354 kilometers in centroid 3. There is a corresponding shift in salinity.

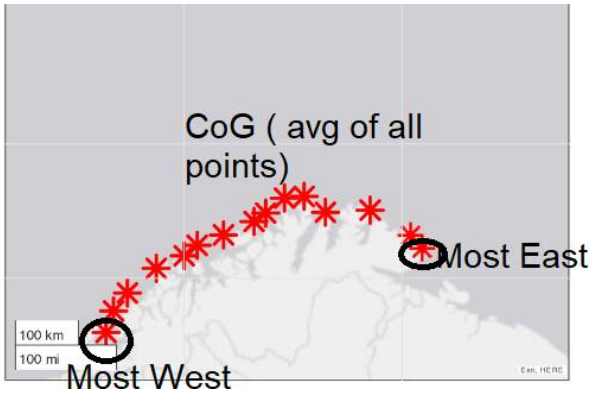

Figure 4: The spawning locations along the North Coast of Norway, showing the Centroid of Gravity (CoG), a red asterisk. The CoG shifts in response to increasing temperature in the West Barents Sea.

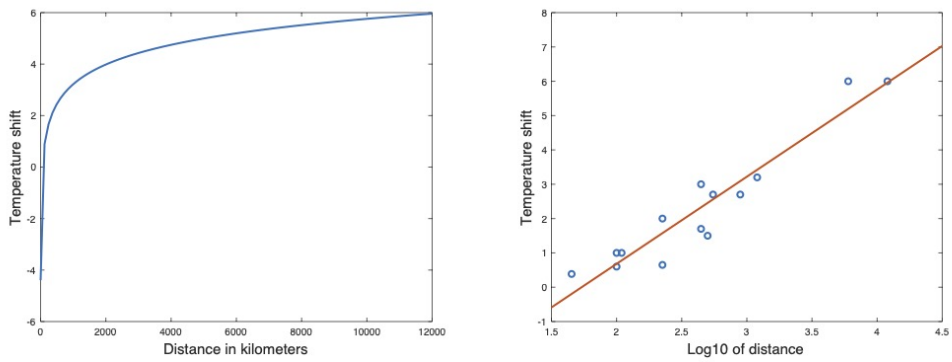

Figure 5: The Capelin Thermometer (left) and its regression (right). The Thermometer shows the shift in centigrades as a function of the log (base 10) of the shift in kilometers, $r = 0.950$, $R_2^2 = 0.903$, Adjusted $R_2^2 = 0.895$.

data (left) and the regression upon which it is based (right). We can now consider the Capelin Thermometer and the Capelin Clock as independent instruments, and we can use them to measure the relationships between the temperature changes and location of the corresponding ocean currents and the time that it takes these changes to occur.

2 Temperature and Salinity Measurements

The existence of the RAW (Returning Atlantic Water) Current has been known for a long time [16, 33]. In fact, it was even recorded as early as 1914 by Hjort [26], see Figure 7. However, even today, its ability to expose the coast of Northeast Greenland to warm Atlantic Water from under the EGPC and melt the glacier streams of the main Greenland Glacier is not fully appreciated. The disappearance of the sea ice along the coast of East Greenland in recent years [47] has made it possible to take direct measurements, see the Methods section; they have been made in the fall expeditions of the research vessels of the Icelandic Marine and Freshwater Research Institute for the last six years, from 2016 through 2021. We use a set of measurements along the East Coast of Greenland to record the movement of warm Atlantic Water from the RAW onto the Greenland Continental Shelf.

In addition to providing temperature and salinity profiles for several latitudes for six years, these measurements allow us to calibrate the Copernicus Models, see the Methods section, of the European Union in a way not previously possible. Our calibration data set comprises a number of years; details can be found in Section 5. This calibration gives us confidence in using these models to calculate rates of change in marine temperatures at depth. In Figures 8 to 10, we present the measurements on the left and the corresponding Copernicus simulations on the right.

In Figures 8 to 10, we show the temperature and salinity profiles of sub-Arctic Ocean along the East Coast of Greenland. The profiles are measured along the 68 to 74 North Latitudes, shown on the map in Figure 11 that shows the latitudes where the measuring stations were located in 2018. The measurements were taken during the September to October expeditions of the research vessel of the Marine and Freshwater Research Institute of Iceland. The 72 North Latitude lies above the Norwegian Island of Jan Mayen and above the fjord Scoresbysound in Greenland, see the map on in Figure 11. The left pictures in each figure show extrapolations of the direct measurements made by the research vessels, with contours made by Matlab's *contourf* function. The locations of the measuring stations are provided in Supplementary Materials B. The right pictures show the data from Copernicus. The Figures are labeled by the year

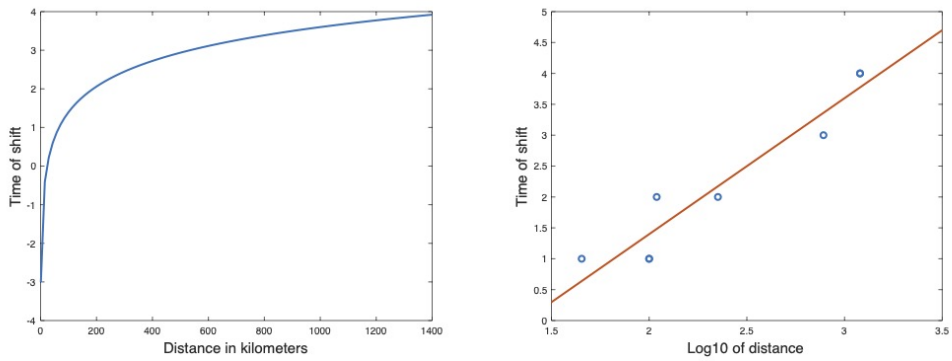

Figure 6: The Capelin Clock (left) and the regression upon which it is based (right). The Clock shows the persistence of the shift as a function of the log (base 10) of the shift in kilometers, with $r = 0.957$, $R_2^2 = 0.915$, Adjusted $R_2^2 = 0.901$. For small times (shown on plot, and measured in years), we interpret the persistence of the shift as the time it took the shift to become persistent, hence the name clock.

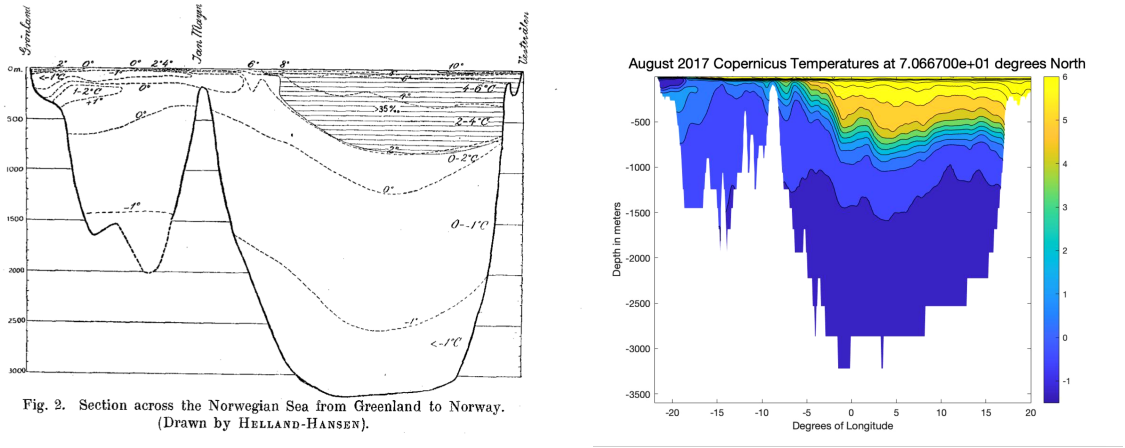

Figure 7: Left: Cross sections of the sub-Arctic Ocean showing marine temperatures circa 1914 [26]. The continental shelf of Norway is on the right, the continental shelf of Greenland to the left. The ridge in the middle is the Jan Mayen Ridge. Right: Copernicus data from August of 2017 at 70.667 degrees North. The RAW is visible on both figures forming a (light blue) lobe of 1-2 ^{o}C water flowing south along the edge of the Greenland continental shelf.

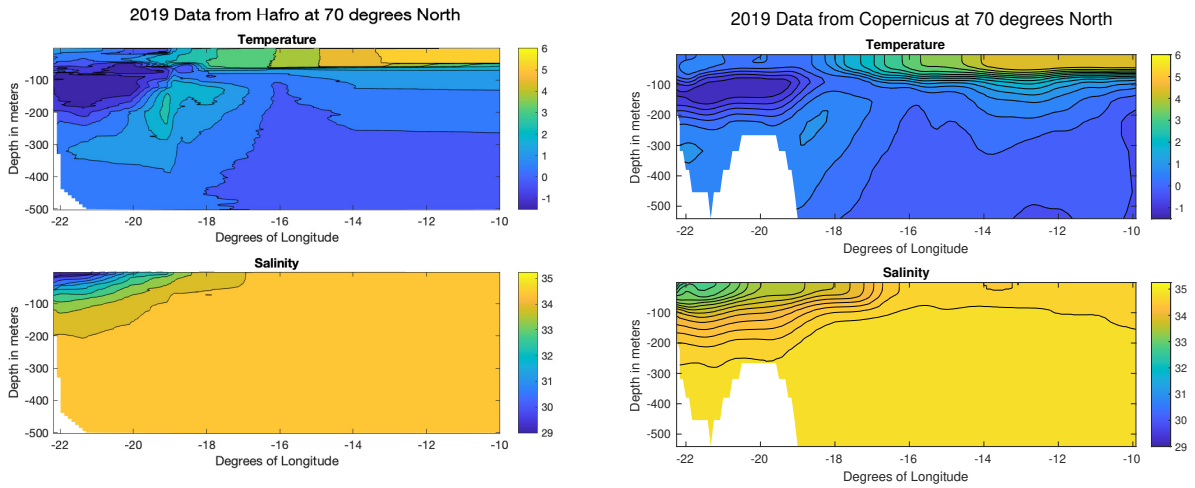

Figure 8: Cross sections of temperature and salinity along the the 70 North Latitude. Extrapolations of measurements of the Icelandic Marine and Freshwater Research Institute research vessels on the left, data from the Copernicus database on the right. Here and below, temperature is measured in ^{o}C and salinity in ppt.

in which the measurements were taken and the Copernicus data was simulated for the same year. On the top figures we clearly see the cold EGPC (in blue), going south, with temperatures down to -1.5 degrees centigrade; it is also fresher, as seen on the bottom figures (yellow is saltier). Below the EGPC, we see the RAW, also going south, with temperature above 2 degrees centigrade (green color). The RAW is also saltier, as seen on the bottom figures. This is why the current lies below the EGPC, and remarkably it has access to the outlets of the Greenland glacier reaching below sea level. On top of figures is a warmer relatively fresh layer, produced by weather-related mixing of the cold and warmer waters. The agreement between the Copernicus Data and the direct measurements is remarkably good, see Supplementary Materials B,though the direct measurements show a more pronounced RAW current and further penetration of the warm Atlantic Water under the EGPC.

In Figure 11, we use the simulations from Copernicus to show the changes that have taken place along the 72 North Latitude. In this figure, we show the temperature (top) and salinity (bottom) profiles of the sub-Arctic Ocean along the East Coast of Greenland. The profiles shown are from Copernicus along the 72 North Latitude, shown on the map along with the other latitudes measured in 2018. Measurements were taken by the Marine and Freshwater Research Institute of Iceland during their September expeditions, and the simulations from Copernicus are in good agreement, see Supplementary Materials B.On one hand, the profiles on top from the years 1998, 2000 and 2003, left to right, clearly show that the continental shelf of Greenland at this latitude is still protected from the warm RAW. On the other hand, the bottom profiles taken during the years 2016, 2017 and 2018, left to right, show how the RAW makes it onto the continental shelf of Greenland, in the latter two years, and penetrates under the EGPC to reach the coast of Greenland. Four years later, it has done the same up by 74 North Latitude, see Figure 10.

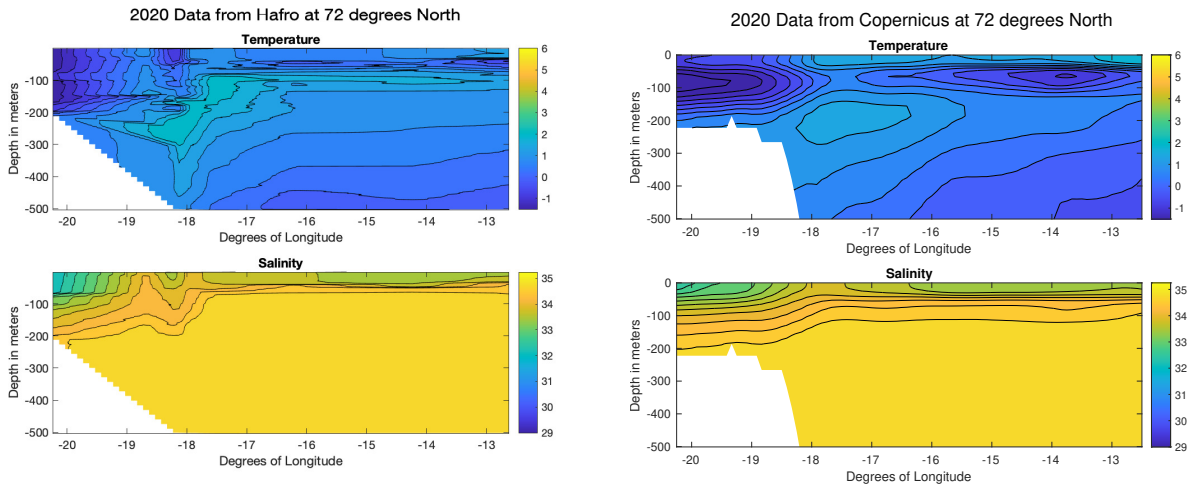

Figure 9: Cross sections of temperature and salinity along the the 72 North Latitude. Extrapolations of measurements of the Icelandic Marine and Freshwater Research Institute's research vessels on the left; data from the Copernicus database on the right.

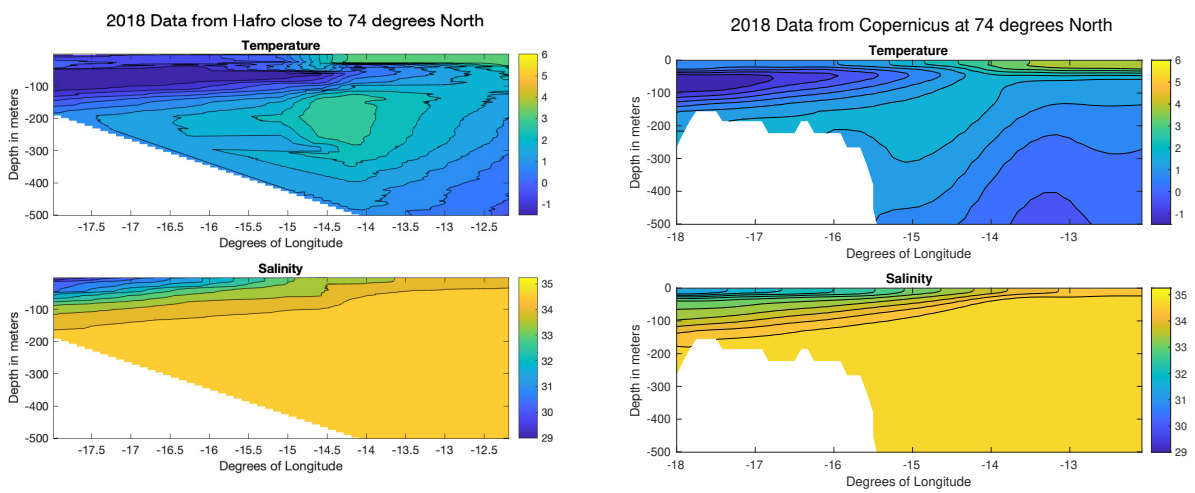

Figure 10: Cross sections of temperature and salinity along the the 74 North Latitude. Extrapolations of measurements of the Icelandic Marine and Freshwater Research Institute's research vessels on the left; data from the Copernicus database on the right.

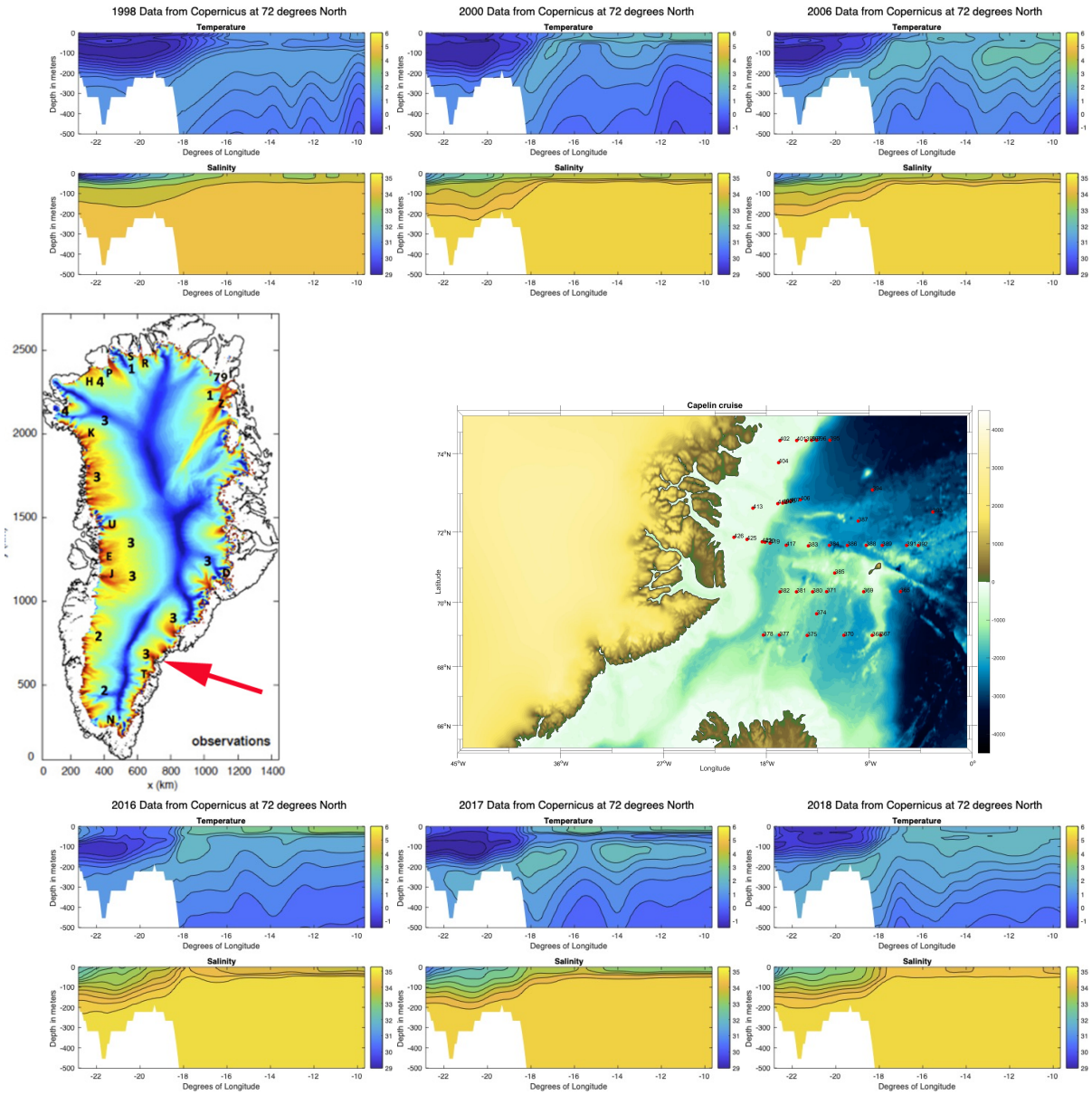

Figure 11: **Top:** Temperature and salinity profiles constructed from Copernicus data along the 72 North Latitude, for years 1998, 2000 and 2006, from left to right. The area under the EGPC is still protected against the warmer and saltier RAW. **Middle:** Right: The glacier streams draining the Greenland Glacier, the 79th Glacier Stream (1) reaches the sub-Arctic Ocean on the 79th latitude in Northeast Greenland and the Zacharias Glacier Stream (2) is right below it. Those two drain the bulk of the main Greenland Glacier in Northeastern Greenland. The red arrow points at Koge bugt, where the melting was the greatest in the 1990s [39]. Left: The map of the stations where the temperature and salinity profiles of sub-Arctic Ocean along the East Coast of Greenland were taken, during the September 2018 expedition of the research vessel Árni Friðriksson, of the Marine and Freshwater Research Institute of Iceland. **Bottom:** Temperature and salinity profiles from Copernicus database along the 72 North Latitude, for years 2016, 2017 and 2018, from left to right. Notice how the RAW (green, with yellow salinity) makes its way onto the Greenland continental shelf during the latter two years.

3 Prediction: The Age of Accelerated Melting

We will now use the Capelin Thermometer to measure temperature shifts in the ocean and how far the currents can move according to those shifts. We will also measure, using the Capelin Clock, how long this shift may take. We can then estimate when warm Atlantic Water from the RAW may reach the coast of Northeast Greenland up towards 80th latitude, so that both the Zacharias and 79th glacier stream are exposed to water of temperature of 2 degrees Centigrade and above, see Figure 11. Historically, the ocean temperature has been below -1 degrees at these glacier streams. What the capelin data shows is that an increase in marine temperature is associated with a shift in location. Thus we will ask: what is the shift in kilometers that corresponds to the temperature of the water in the fjords of Northeastern Greenland increasing from -1 degrees to 2 degrees Centigrade?

The Capelin Thermometer answers this question. Namely, the interpolation formula

$$T = 2.539 \log_{10}(y) - 4.396,$$

from our collated data set relates the increase in temperature T in ^{o}C to the distance y in kilometers that the capelin migrations may shift, with regression coefficient $r = 0.950$. Solving for distance y, we find that

$$y = 10^{(T+4.396)/2.539}.$$

When $T = 3$, an increase of 3 degrees Celsius, we see that $y = 818.39$ km. Since each latitude is 111 km, starting at the 74th latitude, this shift would move the capelin 152.39 kilometers north of 80th latitude North, well above both the Zacharias and the 79th glacier streams discussed above.

The next question is how long would this shift take? Or how long will it take the RAW to move warm Atlantic Water onto the Greenland continental shelf, under the EGPC, all the way up to the 80th latitude from its present position on the shelf by the 74th latitude? We can use the Capelin Clock to answer this. The interpolation formula

$$t = 2.201 \log_{10}(y) - 3.004,$$

again from our collated data set, gives that information, where time t is measured in years and shift distance y in kilometers. Here the regression coefficient is 0.957. Substituting the shift computed above for y, we find

$$t = 2.201 \log_{10}(818.39) - 3.004 = 3.407 \approx 3.4$$

to be the time that a shift of that magnitude takes to occur. The last step reflects the accuracy in Rose's data, it is only one significant digit. Thus, using the Capelin Clock and Capelin Thermometer together, we predict that rapidly accelerating melting of the glacier streams in the Northeastern Coast of Greenland could start taking place in less than three and a half years.

The estimate derived above is an estimate of how much further north the capelin could go using the RAW in the next 3.4 years based on their historical shifts. (Note that we are implicitly assuming here that the capelin will use the RAW to follow the receding sea ice [47], staying as close to their feeding grounds along edge of the sea ice and the outlets of the Greenland Glacier as they can.) It is possible that the extension of the RAW along the Greenland continental shelf will be slower and its amplification be periodically slowed down by the influence of the North Atlantic Oscillation (NAO) [27] or increased freshwater flux through the Fram Strait [30].

Let us then turn to the Copernicus data to obtain a direct estimate of the temperature changes from the simulations. We can use the simulations dating back to 1993 to determine the trend in the increase of the marine temperatures. In 2016, the RAW pushed warm Atlantic Water onto the Greenland continental shelf as far north as the 72 North latitude for the first time in recent history; four years later, in 2020, it was doing the same by the 74 North latitude, see Figure 10. Linear extrapolation from these two latitudes suggests a slower and smaller shift of the warm current than the one

predicted by the Capelin Clock and Capelin Thermometer; it predicts two latitudes in no more than 4 years. A higher estimate for the warming on the shelf by the 80th latitude North would, therefore, be 12 years.

We now relate these estimates explicitly. According to our work, the time until accelerated melting of the Northeastern Greenland glacier streams starts is likely to be:

$$3.4 \text{ years} < \text{starting time} < 12 \text{ years}.$$

The lower estimate is provided by the capelin data, the higher estimate by the Copernicus data calibrated by the measurements of Iceland's Marine and Freshwater Institute.

4 Discussion

We have identified the changes in the RAW, the ocean current that could be instrumental in the increased melting of the glaciers in Northeast Greenland. This current is ideally suited to the temperature preference of the capelin during its feeding migrations, see [48, 49, 18, 5]. From the Copernicus database, we see that the RAW is pressing onto the Greenland continental shelf, along the Northeastern Coast of Greenland, under the EGPC, due to its greater salinity. This is how Atlantic Water from the warmer RAW gains access to the Greenland Glacier Streams.

The recent paper [51] confirms our suggestion that most of the ice-loss will occur by increased ice-flow due to undercutting by the warm RAW in the fjords of Northeast Greenland. In the paper, the authors examine the ice-loss from different types of glaciers in Greenland, and it is concluded that the greatest ice-mass is lost by glaciers that are in contact with deep ocean water, the so-called DW glaciers. The second-greatest loss is by the so-called FS glaciers, glaciers that have a floating ice-shelf. The ice-shelf collapsed in 2012 resulting in substantial thinning of the 79th and Zacharias glacier-streams, see [31]. Those ice-streams currently are FS glaciers because they do not have contact as yet with the RAW, but our contention is that they will turn into DW glaciers, vulnerable to undercutting, within the predicted time-frame.

Currently, the two glacier-streams, discussed above, sit at the mouth of the largest fjord in Greenland that is still covered with ice, see Figure 12, from [34]. They lie on opposite sides of an island in the mouth of the fjord, as shown on the left figure, and there are no coastal mountains blocking their paths. If the RAW gains access to this fjord (and it can, both from the south and from the north, at 200 meters depth as shown on the right figure), the bulk of the ice in Northeastern Greenland could be released [31].

The rest of the Greenland coastline in the East, Southeast, Southwest and West is lined by coastal mountains, see Figure 12, that block the ice-sheet and allow a stable or metastable equilibrium to form after periods of great melting. This may have happened in Southeast Greenland after the great melting in the 1990s [36]. However, this is not possible for the 79th, Zacharias, nor Humbolt or Petermann glaciers in the North, since coastal mountains do not block their progress. Hence, their melting is likely irreversible.

5 Methods

The data in [42] relating the shift in location of the capelin with temperature was obtained by searching the literature for recorded shifts. The sources are listed in Tables 1 and 2 in [42]. We augment Rose's data, see Supplementary Materials A, by more accurate recent measurements of spatial shifts with temperature from Iceland, the Barents Sea and Newfoundland. In Iceland, the shift of the spawning migration is recorded. In the Barents Sea, the shift is in the spawning locations and in Newfoundland the shift is in the feeding migrations, or main feeding locations are measured. In all three cases, the center of gravity is determined to find the location, see [46], following the methods

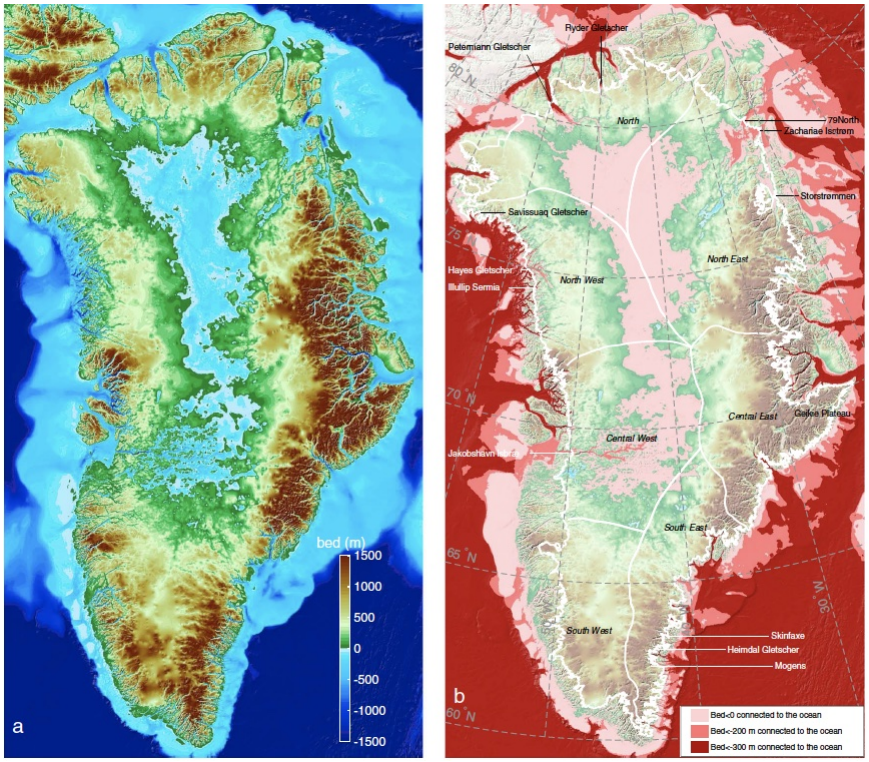

Figure 12: **(Right)** The topographical features of Greenland without ice. **(Left)** The access of seawater, (reddish) pink $\leq$ -200 meters, (light) pink $\leq$ 0 meters, red ≤ -300 meters. The (crooked) white line marks the boundary of the ice.

in respectively, [45], [3] and [8]. The corresponding temperature and salinity shifts were both measured directly, and temperature was also measured remotely.

The measurements presented in the paper were performed by the vessels of the Marine and Freshwater Institute in Iceland along several latitudes ranging from the 68th North to 76th North, every fall (September to October) from 2016 to 2021. The area, covered by these latitude along the East Greenland Coast, is remote and has become accessible only in recent years with the receding sea ice [47]. Several measurements are taken along each latitude, see Supplementary Materials B. Temperature and salinity is measured down to 500 meters depth, along with turbidity and other oceanographic data. Water samples are taken to calibrate the measuring device. Acoustic measurements, see below, are also made along the latitude to look for capelin schools and their behavior during each 24 hour period.

5.1 Data Sources

Data has been collected by the Marine Science Institutes in Canada, Iceland and Norway for the last 50 years. In particular, the Marine and Freshwater Research Institute in Iceland has collected acoustic data for the migrations of the Icelandic capelin for the last 50 years. These surveys have been collected twice a year. A stock assessment was conducted in the fall and a survey of the spawning migration in early winter [49]. Additional surveys for the feeding migration were also conducted for several years while fishing was allowed during the feeding migration [50]. In addition to acoustic surveys showing the distributions, density and vertical spread of the schools and their migrations [37], other data was collected. These include measurements of the currents, temperature, both surface and vertical, salinity, and primary and secondary (plankton) production. Some measurements of chemical composition of the ocean water have also been made in recent years.

Data for the other stocks and regions is also available, although the stock assessments are less extensive. The Institute of Marine Research in Bergen had conducted similar surveys in the Barents Sea [23, 24], for time stretching back 30 years. They have traditionally conducted stock assessments in the fall, but starting in 2019 have started surveying the beginning of the the spawning migration of the capelin in the Barents Sea. Similar surveys of the capelin stock have also been conducted by the Fisheries and Oceans Canada, Northwest Atlantic Fisheries Centre in St. John's, Newfoundland, Canada, for a more limited time [20, 12, 9, 8]. However, 70 years of temperature data and 20 years of bio-chemical data is also available for this area.

5.2 Simulations with assimilated data

Oceanic data has also been obtained from Copernicus, the European Earth Observation and Monitoring Programme (https://marine.copernicus.eu/). We have made use of Copernicus' models for marine temperature and salinity throughout this paper and compared these simulation results to direct measurements. This study has been conducted using E.U. Copernicus Marine Service Information [13], [14] and [15]. In particular, we used the two https://resources.marine.copernicus.eu/products: *Global Ocean Physics Reanalysis* and *Global Ocean* $1/12^o$ *Physics Analysis and Forecast updated Daily*, with 50 depth levels and both a daily and monthly mean of the variables temperature and salinity. The dates were from the beginning of 1993 to the end of 2021 and have a 12.5 by 12.5 km resolution. The layer [14] is used for dates between 1993 and 2020 and [15] for dates between 2019 and 2021.

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