Are "Great Salinity Anomalies" Advective?

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ABSTRACT

"Great Salinity Anomalies" (GSAs) have been observed to propagate around the North Atlantic subpolar gyre. Similar anomalies occur in the Third Hadley Centre Coupled Atmosphere–Ocean GCM (HadCM3) of preindustrial climate. It has been hypothesized that these salinity anomalies result from the advection of anomalously low salinity waters around the subpolar gyre. Here, the consequences of using passive tracers in the HadCM3 climate model to tag the anomalously low salinity water associated with a GSA in the Greenland and Labrador Seas are reported. Rather than predominantly advecting around the modeled subpolar gyre in accordance with the upper-ocean salinity anomaly, the tracers mix to intermediate depths, before becoming incorporated into the model's North Atlantic Deep Water. Horizontal advection of the tracer in the upper ocean is limited to around 1000 km, compared with the gyre-scale propagation of the salinity anomalies. It is concluded that GSAs are unlikely to be caused by the advection of salinity anomalies; rather anomalous oceanic currents or surface fluxes are responsible.

1. Introduction

The North Atlantic Ocean plays an important role in the global climate system, as the primary location of the sinking arm of the thermohaline circulation (THC). The THC transports heat northward in the Atlantic, maintaining anomalously warm conditions in surrounding regions, in particular northwest Europe. In the past there have been periods when the THC was much weaker than at present, or completely shut down, such as in the Younger Dryas (Skinner and Shackleton 2004; Came et al. 2003), resulting in a strong cooling of the North Atlantic region. Since the Younger Dryas the THC has been comparatively stable, maintaining the warmth of the Holocene Period, but there have nevertheless been fluctuations in the THC (Rasmussen et al. 2003; Kristensen et al. 2004).

The sinking arm of the THC requires a source of dense surface waters in the northern North Atlantic. At temperatures close to the freezing point, density variation is dominated by salinity, so variations in salinity can impact strongly on deep water formation. The salinity of northern North Atlantic waters is controlled by many factors, which act over different time scales. At decadal to centennial time scales the advection of salt from low latitudes by the THC counteracts the net input of freshwater from precipitation and runoff at high latitudes. However, at shorter time scales, variations within the North Atlantic dominate. Unlike temperature, salinity has no atmospheric damping, so anomalies represent the integrated impact of previous forcings.

One of the best documented modes of salinity variability is in the subpolar gyre region of the North Atlantic. Several "Great Salinity Anomalies" (GSAs) have been observed to propagate around the North Atlantic subpolar gyre over the past 40 yr. The first of these—the Great Salinity Anomaly—was documented by Dickson et al. (1988) and propagated around the subpolar gyre from 1968 to 1982. It was initiated by an anomalously large export of low-salinity water and sea ice through Fram Strait into the East Greenland Current (EGC), which subsequently advected into the Labrador Sea (Aagaard and Carmack 1989; Häkkinen 1993).

More recently there have been two more similar

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events (Belkin et al. 1998; Belkin 2004), but these formed to the west of Greenland in the Labrador Sea/Baffin Bay region, as a result of severe winters and increased sea ice extent, which may have been enhanced by an increased flow of low-salinity water through the Canadian Archipelago (Houghton and Visbeck 2002). Belkin et al. (1998) identified two modes of GSA origin, *remote*, whereby anomalously high export of low-salinity waters from the Arctic initiates an event, and *local*, where severe winters form the initial anomaly in situ.

Reduction in the salinity of the upper ocean in regions of deep water formation is likely to have impacts on the strength of the THC. This is because a reduction in salinity of 1 has the same impact on density as a temperature increase of around 10°C in areas of deep water formation where temperatures are close to the freezing point. Using a model forced by reanalysis data, Häkkinen (2002) found that periods with anomalously low salinities in the Labrador Sea were associated with reduced meridional overturning. In another modeling study, it was found that the meridional overturning weakened by 20% as a result of the anomalous ice export through Fram Strait comparable to that associated with the Great Salinity Anomaly (Häkkinen 1999). Coupled climate model simulations of present-day climate have exhibited GSA-type behavior (e.g., Wadley and Bigg 2004), and this has been found to be related to fluctuations in the meridional overturning strength (Manabe and Stouffer 1999). However, it has been observed that the Great Salinity Anomaly only weakened deep convection in the Greenland Sea after the time of its passage (Malmberg and Jonsson 1997).

By contrast, at midlatitudes in the North Atlantic it has been found that the North Atlantic Oscillation generates anomalies much more by anomalous Ekman advection than freshwater fluxes (Mignot and Frankignoul 2003). Salinity anomalies are strongly advected and distorted by mean oceanic currents, and so they only partly reflect the forcing anomalies that give rise to them (Mignot and Frankignoul 2004).

In this paper we examine the hypothesis that GSAs result from the advection of anomalously low salinity water using a coupled climate model. The observational evidence is certainly not inconsistent with advection of low-salinity waters around the North Atlantic subpolar gyre, but other processes may be important or dominate. First, the surface fluxes of freshwater from evaporation, precipitation, and runoff modify salinity, and, with the right spatial and temporal variability, could force salinity anomalies consistent with a GSA. Second, anomalies in mixed layer depth change the volume of water that is directly diluted by the surface freshwater flux, which in turn creates salinity anomalies without a change in the freshwater flux. Third, changes in the oceanic advection of salt, caused by changes in the position and/or strength of oceanic currents, can induce changes in the local salinity.

We use a coupled climate model simulation of preindustrial Holocene climate, which exhibits GSAs in the North Atlantic subpolar gyre (Wadley and Bigg 2004), to test the hypothesis that GSAs result from the advection of anomalously low salinity water around the subpolar gyre. By the addition of passive tracers to tag low-salinity waters in the climate simulation, it becomes apparent that, in the model simulation at least, advection is only controlling the evolution of the anomalies on relatively small scales (~1000 km), whereas other processes are responsible for anomaly propagation at gyre scale.

2. The coupled climate model

The model is described in detail by Gordon et al. (2000), Pope et al. (2000), and Cox et al. (1999). The atmospheric general circulation model has a horizontal grid resolution of 2.5° × 3.75° and has 19 vertical levels, using hybrid coordinates. The ocean general circulation model has a horizontal resolution of 1.25° × 1.25° and 20 levels in the vertical, 10 of which are in the upper 300 m. There is a simple thermodynamic sea ice model based on Semtner (1976), with parameterizations of ice drift and leads, and simple ice advection by ocean surface currents. The diffusion of tracers is of particular interest when studying GSAs. Temperature, salinity, and passive tracers are subject to the same internal advective and diffusive forcing. Horizontal mixing uses a version of the adiabatic diffusion scheme of Gent and McWilliams (1990) with a variable thickness diffusion parameterization (Wright 1997; Visbeck et al. 1997). There is no explicit horizontal diffusion of tracers. The along-isopycnal diffusivity of tracers is 1000 $m^2 s^{-1}$. Near-surface vertical mixing is parameterized by a Kraus–Turner mixed layer scheme (Kraus and Turner 1967). Below the upper layers the vertical diffusivity is an increasing function of depth only.

The model requires no flux adjustments to prevent large climate drifts in the simulation. Surface fluxes and ocean poleward heat transports are in broad agreement with observed estimates, and although there are salinity drifts in the simulation, they are not large enough to significantly affect the ocean circulation (Gordon et al. 2000). The variation of simulated global mean surface temperature is consistent with observations, although regional variability shows significant differences. In particular, the model has too much ENSO-related variability, and whilst the Arctic Oscillation/North Atlantic Oscillation variability is reproduced, there is an excessive teleconnection with the North Pacific (Collins et al. 2001). The amplitude of the maximum North Atlantic overturning streamfunction shows multidecadal variability with an amplitude of 1–2 Sv (1 Sv $\equiv 10^6$ m^3 s^{-1}; Wood et al. 1999).

The Third Hadley Centre Coupled Ocean–Atmosphere GCM (HadCM3) control run for preindustrial climate was analyzed for GSAs for years 179–278 following the model initialization. A number of GSAs were found to propagate around the subpolar gyre, with both anomalously low and high salinity. These are described in Wadley and Bigg (2004). If the anomalies are advective, as hypothesized by Dickson et al. (1988), Belkin et al. (1998), and Belkin (2004), a passive tracer used to tag an anomaly at its inception should advect with the salinity anomaly.

A particular GSA event in the HadCM3 model was chosen for the passive tracer experiment. This GSA in HadCM3 has been studied by Wadley and Bigg (2004), and its spatial and temporal evolution are similar to that of the 1968–82 GSA described by Dickson et al. (1988). The addition of passive tracers requires the model to be rerun. For logistical reasons, we used a different computer to rerun the model, which resulted in a nonidentical realization of the model weather and therefore climate evolution. With model restarts being available at 10-yr intervals, and the chosen GSA starting at year 215 in the HadCM3 realization, the model was rerun starting at year 210. A similar GSA evolved, but starting approximately one year earlier, suggesting that the initiation of this particular GSA was inherent in the year 210 model state but that the trigger for the start of the anomaly was dependent on the internal model variability between years 210 and 215.

Figure 1 shows a Hovmoeller plot of monthly surface salinity anomalies around the modeled North Atlantic subpolar gyre for years 210–230 of the rerun of the HadCM3 model. Depth-integrated salinity anomalies show a very similar pattern, so the vertical redistribution of salt is not responsible for the salinity anomalies in the surface layer. The position of the points used to construct the Hovmoeller plot is shown in Fig. 1. The GSA event starts in year 214 in the region of Fram Strait and propagates around the gyre, reaching Cape Farewell in year 218, the North Atlantic Current in years 220–223, and the Faroe–Shetland Channel in year 224 and returns to the west of Svalbard in year 228. The signature of the anomaly is not entirely continuous around the gyre, and this is also the case with all the other anomalies seen in Wadley and Bigg (2004). This

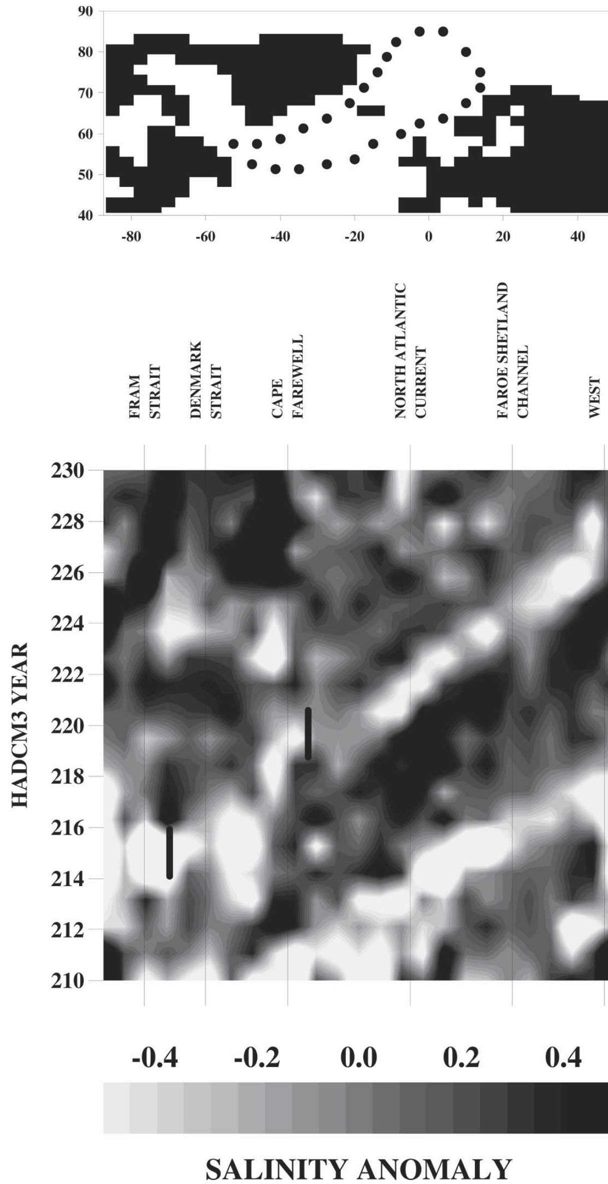

FIG. 1. Hovmoeller plot of monthly surface salinity anomalies from the rerun of the HadCM3 model for years 210 to 230. The points selected to construct the plot are shown above. The black lines show the location of the passive tracer releases during the passage of the model GSA.

is not an artifact of the positions used to construct the Hovmoeller plot. If the anomalies are advective in nature, discontinuities could result from local forcings affecting the surface salinity, which are later compensated for within a deeper anomaly, although this would also be a natural consequence of the anomalies not being advective.

Having established the evolution of the model GSA when integrating the model on our computer, the

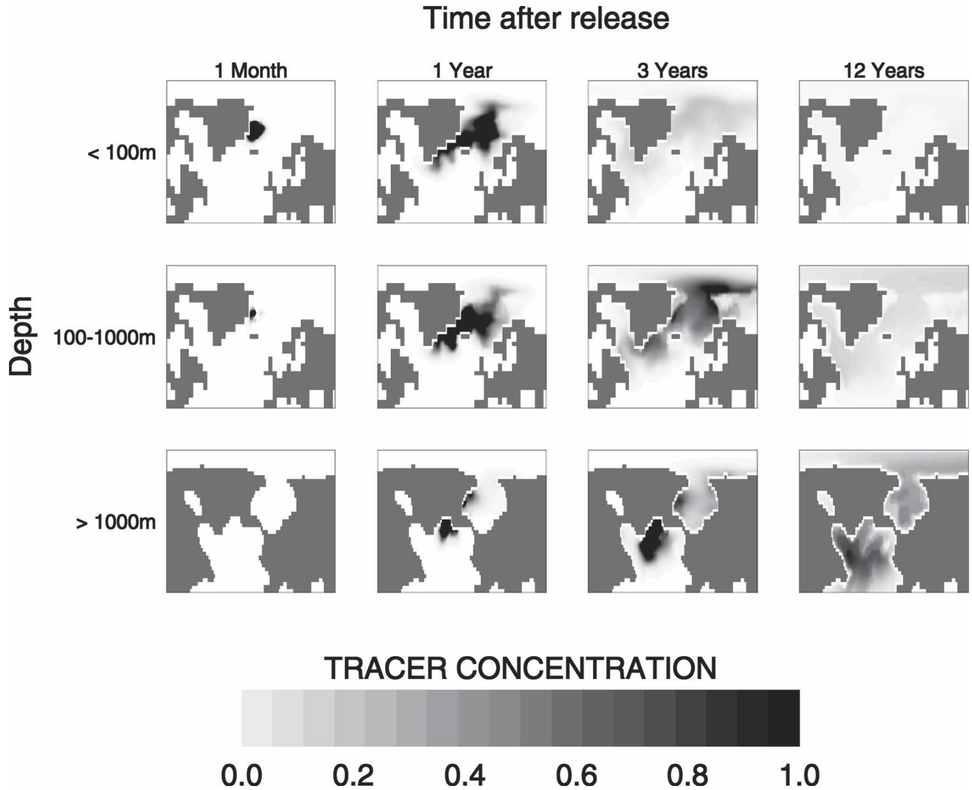

FIG. 2. Evolution of the passive tracers at three depth intervals for the releases in the model EGC. The mean concentration from all 12 releases is shown. White is zero concentration increasing linearly to black where the column-integrated tracer concentration is ≥ 0.001 of that at the point of release.

model was rerun with passive tracers added in the East Greenland and Labrador Currents. Tracers were added as an instantaneous increase in tracer concentration to the surface level at a single grid point and were rapidly mixed vertically throughout the mixed layer and dispersed horizontally to occupy a region several grid boxes in extent, and comparable to the local size of the salinity anomaly. Sensitivity tests showed that adding the tracer evenly over the mixed layer, rather than to the surface level only, made virtually no difference to the evolving tracer field, as the vertical mixing uniformly distributes the tracer through the mixed layer regardless of the depth at which it is released.

To take account of the seasonality in the model climate, and interannual variations in model state, 12 independent tracer releases were made at each location, separated by 2-month intervals, during the passage of the salinity anomaly. For the East Greenland Current release, the releases were from September 214 to July 216 and for the Labrador Current releases were from September 218 to July 220. This allows any seasonal changes in the tracer evolution to be assessed, as well as differences between the two years. The timing of the tracer releases with respect to the passage of the salinity anomaly can been see in Fig. 1. The model was integrated for 12 yr beyond the last tracer release at both locations.

3. Tracer experiments

a. East Greenland Current tracer releases

Initially we will look at the average evolution of all 12 releases before looking at the variability between releases. If advection of the Greenland Sea salinity anomaly is responsible for the propagation of the salinity anomaly around the subpolar gyre, we would expect to see the passive tracer also propagate around the gyre, with a relatively limited dispersal of tracer out of the upper-layer gyre circulation.

Figure 2 shows the mean evolution of the 12 tracer releases into the East Greenland Current binned into different depths. After one month the tracer is still confined to the East Greenland Current region and is mostly within the upper 100 m of the water column. After one year the tracer has spread eastward around the Greenland Sea gyre, and 33% has advected south-

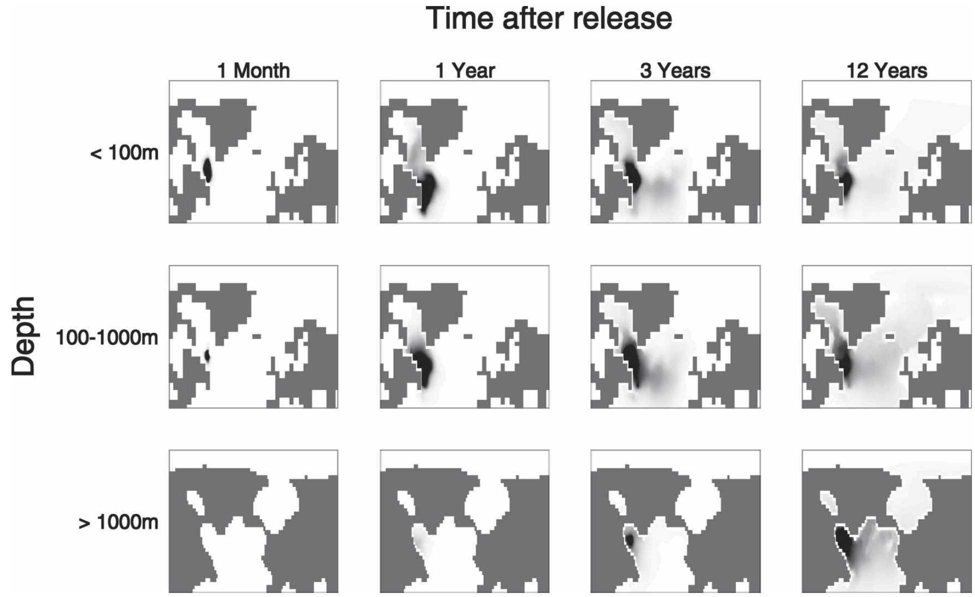

FIG. 3. Same as in Fig. 2, but for the releases in the Labrador Sea.

ward through the Denmark Strait, circulating around the subpolar gyre. However, unlike the salinity anomaly, 64% of the tracer is now below 100-m depth, because of vertical mixing in the Greenland Sea. After 3 yr, only 14% of the tracer is left in the upper 100 m, its extent widening to include the Labrador Sea/Baffin Bay, as well as the Nordic and Barents Seas. A greater proportion of the tracer lies between 100 and 1000 m in these regions, but 34% is in the deep northwest Atlantic in the region where the deep Denmark Strait overflow contributes to the formation of North Atlantic Deep Water (NADW). After 12 yr the tracer is mostly entrained into the NADW, with only 6% left in the upper 100 m, whereas the surface salinity anomaly has returned to the Nordic Seas.

b. Labrador Sea tracer releases

The mean evolution of the tracer releases in the East Greenland Current shows that very little of the tracer reaches the Labrador Sea and that this part of the GSA evolution does not appear to be advective in nature. Indeed, in Fig. 1 the anomaly weakens beyond Cape Farewell, before reestablishing itself in the southern Labrador Sea. We therefore performed more tracer releases in the southern Labrador Sea to determine whether the subsequent part of the modeled GSA is advective. The first releases actually occur when salinities are anomalously high in the region, but it will be shown that the salinity at the point of release does not have a significant impact on the tracer's evolution.

Twelve tracer releases were made in the Labrador Sea during the passage of the GSA (see Fig. 1). The average evolution of the tracers is shown in Fig. 3. The tracer is advected southward by the Labrador Current before moving eastward in the North Atlantic Current after 3 yr. Vertical mixing takes the tracer to 1000 m, with some penetrating below 1000 m where deep water formed in the Labrador Sea contributes to NADW formation. By year 12 much of the tracer (45%) is at intermediate and deep depths in the northern North Atlantic, with relatively little (6%) remaining in the upper 100 m, where the surface salinity anomaly has reached the Nordic Seas. The evolution of the tracer would suggest that the surface salinity anomaly in the southern Labrador Sea propagates approximately half way across the North Atlantic before being mixed down to intermediate and deep depths. This tracer experiment does not support the hypothesis that advection is responsible for the propagation of low-salinity anomalies from the Labrador Sea region to the Faroe–Shetland Channel and beyond, whereas Dickson et al. (1988) calculated that approximately two-thirds of the salinity deficit in the Labrador Sea region passed through the Faroe–Shetland Channel in the 1968–82 GSA event.

c. Variability between tracer releases

We will now look at the variability between tracer releases at each location. The proportion of tracer in the Nordic and Arctic seas, the Labrador Sea, and the North Atlantic was calculated for each month after each tracer release, for three depth intervals. The southern Labrador Sea passive tracers showed very

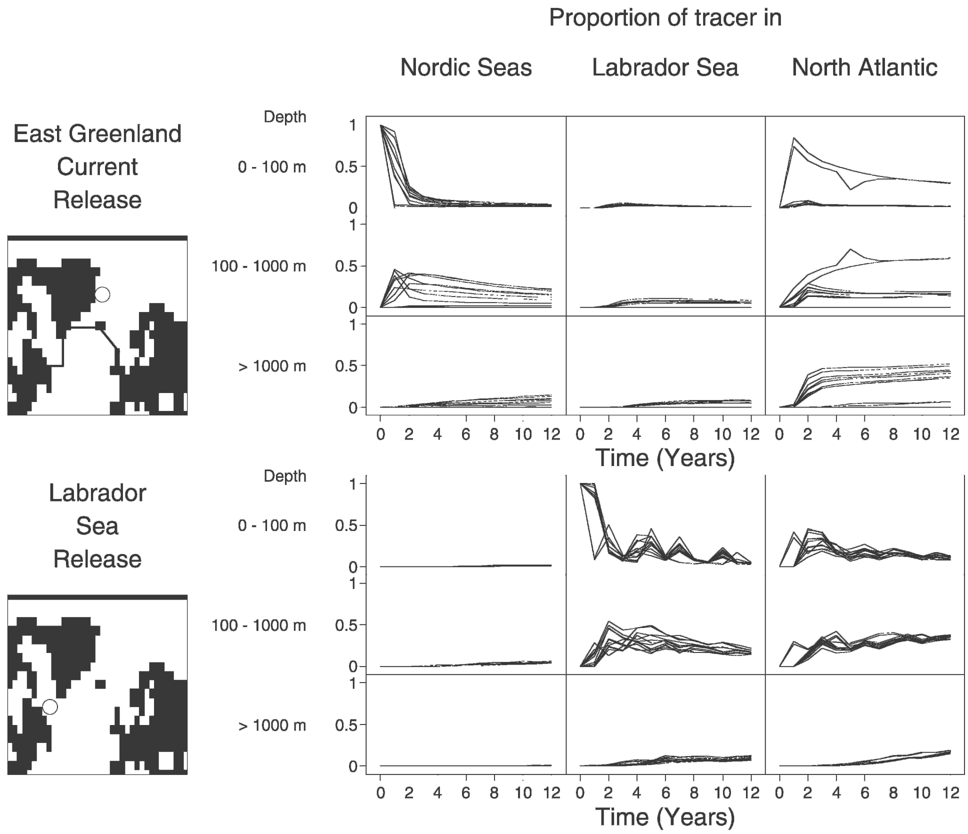

FIG. 4. Evolution of individual passive tracer releases from the (top) EGC and (bottom) Labrador Sea. The release points are shown in the corresponding maps. The top map shows the lines dividing the three regions in which the proportion of tracer has been calculated and plotted in the right-hand panels.

little difference between the individual releases, either with season or between years (Fig. 4). Upper-ocean (<100 m) concentrations in the Labrador Sea fall rapidly after the first year, with approximately one-third of the tracer mixing downward, and two-thirds entering the North Atlantic Current above 1000 m. Beyond 6 yr, there is a steady increase in the concentration in the deep water (>1000 m), as the tracer is entrained into the NADW.

The East Greenland Current tracers show more variability, with 2 releases (September 214 and November 214) behaving rather differently from the other 10. These releases leave the Nordic Seas through the Denmark Strait with 88% and 75% of the initial release leaving the Nordic Seas after 2 yr, respectively, compared to an average of 37% for the other 10 cases. It is only these two releases that have the potential to advect significant amounts of tracer to the Labrador Sea region. However, on average, only 17% of the tracer advects into the Labrador Sea region in these cases, with only one-half of this being in the mixed layer (Fig. 3). This is consistent with the weakening of the low-salinity anomaly in the southern Labrador Sea (Fig. 1). The tracer is, instead, mixed deeply following its passage through the Denmark Strait and becomes entrained into the NADW below 1000-m depth (Fig. 5a).

By contrast, other tracer releases remain substantially in the Nordic and Arctic seas. The tracer initially circulates around the Greenland Sea gyre before mixing to intermediate depths throughout the Nordic and Arctic seas and entering the deep North Atlantic through the Denmark Strait overflow (Fig. 5b). In the most extreme example of this, the properties of the water in the East Greenland Current are not advected south of the Denmark Strait at all and could have no contribution to anomalies in the subpolar gyre.

d. Seasonality and interannual variability

To assess the impact of seasonality on the dispersal of the passive tracer, further releases were performed at 2-month intervals for a further 3 yr, giving 30 releases over a 5-yr period. The initial 2-yr release period was insufficient to determine whether seasonality or vari-

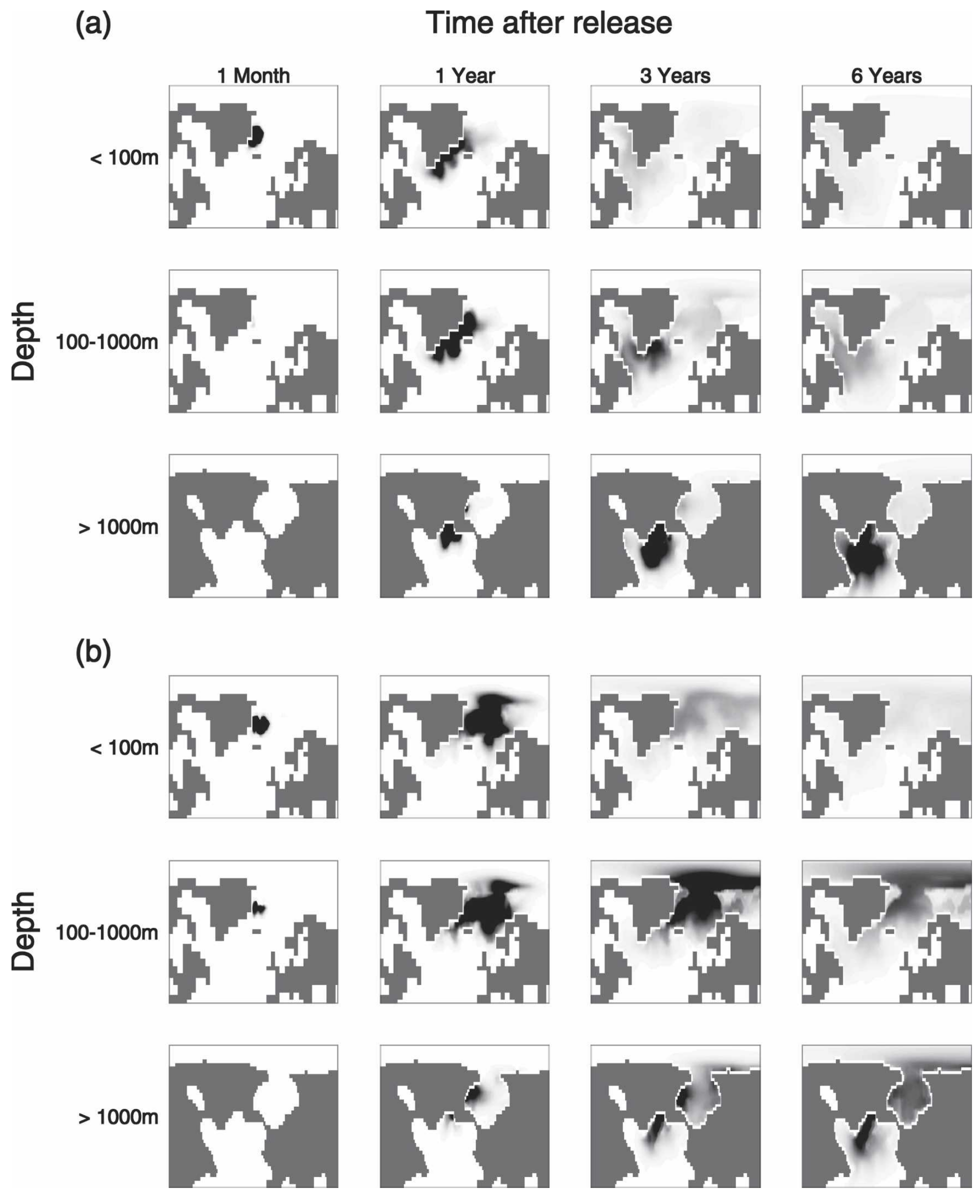

FIG. 5. Evolution of two individual passive tracer releases in the model EGC. One release in September 214 (a) advects through the Denmark Strait, leaving less than 10% of the release in the Nordic and Arctic seas, whereas about 70% of the release in March 215 (b) remains in the Nordic and Arctic seas after 6 yr. Thirty releases at 2-month intervals over 5 yr show that the month (i.e., season) in which the release is made does not predominantly determine the tracer's destiny. White is zero concentration increasing linearly to black where the column-integrated tracer concentration is ≥ 0.001 of that at the point of release. See Fig. 2 for the concentration grayscale.

ability unrelated to the seasonal cycle was responsible for the variations in the tracers' destination. Table 1 shows the proportion of tracer remaining in the Nordic and Arctic seas 2 yr after release, together with monthly and annual means over the 5-yr period. In years 3–5 salinity was above average in the Greenland Sea (Fig. 1), and this could be related to the passive tracers' movement.

The proportions of tracer remaining in the Nordic and Artic seas for the bimonthly releases shows some seasonality, but this is less than the variability between individual years (Table 1). Autumn and winter retentions are around 45%, compared with around 60% in spring and summer. This is consistent with increased vertical mixing in the wintertime, which allows the tracer to reach the North Atlantic through the Den-

Table 1. Proportion of passive tracer remaining in Nordic and Arctic seas 2 yr after release in the EGC (see Fig. 4 for location).

Year	September	November	January	March	May	July	Annual mean
216/217	0.12	0.25	0.42	0.56	0.58	0.41	0.39
217/218	0.31	0.59	0.82	0.89	0.86	0.81	0.71
218/219	0.75	0.73	0.73	0.78	0.73	0.58	0.72
219/220	0.46	0.48	0.5	0.48	0.58	0.45	0.49
220/221	0.54	0.45	0.48	0.5	0.57	0.48	0.5
Monthly mean	0.44	0.5	0.59	0.64	0.66	0.55	

mark Strait overflow, where it becomes incorporated into NADW.

The annual mean values show that the greatest proportion of tracer reached the North Atlantic following releases in year 216/217, coincident with the lowest salinities in the Greenland Sea, and the least tracer reached the North Atlantic following releases in years 217/218 and 218/219, when Greenland Sea salinities were anomalously high (Fig. 1). However, the tracer that does reach the North Atlantic is predominantly at NADW depths and is not associated with the upper-level gyre circulation. Thus it appears that during this 5-yr period in the HadCM3 model, mixed layer waters in the Greenland Sea become entrained into NADW most rapidly when surface salinities are low.

4. Discussion and concluding remarks

The use of passive tracers to tag salinity anomalies in the modeled North Atlantic subpolar gyre leads to a different interpretation of GSA propagation than currently held from observational studies. Modeled patterns of anomalously low and high salinity are seen to propagate around the subpolar gyre, and these patterns have been shown to be consistent with those of the "Great Salinity Anomaly" (Wadley and Bigg 2004), which led Dickson et al. (1988) to propose an advective mechanism. However, passive tracer released to tag the anomaly in both the modeled East Greenland Current and Labrador Current only follows the upper-layer gyre circulation for around 1000 km and becomes mixed to intermediate depths, before ultimately being incorporated into the NADW. This is the case with releases in both locations, in all seasons, and throughout the "passage" of the anomalies.

So should we believe this model-based finding? The model results clearly conflict with the advective hypothesis, which suggests that two-thirds of the salt deficit in the Labrador Sea passes through the Faroe–Shetland Channel by advection of the initial anomaly (Dickson et al. 1988). Nine years after release, we find only 4% of the tracer in the upper level of the Nordic Seas from the EGC releases, and five years after release from the Labrador Current, only 5% of the tracer is in the Nordic Seas. Yet the surface salinity signature is consistent with the observed GSAs. Either GSAs are not advective, or the climate model is behaving differently from reality. In the HadCM3 model, GSAs occur at approximately decadal time scales, and recent observations indicate a similar frequency, which suggests that there is not anything unusual about either the real or modeled circulation during these events, which could explain the tracer behavior. This all points toward GSAs not being advective, but rather being an artifact of either surface freshwater flux anomalies or anomalies in the oceanic currents and their associated advection of salt. Further coupled model sensitivity tests will be reported in the future to address this question of mechanism.

This result also has implications for our understanding of the processes controlling the thermohaline circulation. It has been hypothesized that the presence of a low-salinity anomaly in regions of deep water formation would suppress vertical mixing and weaken the supply of source waters for the THC (e.g., Häkkinen 1999). However, unless deep convection was completely shut down in the region of the anomaly, deep mixing would dilute the salinity anomaly sufficiently that the upper-layer salt deficit would be much reduced. This is consistent with the findings of Saenko et al. (2003), who found that upper-layer salinity anomalies induced by sea ice melt propagate downward within regions of deep water formation, removing the excess buoyancy from the surface ocean. Our tracer experiments also support this view, clearly showing that surface waters in both the Greenland Sea and Labrador Sea can be source waters for NADW, rather than waters that merely circulate around the upper subpolar gyre.

In this paper we have demonstrated that GSAs are unlikely to be associated with the advection of anomalously low salinity around the North Atlantic subpolar gyre. Future work will look at the processes that give rise to GSA-type variability in the coupled model climate system, examining the impact of surface fluxes and ocean circulation changes.

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