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Key Points:
- Subsurface subtropical waters supply the near surface waters of the ESG
- Subsurface source waters have their origin as subtropical mode water
- Subtropical surface waters do not determine temperatures in the ESG

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Tracing the pathways of the upper limb of the North Atlantic Meridional Overturning Circulation

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Abstract The warm sea surface temperatures (SSTs) of the eastern subpolar gyre (ESG) in the North Atlantic have been widely linked to the climate and climate variability of Great Britain and northwestern Europe. The source of the ESG waters, and its heat, has long been identified as surface subtropical waters that flow into the subpolar gyre as part of the upper limb of the Meridional Overturning Circulation. Recent studies, however, have cast doubt on that identification. Here we use synthetic floats launched in a high-resolution ocean general circulation model to identify the supply waters to the ESG and to determine the influence of those pathways on SSTs in that climatically important region. The synthetic floats reveal two pathways: a dominant *subsurface* subtropical to subpolar pathway and a less traveled surface pathway carrying recirculated waters eastward from the western subpolar gyre. The former pathway supplies anomalously warm water to the region; the latter pathway supplies anomalously cool water.

1. Introduction

Connectivity between the North Atlantic subtropical and subpolar gyres, via the upper limb of the Meridional Overturning Circulation, has strong implications for poleward heat transport and its variability in this basin. The overturning circulation in the subtropical basin carries 88% of that basin's total poleward heat transport [*Johns et al*., 2011]. An open question is the extent to which anomalous heat associated with anomalous overturning in the subtropical basin [*McCarthy et al*., 2012] is transmitted to the subpolar basin. Traditionally, this transmission has been assumed to occur via the surface throughput that connects the subtropical to the subpolar waters, specifically through surface advection of heat anomalies along the Gulf Stream (GS)/North Atlantic Current (NAC) pathway into the eastern subpolar gyre (ESG) [*Sutton and Allen*, 1997]. Seemingly, a major piece of evidence for this surface advective pathway is the stark zonal asymmetry in North Atlantic subpolar SSTs: SSTs in the east exceed those in the west by ~10°C (Figure 1). The traditional explanation for this asymmetry is the connectivity between the subtropical and subpolar gyres: warm subtropical surface waters, headed northward to replenish regions of deep convection [*Stommel*, 1958; *Gordon*, 1986], are transported to the ESG via the GS and NAC. In the past two decades, this connectivity has been established by Eulerian estimates of the surface velocity field derived from a bin averaging of surface drifter velocities (including *Fratantoni* [2001, Plate 6] and *Brambilla and Talley* [2006, Figure 2]). However, two recent studies have raised questions regarding the degree to which surface waters of subtropical origin supply the ESG.

Using synthetic float data from an ocean general circulation model (OGCM), *Burkholder and Lozier* [2011a] examined Lagrangian transport pathways connecting the GS region to high latitudes in the North Atlantic. Though previous estimates had suggested that 20–25% of GS waters enter the subpolar gyre [*Brambilla and Talley*, 2006], <5% of *Burkholder and Lozier* [2011a] synthetic floats launched at 15 m within the GS were able to do so within 4 years. This lack of surface water connectivity also appears in the Lagrangian observational record: in *Brambilla and Talley*'s [2006] study of 273 surface drifters passing through the GS region between 1990 and 2002, only one drifter reached the subpolar gyre within its unusually long lifetime of 495 days. Though a follow-on study using a data set with a greater temporal range noted interannual variability in surface throughput, at most just 3% of surface drifters that passed through the Gulf Stream reached 53°N; only 7% reached 50°N [*Häkkinen and Rhines*, 2009]. As noted in *Brambilla and Talley* [2006], the relatively short lifetimes of the surface drifters within the observational record (271 ± 260 days for the drifters analyzed in their study) are likely insufficient to allow for a true estimate of the near-surface subtropical to subpolar transport.

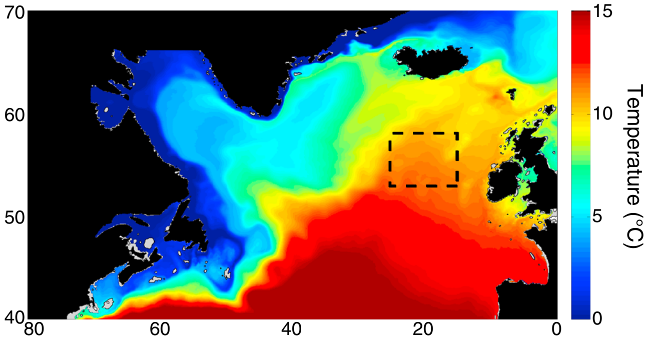

Figure 1. Climatologically averaged temperatures at 50 m in FLAME. Black box indicates the launch positions of ESG floats. Bathymetry ≤ 200 m is shown in gray.

However, model examinations of longer-lasting Lagrangian drifters [*Brambilla and Talley*, 2006; *Burkholder and Lozier*, 2011a] indicate that regardless of lifetime, the intergyre exchange falls short of the expected 20–25% subtropical to subpolar throughput.

Prior studies have suggested alternate pathways: In *Burkholder and Lozier* [2011a], which examined synthetic floats launched in the GS region at various depths (15–1300 m), the ability of floats to reach high latitudes was maximized by floats launched at 700 m, suggesting a strong subsurface subtropical to subpolar Lagrangian pathway. However, the arrival depth of *Burkholder and Lozier* [2011a] 700 m floats in the ESG was ~350 m, leaving the influence of these deeper trajectories on the surface waters of the ESG unclear. A second potential source of waters to the ESG is recirculated subpolar water. *Brambilla and Talley*'s [2006] surface drifter analysis indicated that drifters entering the Icelandic basin originated primarily within the subpolar gyre. While *Brambilla and Talley* [2006] acknowledged that the 2-D drifters that they analyzed were likely limited in their ability to track true Lagrangian pathways, the study suggested that recirculated subpolar surface waters likely played a role in supplying the ESG.

The main goals of this study are to identify the Lagrangian pathways to the ESG, determine the relative dominance of those pathways, and characterize the roles of those pathways in supplying heat to the region. By addressing these issues, we aim to improve the understanding of how SSTs in this important region are set.

2. Identifying the Pathways That Supply the ESG

This study utilizes 15 years (1990–2004, 3 day temporal resolution) of output from a realization of the FLAME (Family of Linked Atlantic Model Experiments) OGCM [*Böning et al.*, 2006; *Biastoch et al.*, 2008] to simulate water parcel pathways. FLAME is a *z* coordinate model of the North Atlantic with 1/12° horizontal resolution and 45 vertical levels spaced 10 m apart near the surface and 250 m apart at depth, with a gradual transition between the two spacings with depth. Following a 10 year spin-up, the FLAME realization utilized for this study was forced at the surface with monthly averaged National Centers for Environmental Prediction and National Center for Atmospheric Research anomalies superposed on European Center for Medium-Range Weather Forecasts monthly climatologies. Heat fluxes in the model were computed following the linearized bulk formulation of *Eden and Willebrand* [2001]. This model realization was previously used in other studies of North Atlantic Lagrangian pathways, including *Bower et al.* [2009], *Gary et al.* [2011], and *Burkholder and Lozier* [2011a, 2011b].

In the present study, FLAME velocity fields were used to produce synthetic back trajectories: from launch positions within the ESG, prior positions were established by integrating the 3-D velocity field backward, rather than forward, in time. The horizontal velocities used for this computation were stored as outputs from the initial model run. The vertical velocities were calculated at each model grid point from the vertical integral of the horizontal divergence, beginning at the surface and progressing downward through the water column. Floats were seeded within a 1/2° × 1/2° grid over a domain stretching from 25 to 15°W and 53 to 58°N (Figure 1, black box). For consistency with *Burkholder and Lozier* [2011a], and to allow sufficient time for the float pathways to reveal their source regions, floats were released in batches every 30 days for 11 years and run for 4 years. Floats were launched from 50 m and 100 m in order to highlight the contribution of Lagrangian pathways to waters that are located near the base of the Ekman layer (50 m) and below the Ekman layer (100 m) in the ESG [*Rio and Hernandez*, 2003]. Both depths are believed to have a direct influence on the SSTs of the ESG, where mixed layers extend well beyond 100 m for much of the year [*de Boyer Montégut et al.*, 2004]. In total, 61,446 synthetic floats were generated and analyzed: 100 randomly selected trajectories from the launches are plotted in Figure 2.

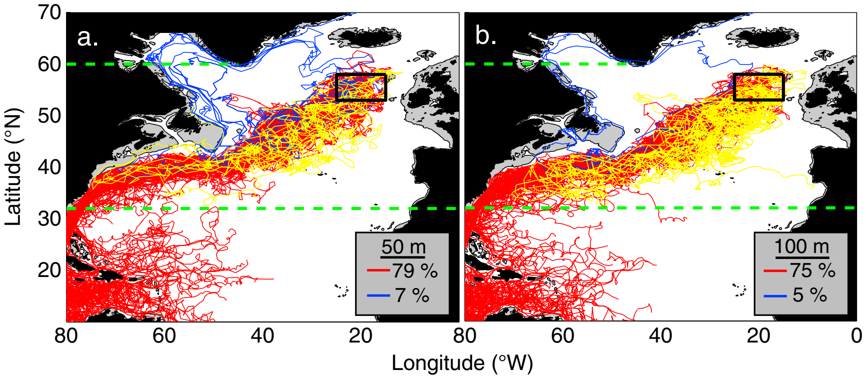

Figure 2. Trajectories of 100 randomly selected floats advected backward in time for 4 years from the ESG (black box) when launched at (a) 50 m and (b) 100 m. Subtropical, subpolar, and other floats are shown in red, blue, and yellow, respectively. Mean percentages of floats arriving from each pathway are shown in the gray box. Green lines indicate the 32°N and 60°N boundaries used to qualify floats as following the subtropical and subpolar pathways, respectively. Bathymetry ≤ 200 m is shown in gray.

The trajectories in Figure 2 are separated into three groups: those that originated in the western subtropical gyre ("subtropical floats," red), those that originated in the western subpolar gyre ("subpolar floats," blue), and those that had no clear launch origin over the 4 years ("other floats," yellow). Subtropical floats are considered to be floats that reached latitudes south of 32°N during their lifetime, a definition chosen to ensure that subpolar floats caught in the recirculation gyre north of the Gulf Stream [*Hogg et al*., 1986] were excluded. Subpolar floats are defined as those that originated north of 60°N and west of 45°W. Other floats did not meet either of these definitions. With these delineations, $>$80% of the floats are classified as either subtropical or subpolar when launched from either 50 or 100 m.

3. Float Transformations Along Lagrangian Pathways

Regardless of launch depth, the vast majority of floats (≥75%) reaching the ESG originated in the subtropics (Figure 2). In contrast, ≤7% of floats were carried to the ESG by the subpolar pathway, validating *Brambilla and Talley*'s [2006] conjecture that the preponderance of surface drifters with a subpolar origin passing through the eastern part of the gyre was an artifact of the drifters' restriction to the 2-D surface flow field. Interesting differences in the pathways are revealed from an investigation of the vertical distribution of the floats and the property changes along the pathways (Figure 3 for the 100 m floats; changes along the 50 m pathways are qualitatively similar.) Floats of subpolar origin move southward as part of the Labrador Current on their way to the ESG (Figures 3a and 3c). After rounding the Grand Banks, the floats intersect subtropical waters southeast of Newfoundland. At this intersection with the GS/NAC waters, the floats generally become much warmer (Figure 3c), slightly deeper (Figure 3a), saltier, and less dense. From an inspection of property changes along the subpolar trajectories' length, it is apparent that the largest property changes are due to the strong mixing in the region of the Grand Banks. Changes in the depth of the simulated floats are decidedly less pronounced than the changes in temperature: floats reaching 50 and 100 m in the ESG had mean depths of 65 ± 63 and 72 ± 63 m, respectively, when they crossed 60°N in the western subpolar gyre (Figure 3a). Essentially, they start and end as surface waters.

Contrary to the simulated floats of subpolar origin, floats launched at 50 and 100 m in the ESG that originate in the subtropical gyre have mean depths of 235 ± 153 and 273 ± 167 m, respectively, at 32°N (Figure 3b for the 100 m floats). Interestingly, only 6.7% (5.0%) of the floats launched at 50 (100) m in the subpolar gyre that followed the subtropical pathway had depths of ≤50 m at 32°N. Thus, as in the *Burkholder and Lozier* [2011a] study, there is little evidence that surface waters are involved in any significant way in the intergyre exchange process.

Predictably, as the subtropical floats are transported between the subtropical and subpolar gyres, they lose heat, arriving in the subpolar gyre with mean temperatures that are significantly cooler (Figure 3d) than when they exited the subtropical gyre. This change in temperature is accompanied by a freshening, a shoaling (Figure 3b), and densification along the subtropical pathway. However, unlike the property transition in the subpolar floats, the transition in float temperatures, densities, and depths along the subtropical pathway is gradual, with no

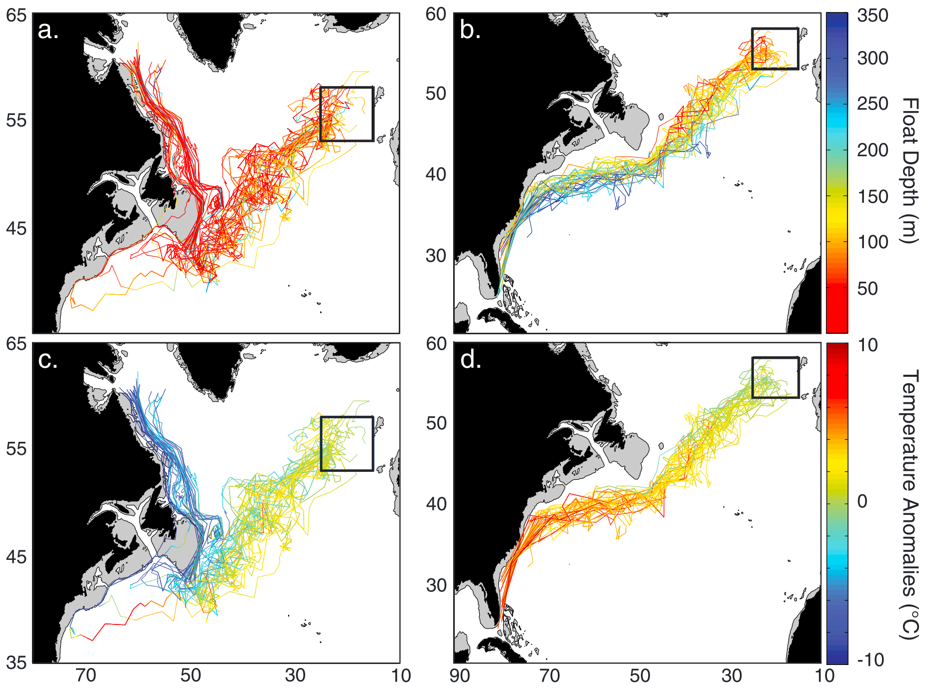

Figure 3. (a, b) Float depths and (c, d) temperature anomalies of 50 randomly selected floats launched at 100 m in the ESG and run backward in time to their origin in the western subpolar gyre in Figures 3a and 3c and western subtropical gyre in Figures 3b and 3d. Colors in Figures 3c and 3d indicate the difference in the temperature of the floats at a particular time and their temperature at the time of their launch in the ESG. Floats originating in the subtropical gyre had mean launch temperatures of 10.99 ± 1.24°C and 10.51 ± 0.97°C at 50 and 100 m respectively in the ESG. Floats originating in the subpolar gyre had mean launch temperatures of 10.83 ± 1.32°C and 10.22 ± 1.14°C at 50 and 100 m, respectively. Bathymetry ≤ 200 m is shown in gray.

particular location accounting for a significant loss of heat along the path. Thus, the property changes recorded by the subtropical floats likely result from the mixing of subtropical waters with denser waters along the path of the GS and NAC and, as the floats become shallower, loss of heat to the atmosphere [*McCartney and Talley*, 1982].

Importantly, the view of subtropical to subpolar Lagrangian transport presented in this study (Figure 4b) fundamentally differs from the traditional view of North Atlantic circulation, in which the GS carries surface waters to high latitudes in the subpolar region (Figure 4a). This traditional view has been bolstered by trajectories of surface drifters, but in regions of the ocean, such as the GS/NAC system, where strong air-sea fluxes lead to convective overturning of surface waters, the restriction of drifters to the surface precludes their use as tracers of ocean pathways over any appreciable distance. Thus, surface drifters cannot be expected to trace the overturning throughput from the subtropical to the subpolar gyre. Even using short segments of surface drifter tracks to reconstruct the surface velocity field can be problematic: as noted in *Rypina et al.* [2011],

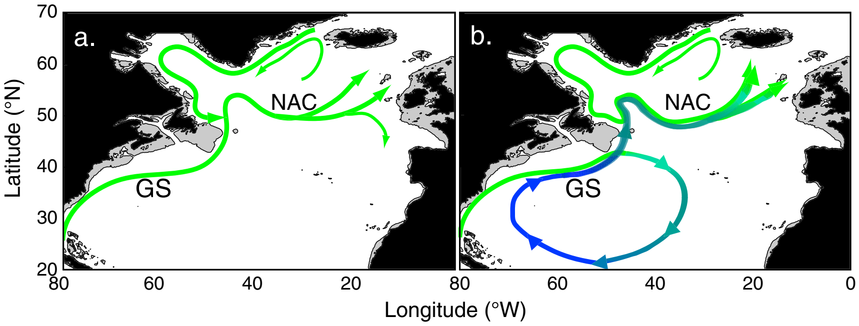

Figure 4. Schematics of the (a) traditional and (b) present view of North Atlantic circulation features supplying the ESG. Green (blue) arrows indicate surface (subsurface) water pathways. FLAME bathymetry ≤ 200 m is shown in gray. The schematic in Figure 4a is based on surface circulation schematics presented in *Fratantoni* [2001].

Table 1. Average and Standard Deviation of ESG Launch Temperature Anomalies (°C) for Floats That Reached the ESG via the Subtropical and Subpolar Pathways Shown in Figure 2[a]

Depth in Subpolar Gyre (m)	Subtropical Pathway (°C)	Subpolar Pathway (°C)
50	0.04 ± 1.13	−0.08 ± 1.24
100	0.04 ± 0.83	−0.16 ± 1.01

[a] Anomalies are relative to the average float launch temperature for each launch location.

the traditional method of deriving surface velocity fields from the averaged velocities of individual surface drifters within some spatial grid (as in *Fratantoni* [2001], *Flatau et al.* [2003], and *Brambilla and Talley* [2006]) can create a false impression of the continuity of the GS surface transport [*Rypina et al*., 2011]. Averaging velocities within spatial grids where there are strong density and/or potential vorticity gradients ignores the dynamical constraints that would prevent surface drifters from crossing those gradients. Past studies have illustrated the strong potential vorticity gradient located along the axis of the shallow GS [*McDowell et al*., 1982] and modeling work has linked this gradient to reduced cross-gyre transport [*Lozier and Riser*, 1990] in the near-surface waters. Essentially, the warmest (and least dense) waters of the subtropical gyre, the surface waters, are recirculated within the gyre and not exported to the subpolar gyre. Climatological maps of the surface density field in this basin have long confirmed that these light waters are not found in the subpolar gyre.

The subsurface subtropical pathway presented here is consistent with prior studies: both modeling [*Burkholder and Lozier*, 2011a] and observational evidence [*Bower and Lozier*, 1994] suggest that increased subtropical to subpolar particle exchange occurs below the surface where the potential vorticity gradient is weaker. Interestingly, the average depth of the waters in the subtropical gyre that are destined for the ESG is the approximate depth of the Subtropical Mode Water in the North Atlantic. These mode waters are produced via wintertime convection in the region south of the GS. Thus, it is proposed that these mode waters provide the connection between the surface throughput from the tropics to the subtropics [*Palter and Lozier*, 2008] and the subsurface throughput from the subtropical to the subpolar gyres: surface waters, imported from the tropics through the Florida Straits, enter the GS region and are involved in the wintertime production of mode waters. It is suggested that these mode waters, on average a thick 200–300 m wedge centered at 300 m [*Talley and Raymer*, 1982; *Kwon and Riser*, 2004; *Fratantoni et al*., 2013] in the western subtropical North Atlantic, are the source waters to the surface ESG. Essentially, mode water production takes subtropical surface waters and makes, in effect, subpolar surface water via densification. Thus, rather than a surface connectivity (as in Figure 4a), the connectivity that is proposed is a surface to subsurface to surface spiral (as in Figure 4b).

Supporting evidence for the involvement of the mode waters in this connectivity comes from both observational [*The CLIMODE Group*, 2009; *Fratantoni et al*., 2013] and model [*Gary et al*., 2014] studies. As part of the CLIVAR Mode Water Dynamic Experiment (CLIMODE) field campaign, floats were launched into Subtropical Mode Water [*The CLIMODE Group*, 2009; *Fratantoni et al*., 2013]. Those floats (which bobbed between the isotherms that define the mode water) exported from the subtropical to the subpolar gyre ascend in the water column, moving from the subsurface to the near-surface waters [*Fratantoni et al*., 2010]. Additionally, a recent study of the Subtropical Mode Water in FLAME tracked synthetic floats launched in recently formed mode water. Trajectory analyses revealed a clear export of these mode waters to the subpolar gyre.

4. Supply of Heat to the ESG

We next examine the temperatures and temperature anomalies of floats within the ESG at the time and location of their launch. As expected, the 50 and 100 m floats arriving in the ESG via the subtropical pathway are warmer on average than floats arriving from the western subpolar region: floats originating in the subtropical gyre had mean launch temperatures of 10.99 ± 1.24°C and 10.51 ± 0.97°C at 50 and 100 m respectively in the ESG, while floats originating in the subpolar gyre had mean launch temperatures of 10.83 ± 1.32°C and 10.22 ± 1.14°C at 50 and 100 m, respectively. To avoid the possibility that float position within the launch box biases these mean temperatures (as would occur, for example, if floats of subtropical origin preferentially occupied locations with greater mean temperatures), the temperature anomalies of the floats, relative to the average float temperature at each launch location, were calculated. The resultant anomalies (negative for the subpolar pathway, positive for the subtropical pathway, Table 1) confirm that floats of subtropical origin supply heat to the ESG, whereas floats that recirculate within the subpolar gyre bring anomalously cool waters across the basin. The difference in the magnitude of the anomalies (the subpolar pathways have stronger anomalies than the accompanying subtropical pathways) is likely a function of the larger influence of the subtropical waters in this region. However, more interesting than the (expected) difference in these temperatures is their remarkable similarity: despite the fact that the pathways of origin differ by nearly 10°C, the subtropical and subpolar waters differ by just tenths or hundredths of a degree by the time they reach the ESG, a sign of strong mixing and air-sea exchange along the pathways.

Finally, in order to investigate whether anomalies in the subtropics or western subpolar gyre could be transported along the Lagrangian pathways to the ESG, we analyze the relationship between temperature anomalies within the ESG and the temperature anomalies at the upstream locations of subtropical (subpolar) floats as they crossed 32°N (60°N). Essentially, we ask whether floats that bring anomalously cold or warm water to the ESG were anomalously cold or warm at their site of origin. In other words, is there a throughput for thermal anomalies? We found none: no correlations between upstream and downstream anomalies regardless of pathway or launch depth were significant. Thus, though changes in the relative contributions of the two pathways to the ESG over time may result in changes to the ESG SSTs, any temperature variability in the source regions is unlikely to be directly advected along the pathways that lead to the ESG. Instead, it is suggested that temperature variability in the source regions is communicated to the ESG indirectly via mixing processes or advective pathways that are not continuous between the two regions.

5. Summary and Conclusions

For decades, the warm SSTs of the ESG have been attributed to the transport of warm-surface waters from the subtropics by the GS/NAC system. Here we demonstrate that subsurface subtropical waters are the major source of the near-surface waters in the ESG. We speculate that these subsurface waters have their origin as subtropical mode water, an origin that has implications for the export of not only heat but also of nutrients to the subpolar gyre. The ESG is also supplied, though to a lesser extent, with surface waters from the western subpolar gyre, which on average supply cooler and fresher water to the ESG than the subtropical waters. The three-dimensional nature of the pathways from the subtropical to subpolar gyre highlights the inadequacy of surface drifters as markers of fluid pathways at this gyre/gyre boundary.

This study has implications for how, and on what time scales, heat anomalies from the subtropical gyre are transmitted to the subpolar gyre. Though a clear advective pathway for subsurface subtropical waters to enter the subpolar gyre has been identified, there is no such direct advective pathway for the subtropical heat anomalies. Thus, it seems likely that the time scale for the transmission of the observed subtropical heat anomalies is much longer than the advective time scale for the subtropical to subpolar pathway. While further study is needed to quantify that time scale within a Lagrangian framework, this analysis suggests that SST variability in the ESG would be only weakly linked to subtropical overturning variability on interannual time scales.

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