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1 **Sea surface salinity reemergence in an updated**
2 **North Atlantic in-situ salinity data set**

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21 **Abstract**

22

23 Monthly sea surface salinity (SSS) fields are constructed from observations, using
24 objective mapping on a $1^\circ \times 1^\circ$ grid in the Atlantic between 30°S and 50°N in the 1970-
25 2016 period in an update of the data set of Reverdin et al. (2007). Data coverage is
26 heterogeneous, with increased density in 2002 when Argo floats become available, high
27 density along Voluntary Observing Ship lines, and low density south of 10°S . Using lag
28 correlation, the seasonal reemergence of SSS anomalies is investigated between 20°N
29 and 50°N in $5^\circ \times 5^\circ$ boxes during the 1993-2016 period, both locally and remotely
30 following the displacements of the deep mixed-layer waters estimated from virtual float
31 trajectories derived from the daily AVISO surface geostrophic currents. Although SSS
32 data are noisy, local SSS reemergence is detected in about half of the boxes, notably in the
33 northeast and southeast, while little reemergence is seen in the central and part of the
34 eastern subtropical gyre. In the same period, sea surface temperature (SST) reemergence
35 is found only slightly more frequently, reflecting the short data duration. However,
36 taking geostrophic advection into account degrades the detection of remote SSS and even
37 SST reemergence. When anomalies are averaged over broader areas, robust evidence of a
38 second and third SSS reemergence peak is found in the northeastern and southeastern
39 parts of the domain, indicating long cold-season persistence of large-scale SSS anomalies,
40 while only a first SST reemergence is seen. An oceanic reanalysis is used to confirm that
41 the correlation analysis indeed reflects the reemergence of subsurface salinity
42 anomalies.

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48 **1. Introduction**

49 Namias and Born (1970) first noted a tendency for North Pacific sea surface
50 temperature (SST) anomalies to recur from one winter to the next while disappearing
51 during summer, which substantially increased their persistence. They speculated that
52 the deep winter mixed layer temperature anomalies remained under the shallow
53 seasonal thermocline during summer and were insulated from surface heat exchanges
54 with the atmosphere before being re-entrained into the surface layer during mixed-layer
55 deepening in fall and early winter. This mechanism was further investigated, among
56 others, often by including reanalyzed subsurface temperature data to follow the SST
57 evolution under the seasonal thermocline, in the North Pacific by Alexander and Deser
58 (1995) and Alexander et al. (1999, 2001) and in the North Atlantic by Watanabe and
59 Kimoto (2000) and Timlin et al. (2002). These studies showed that reemergence was
60 stronger when the difference between the depth of the mixed layer in winter and
61 summer was larger. Furthermore, Deser et al (2003) extended the stochastic climate
62 model of Frankignoul and Hasselmann (1977) to the case of a seasonally varying upper-
63 ocean mixed depth. Hanawa and Sugimoto (2004) documented SST reemergence in the
64 world ocean, and found that reemergence was seen when the seasonal variations in
65 mixed-layer depth exceeded 100 m (see also Deser et al. 2003). De Coëtlogon and
66 Frankignoul (2003) showed that advection by the mean ocean circulation could lead to
67 nonlocal reemergence in the western subtropical and subpolar North Atlantic, and
68 Sugimoto and Hanawa (2007) discussed remote reemergence in the North Pacific. In
69 these studies, reemergence was clearly detected in western subtropical and subpolar
70 regions, but it was generally not seen in the eastern subtropical oceans and in the
71 southwestern subtropics. Several factors have been suggested to explain the lack of
72 reemergence in the latter regions: too small seasonal range of mixed-layer depth, large
73 fraction of mixed-layer water permanently subducted in the ocean interior, strong

74 oceanic heat loss, and, for the North Atlantic Madeira mode water (Sugimoto and
75 Hanawa 2005), vigorous salt-finger mixing.

76 The fall and winter mixed layer deepening should lead to a corresponding
77 reemergence of sea surface salinity (SSS) anomalies, but because of sparse observations
78 there has been no observational studies of SSS reemergence. Alexander et al. (2001)
79 considered a simulation with an atmospheric general circulation model coupled to an
80 entraining bulk ocean mixed layer model and found that SSS reemergence was stronger
81 than SST reemergence, presumably because SST anomalies are strongly damped by
82 surface flux and thus persist less than SSS anomalies. Hence, it is of much interest to
83 investigate the persistence and propagation of SSS anomalies in observations, despite
84 data limitations. In the present paper, SSS reemergence is investigated in the North
85 Atlantic mid-latitudes based on correlation analysis, using a new extended monthly
86 observational data set that covers the period 1970-2016, albeit with numerous data
87 gaps. Both local and remote reemergence are investigated in the 1993-2016 period, and,
88 for comparison, SST reemergence is also investigated. An oceanic reanalysis is also used
89 in the better-documented 2005-2018 period.

90 **2. Data and method**

91 *2.1 The updated North Atlantic SSS data set*

92 The SSS fields constructed from observations by Reverdin et al. [2007, hereafter
93 RKFD07] have been extended from 1970-2002 to 1970-2016 ([http://
94 dx.doi.org/10.6096/SSS-LEGOS-GRID-ATL](http://dx.doi.org/10.6096/SSS-LEGOS-GRID-ATL)). As described in RKFD07, the monthly SSS is
95 gridded in 30°S-50°N using objective mapping [Bretherton et al., 1976] at 1°x1° spatial
96 resolution. The product is mainly based on water samples and underwater
97 thermosalinographs installed on research vessels and voluntary observing ships (VOS,
98 [http://www.legos.obs-mip.
fr/observations/sss/](http://www.legos.obs-mip.fr/observations/sss/)), PIRATA moorings in the tropical

99 Atlantic (<http://www.brest.ird.fr/pirata/>), SMOS and CARIOCA drifters [G. Reverdin,
100 personal communication], and Argo floats ([http://www.coriolis.eu.org/Observing-the-](http://www.coriolis.eu.org/Observing-the-ocean/Observing-system-networks/Argo)
101 [ocean/Observing-system-networks/Argo](http://www.coriolis.eu.org/Observing-system-networks/Argo)). The raw SSS data were grouped in monthly
102 $1^{\circ} \times 1^{\circ}$ square bins. Only grid points where the estimated RMS error (normalized by the
103 signal amplitude) does not exceed 0.8 were retained, as in RKFD07, and grid points with
104 too sparse observations were excluded. Figure 1a shows that the spatial coverage of SSS
105 observations (before objective analysis) increases considerably after 2005 when Argo
106 float data become widely available. The data coverage is heterogeneous, with high
107 density along three Europe-South America and Europe-South Africa VOS lines and low
108 density south of 10°S (Fig. 1b). The mean seasonal cycle is first estimated iteratively
109 based on all available data and objective maps, as described in RKFD07. The objective
110 mapping is sequential in time with a forward and backward scheme that incorporates all
111 the data increments first gridded on a $1^{\circ} \times 1^{\circ}$ month grid with an assumed correlation
112 function in time and space, as done in optimal interpolation. This function reproduces
113 the estimated spatial and temporal correlation of the salinity anomalies as estimated in
114 five subdomains and for two extended seasons that correspond to strong or weak
115 salinity near-surface stratification (see RKFD07 for details). The same sequential
116 approach is used for mapping the SSS anomalies obtained by subtracting the seasonal
117 cycle, using as guess the mapped anomaly of the previous step (a month ahead or after)
118 weighted by assuming a 2-month decay-time. Two analyses are performed, one forward
119 and one backward, and their average used. The resulting fields are provided with a
120 parameter that indicates the signal-to-noise ratio expected from the data distribution,
121 thus how close the analysis is to the input data or how it is weighted by the guess field.
122 Except in data sparse regions, the differences between the two analyses are usually
123 smaller than the anomalies portrayed and consistent with the estimated errors. As
124 discussed in RKFD07, mapped anomalies with an estimated relative error as large as 0.8

125 still seem to be retaining part of the signal, albeit with a reduced amplitude. However,
126 anomalies with larger estimated errors were not retained. Although it generates gaps in
127 the analyzed fields, it does not bias the lag correlation estimates.

128 There are several differences between the present data set and the other
129 available SSS products, which are also based on quality-controlled data but only use
130 vertical salinity profiles. By including the other sources of SSS observations listed above,
131 our data set is based in the 1993-2002 period on more than twice the number of $1^\circ \times 1^\circ$
132 bins with SSS observations and a more homogeneous distribution. The differences
133 decrease after 2005 because of the many ARGO floats, although our product still includes
134 20 to 30% more bins with SSS observations than products solely based on salinity
135 profiles. This better sampling has allowed us to use a twice longer period to investigate
136 SSS reemergence in the North Atlantic.

137 There are additional differences between SSS products. In EN4 (Good et al. 2004),
138 salinity is estimated from the vertical salinity profiles by spreading the information
139 vertically, using two correlation length scales, which are set to 200 and 100 m. This
140 smoothing makes it particularly unsuitable for investigating SSS reemergence, which
141 critically depends on the detailed vertical structure of salinity between the depth of the
142 summer and the winter mixed layers. In addition, the persistence-based forecasts use a
143 forward scheme in EN4, rather than an average of a forward and backward scheme, and
144 it has a longer e-folding scale (9.5 months instead of 5-6 months at most), which could
145 further blur reemergence peaks. Finally, the EN4 analysis will relax to climatology in the
146 absence of observations, which would bias the seasonal autocorrelation, unlike in our
147 data set where analyzed data with large estimated errors are dismissed. Because the
148 historical (1945-2003) salinity analysis of Ishii et al. (2006), which uses salinity profiles
149 in addition to SSS data, performed the objective analysis in a two-dimensional space and
150 used rather short spatial (15 m in the vertical) scale, there should be negligible vertical

151 smoothing. However, they use climatology instead of anomaly persistence as first guess,
152 and a short temporal (15 day) correlation scale that likely results in numerous data gaps.
153 Since the analysis of Ishii et al. (2006) also relaxes to climatology where data are sparse,
154 and it does not cover the recent period with enhanced ARGO coverage, it seems far from
155 optimal for our purposes.

156 Ocean reanalyses such as SODA3 (Carton et al. 2018), ORAS5 (Zuo et al. 2019) or
157 GLORYS2v4 (<https://marine.copernicus.eu/> GLOBAL_REANALYSIS_PHY_001_026)
158 assimilate salinity profiles, but no other SSS observations. Hence, like EN4, they use
159 much fewer observations to reconstruct the SSS field. In addition, the assimilation of the
160 T/S profiles depends on specified error covariances or other assumptions that may not
161 be optimal for studying SSS reemergence. For instance, ERA5 uses the T/S profiles
162 processed by EN4, and includes a constraint on SSS by nudging to climatology. However,
163 the reanalyzed products also assimilate sea surface height and the atmospheric forcing,
164 they are dynamically consistent, and they provide salinity values at depth. Hence, a
165 reanalysis will be used to verify whether autocorrelation results indeed reflect SSS
166 reemergence, but a systematic investigation would require that the well-sampled ARGO
167 period be longer than at present.

168 For the present analysis, the $1^\circ \times 1^\circ$ objective fields were binned (averaged), after
169 removing the mean seasonal cycle, in $5^\circ \times 5^\circ$ squares between 10°N and 50°N if at least 3
170 values (among 25) were available. Similar results are obtained if the cut-off is 2 or 4,
171 although there would be more gaps in the latter case. The data density, as defined by the
172 number of available data in each $5^\circ \times 5^\circ$ box divided by 25 (number of grid points) \times 12
173 (number of months) \times 24 (number of years), is given in Fig. 2 before (left) and after
174 (right) objective analysis. Sampling is obviously not always as good as would be required
175 to unambiguously detect SSS reemergence, even after objective analysis, in ways that are
176 not easy to apprehend. The SSS anomaly time series are illustrated for a few $5^\circ \times 5^\circ$ boxes

177 in Fig. 3, both before (yellow) and after (blue) objective analysis. The raw data are often
178 noisy as they represent an average of much fewer values, although series based on the
179 medians rather than the means (not shown) have smaller variance and are closer to the
180 time series derived from the objective analysis. Data gaps are often concentrated in the
181 90s, as illustrated for boxes b and e in Fig. 3. Note that it was verified that spikes such as
182 the negative one in 2001 for the 45°-50°N, 50°-45°W box (Fig. 3a) are not due to
183 observing/instrumentation errors but reflect true fluctuations that might be
184 undersampled and on scale smaller than the 5°x5° month boxes. In some of the boxes,
185 the anomalies have a small trend. In addition, many boxes are dominated by low-
186 frequency fluctuations, as in Fig. 3a, b, and f. Eddy noise can also be prevalent, as shown
187 during the first decade by the raw SSS data in the vicinity of the Gulf Stream (Fig. 3c),
188 when the spatial coverage was limited. Removing a quadratic polynomial by least
189 squares fit to the monthly time series often satisfactorily removes the trend, but because
190 the time series are short (24 years), it can also introduce unwanted behavior and mask
191 reemergence when the low-frequency variability is large. Hence, in the following we
192 systematically investigate reemergence with both detrended (by a linear or quadratic
193 polynomial removed from each of the available 1°x1° time series after objective analysis,
194 but before averaging in boxes) and non-detrended data. Several larger domains (see Fig.
195 7 below) were also considered to reduce data noise and focus on larger-scale anomalies,
196 thus allowing us to search for evidence of additional reemergence peaks.

197 2.2 *Other data*

198 Monthly sea surface temperature (SST) anomalies on a 1°x1° grid, which were
199 obtained by an optimal interpolation of satellite and in-situ SST observations (Reynolds
200 et al. 2002) are taken from the NOAA/OAR/ESRL PSD site (www.esrl.noaa.gov/psd). We
201 use altimeter geostrophic currents produced by Ssalto/Duacs (AVISO, CNES) and
202 distributed by Copernicus Marine Systems (<https://resources.marine.copernicus.eu>

203 product_id=SEALEVEL_GLO_PHY_L4_REP_OBSERVATIONS_008_047). The surface
204 geostrophic currents span the period January 1993 to December 2016 and correspond to
205 Ssalto/Duacs gridded absolute geostrophic velocities. They have daily resolution on a
206 $1/3^\circ \times 1/3^\circ$ grid. Details of the mapping technique used to derive the $1/3^\circ$ gridded data
207 are given by Dibarboure et al (2011), who show that this data set resolves wavelengths
208 greater than 150 km with a temporal resolution of 20 days. We also used the monthly
209 mixed layer depth climatology of Sallée et al. (2021) and salinity fields from the 1993-
210 2018 Mercator Ocean GLORYS2V4 reanalysis at 1 degree resolution with 75 vertical
211 levels. (https://marine.copernicus.eu/GLOBAL_REANALYSIS_PHY_001_026).

212 *2.3 Estimating advection effects*

213 To take into account advection effects that could lead to non-local SSS or SST
214 reemergence by displacing the deep mixed-layer waters after they are capped by the
215 seasonal thermocline, we use the daily estimates of the AVISO surface geostrophic
216 currents. Geostrophic currents are used for simplicity because the wind-driven Ekman
217 currents are primarily limited to the mixed layer above the seasonal thermocline and
218 should not advect the water below it. However, in fall and winter when the surface layer
219 is deep and well mixed, Ekman advection may contribute to its displacements. Also, use
220 of surface geostrophic currents neglects their vertical shear in the upper ocean and may
221 overestimate advection estimates, in particular during summer. In reality, interior water
222 flows along isopycnal surfaces, so the use of surface geostrophic currents also neglects
223 vertical advection, which may be large in regions with strong subduction or obduction.
224 For each starting month, the position of 1381 virtual floats issued on the $1^\circ \times 1^\circ$ grid of a
225 more limited domain that avoids proximity to the continental shelf and the Gulf Stream is
226 estimated in forward mode during the following 2-year period. For instance, for a March
227 starting date, a first run estimates a virtual float trajectory F from March 1, 1993 to
228 February 28, 1995, a second run that from March 1, 1994 to February 29, 1996, and

229 similarly until the last run that goes from March 1, 2014 to February 29, 2016. This
230 provides 22 24-month trajectories R for each virtual float F . For each $5^\circ \times 5^\circ$ box, 22 sets
231 of averaged 24-month trajectories can be estimated by averaging over the floats issued
232 from it, and a mean trajectory estimated by averaging them (Fig. 4).

233 *2.4 Detecting reemergence*

234 Reemergence is investigated in the 20°N – 50°N domain using lag seasonal SSS
235 anomaly autocorrelation functions starting in late winter when the mixed layer is very
236 deep. The calculation is given for the 1993-2016 period because of better sampling and
237 geostrophic current availability. However, extreme sparsity obscures reemergence, and
238 indeed clear reemergence was seldom seen in boxes with limited early data density
239 before objective analysis. For local calculations (no advection), the lag auto-correlation at
240 each grid point and lag is based on all available data pairs (for instance between each
241 March and each of the following Aprils), which does not require that the data be available
242 in other months. In the SSS case, the number of pairs may thus slightly depend on lag and
243 starting month. Non-local reemergence is estimated similarly, but along the time-varying
244 trajectories, as described in section 3b.

245 The statistical signature of reemergence is a fast decrease during spring of the lag
246 seasonal correlation with the late winter value, a correlation minimum in summer when
247 the seasonal thermocline inhibits exchanges with the deeper waters and the shallow
248 mixed layer strongly responds to the atmospheric forcing, a correlation increase during
249 fall when the mixed layer depth increases and entrainment is large, and a correlation
250 peak in early winter. Because reemerged SST anomalies are damped by the surface heat
251 fluxes, the SST reemergence peak could occur before that of SSS, and be smaller. There
252 should be some geographical variability in timing linked to the seasonal cycle of the
253 mixed layer depth, which occurs earlier in the southwestern boxes (de Boyer Montégut
254 et al. 2007; Carton et al. 2008). As illustrated in Fig. A1, the maximum mixed layer depth

255 is largest in the northern part of the domain and over the northern flank of the
256 subtropical gyre, and it is smallest in the northwestern and southwestern boxes. The
257 maximum depth occurs around February and the minimum depth around July, except in
258 some southern boxes where the maximum depth is reached in December and the
259 minimum in May. The range of mixed layer variations (maximum minus minimum, Fig.
260 A2) thus varies between more than 100 m in the northeastern part of the domain, more
261 than 200 m south of the North Atlantic current, and barely more than 20 m in the four
262 southwestern-most boxes. South of 20°N, the seasonal range is typically of the order of
263 20m, with some scatter in the month of minimum depth due to the seasonal changes in
264 winds and clouds over the tropics (Carton et al. 2008).

265 As each starting date may be differently affected by data noise, we have considered
266 February, March and April as starting month for estimating the seasonal autocorrelations
267 at each location. Both original and quadratically detrended data are considered when
268 assessing the presence of reemergence, without requiring that it be seen on both cases.
269 In total, reemergence is thus assessed from 6 different (3 starting months, with and
270 without detrending), albeit correlated, seasonal autocorrelations functions. Yet, its
271 occurrence (or not) cannot always be robustly established, as discussed below. A caveat
272 of the correlation analysis is that a peak attributed to reemergence may in some cases be
273 due to coincident atmospheric forcing. Murata et al. (2020) showed that an early fall
274 heating or anomalous northward advection occurring by chance where the SST was
275 anomalously warm in the preceding winter could lead to a recurrence that was not due
276 to entrainment. Although it is hoped that such occurrences would not substantially affect
277 results based on 24 years of data, they may explain occasional departures from the
278 expected statistical signature of reemergence and, perhaps, lead to a few
279 misinterpretations. Nonetheless, the SSS reemergence suggested by the correlation
280 analysis was verified at two locations using subsurface salinity values provided by the

281 GLORYS2V4 reanalysis in the better-sampled 2005-2018 period. It is also noted that
282 reemergence only occurs if sufficiently large anomalies are present during the previous
283 winter, so that reemergence is not a regular occurrence, as discussed in Taws et al.
284 (2010).

285

286 **3. SSS and SST anomaly reemergence in the 70°-20°W, 20°-50°N domain**

287 *a. No advection*

288 The seasonal autocorrelations of the SSS anomalies were examined for each box
289 between 70°W and 20°W for a February, March, and April starting month, with and
290 without detrending. To illustrate how they were used to assess SSS reemergence, the
291 seasonal SSS autocorrelations for a March starting date and lag increasing from 0 (month
292 3 in the abscissa) to 20 (month 24) are shown in Fig. 5 (red curves) for several boxes in
293 three latitudinal bands, where we use data with or without detrending primarily on the
294 basis of their behavior at long lags. The corresponding seasonal SST autocorrelations
295 (blue curves) are briefly discussed below. The boxes were in part arbitrarily chosen to
296 illustrate a variety of situations, but all the boxes between in the 40°-45°N (30°-35°N)
297 latitudinal bands are considered in Fig. 6 (Fig. A3), providing a more systematic view of
298 local SSS reemergence. Because the sample is limited and the SSS anomalies are noisy,
299 the statistical signature of reemergence is often ambiguous, leading to unavoidable
300 subjectivity in our assessment. Moreover, the lagged autocorrelation peak is only
301 marginally significant in some cases (the one-sided 10% (5%) significance level is 0.27
302 (0.34) for complete data), in part because of low-frequency contamination and data
303 noise. Note that reemergence in Fig. 5 and A3, which are based on a March starting date,
304 may be clearer with a February or April starting month, while the starting month in Fig. 6
305 is chosen to best illustrate SSS reemergence.

306 A clear example of SSS reemergence is found in the northeastern box (45° - 50° N, 25° -
307 20° W), which is relatively well sampled (Fig. 2) and where the climatological winter
308 mixed layer exceeds 200 m (Fig. A1) and the seasonal range of mixed layer depth is \sim
309 170 m (Fig. A2), thus providing favorable conditions for reemergence. As shown for a
310 March starting month in Fig. 5e, the seasonal autocorrelation rapidly decreases with
311 increasing lag from March to August, shortly after the mixed layer reaches its minimum
312 depth. The autocorrelation then increases to reach a broad peak between November to
313 January, and it decreases again, quite rapidly after March. This evolution is consistent
314 with a maximum entrainment rate in November/December (Carton et al. 2018). At larger
315 lag, there is a second autocorrelation minimum in the following August followed by
316 another increase in late fall, suggesting a second reemergence. Similar results are found
317 for a February or April starting month, indicating robustness. Note that these seasonal
318 variations are superposed on a slow decay that reflects low-frequency variations and the
319 long SSS memory at this location. In our summary assessment (Fig. 7a), this box is shown
320 in purple, which indicates clear reemergence.

321 Although the mixed layer conditions are similar in the adjacent box to the west (30° -
322 25° W, 45° - 50° N, Fig. 5d) and data sampling is only slightly poorer (Fig. 2), there is no
323 indication of SSS reemergence for neither March nor April starting month, but for a
324 February starting month there is a broad correlation peak from August to November (not
325 shown) that might reflect an early reemergence (the deepest mixed layer is in February).
326 As the autocorrelation strongly depends on the starting month indicates a lack of
327 robustness, this box is blue in Fig. 7a, which indicates hints of reemergence. Further
328 west, the (40° - 35° W, 45° - 50° N) box shows no indication of SSS reemergence (Fig. 5c)
329 despite its large mixed layer depth range (Fig. A2), presumably because of very poor data
330 coverage until mid-2001 (Fig. 3b). This box is ochre in Fig. 7a, which indicates no
331 reemergence. SSS reemergence is seen, albeit noisy, (Fig. 5b) in the better sampled (50° -

332 45°W, 45°-50°N) box, with a correlation minimum in August followed by a broad
333 increase peaking in March, even though the winter mixed layer is shallow and its
334 seasonal range is only 15 m in Fig. A2. However, the range is larger in Carton et al.
335 (2018). Reemergence also seems to occur in the (55°-50°W, 45°-50°N) box (Fig. 5a),
336 where the mixed layer depth range is larger (70m, Fig. A2). These two boxes are purple
337 in Fig. 7a. In summary, reemergence is seen in 5 out of the 8 boxes of the higher latitude
338 band that we could consider.

339 In the 35°-40°N latitudinal band, the eastern box (25°-20°W) has a mixed layer
340 seasonal range of ~100m (Fig. A2), good sampling (Fig. 2), an autocorrelation minimum
341 in late summer and maximum between November and January (Fig. 5j). This clearly
342 indicates SSS reemergence. Further west (40°-35°W), the mixed layer depth range is
343 similar but sampling poorer, albeit rather evenly distributed in time, so that the
344 correlation minimum in August and the peak in October and November also strongly
345 suggest reemergence (Fig. 5i). On the other hand, there is no indication of SSS
346 reemergence in (50°-45°W; Fig. 5h), where the winter mixed layer is very deep due to
347 strong atmospheric cooling over the path of the North Atlantic current, leading to large
348 subduction and obduction (Qiu and Huang 1995). Since SST reemergence is seen there
349 (blue curve), the lack of a SSS reemergence peak probably results from poor sampling
350 (Fig. 2). Finally there is no indication of SSS reemergence in the two westernmost boxes
351 (Fig. 5f,g), although there are hints of it for different starting dates, as indicated in Fig. 7a.

352 Finally, the seasonal autocorrelations are shown for 5 boxes in the 20°-25° latitudinal
353 band. SSS reemergence is seen in (45°-40°W) (Fig. 5n), where the maximum winter
354 mixed layer is less than 100 m, the mixed layer depth range is 68 m, and an
355 autocorrelation minimum in summer precedes a winter correlation peak. Less favorable
356 conditions for reemergence are found to the east (Fig. 5m, 42 m range), where a
357 reemergence peak is only clearly seen for a February starting date (not shown), and to

358 the west (Fig. 5o, 55 m range). Nonetheless, since both cases have an autocorrelation
359 minimum in summer, SSS reemergence is considered as clearly occurring (purple in Fig.
360 7a). There is also evidence of SSS reemergence in (70°-65°W) and (65°-60°W) (Fig. 5k,
361 l), despite limited sampling, in particular in the latter box, and a small seasonal range of
362 mixed layer variation (23 and 20 m, respectively). Indeed, an autocorrelation peak
363 occurs around October and December, respectively, which corresponds well to the
364 December mixed layer depth maximum (Fig. A1). Note that the autocorrelation minimum
365 only occurs in September, several months after the mixed layer is shallowest (Fig. A1),
366 but these boxes, at least in their southern part, are strongly influenced by a large
367 freshwater influx in late summer primarily originating from the Amazon and the Orinoco
368 and advected by the North Brazil Current (e.g., Foltz et al. 2015). They can also be
369 strongly impacted by the occasional hurricanes in fall, so caution is required.

370 To document a whole latitudinal band, the seasonal SSS autocorrelation is shown for
371 all the boxes between 40° and 45°N (Fig. 6, red curves). In this case, the starting month
372 and detrending were selected to best show local SSS reemergence. East of 35°W, the
373 seasonal range of mixed layer depth is larger than 100m (Fig. A2), and local SSS
374 reemergence is clearly seen in the two easternmost boxes as the autocorrelation has a
375 summer minimum and a winter peak for February and March starting dates (Fig. 6i,j),
376 although it only appears for an April starting date in (35°-30°W) (Fig. 6h), perhaps
377 because of poorer sampling (Fig. 2). Sampling is also limited further west until 60°W, in
378 particular in (55°-50°W) where raw sampling is very poor. However, an early SSS
379 correlation peak (from August to November) is seen in (50°-45°W, Fig. 6e) where the
380 mixed layer depth range is large (94m). Because this correlation peak occurs much
381 earlier than the maximum mixed layer depth, SSS reemergence is considered as only
382 hinted at in Fig. 7a. Further west, a winter SSS reemergence peak is seen in (65°-60°W),
383 despite a shallow winter mixed layer depth and limited seasonal range (38m). Note that

384 a summer minimum is seen for an April starting date, but the winter peak is larger for a
385 March one, which is thus displayed (Fig. 6b). Finally, the signature of SSS reemergence is
386 seen in (70°-65°W), despite a limited seasonal range (Fig. 6a).

387 For further illustration, the seasonal SSS auto-correlations are also shown in Fig. A3
388 (red curves) in the whole 30°-35°N band. SSS reemergence likely occurs in (70°-65°W),
389 (60°-55°W), and (40°-35°N), which have a rather large seasonal range of mixed layer
390 depth (149 m, 106 m, and 77 m, respectively), but, except in (45°-40°W) for an April
391 starting date (not shown), there is no sufficient evidence of it elsewhere. In particular, SSS
392 reemergence clearly does not occur in the subtropical gyre east of 35°W, despite
393 seasonal ranges of ~ 100 m.

394 We also estimated the SSS seasonal auto-correlations using the raw SSS data
395 averaged in the 5°x5° boxes instead of the analyzed ones. As expected from much sparser
396 and noisier data (Fig. 2 and 3), fewer boxes show evidence of SSS reemergence, and SSS
397 reemergence only appears more clearly in the raw data in a few boxes (not shown).

398 For comparison, the corresponding seasonal SST anomaly autocorrelations are
399 shown in Fig. 5 (blue curves) in the same 1993-2016 period. Note that the choice of
400 detrending or not in Fig. 5 was based on SSS and may not be optimal for SST as trends
401 can differ. Evidence of SST reemergence is seen, albeit often noisily, in panels (d), (e), (h),
402 (m), (n), and (o). There are hints of SST reemergence in panel (a), (f), (i), (k), and (l) but
403 no sufficient evidence of it in panels (b), (c), (g), and (j). Interestingly, the autocorrelation
404 minimum in panels (k) and (l) occurs in July, earlier than for SSS, which is probably
405 because the freshening influence from the tropics, has limited impact on SST. Our
406 assessment of SST reemergence is summarized in Fig. 7c. SST reemergence is most
407 clearly seen in the most of the northern and central parts of the domain. SST
408 reemergence occur in the northeastern corner, where seasonal range of mixed-layer
409 depth is large, as noted before. The reemergence of SST is not seen in the eastern part of

410 the subtropical gyre between 30°N and 40°N, east of 40°W, nor in the subtropics west of
411 60°W. There is evidence of SST reemergence at many southern boxes, although the
412 annual cycle of mixed-layer depth is rather small (Fig. A1).

413 Unfortunately, the 5° x 5° SSS data are too noisy to often detect SSS reemergence
414 during the second year, which would require an auto-correlation minimum around
415 month 18-20 (June to August) followed by a peak around month 23-26 (November to
416 February). Nonetheless, there are hints of a second SSS reemergence in Fig. 5 (panels e
417 and n) and Fig. 6 (panel g). Note that a second reemergence may also occur remotely
418 because of advection by the mean currents, although we found little evidence of it (see
419 below).

420 To reduce the influence of advection, measurement errors, data gaps, and small-scale
421 features, we have considered SSS and SST anomalies averaged over broader, but
422 reasonably homogeneous areas, namely the northeastern and southeastern parts of the
423 domain, as well as the western and eastern halves of the subtropical gyre, and
424 considered longer lags. Because of the larger areas, there is no gap in the anomaly time
425 series. Figure 8 shows the lag correlations for a March starting date for the four domains
426 after removing a linear trend to better distinguish interannual persistence from long-
427 term fluctuations. Similar results are obtained for a February and April starting date (not
428 shown). In the northeastern domain (40°-20°W, 40°-50°N), SSS anomalies are very
429 persistent, yet a first, a second, and a third SSS anomaly reemergence peaks following
430 relative summer minima are clearly visible, and there may even be a fourth one (Fig. 8a).
431 The latter is also suggested for a February starting date, but not an April one, although
432 longer lags should be considered to unambiguously detect a fourth peak. Hence, the
433 large-scale wintertime SSS anomalies only decay very slowly in this region, recurring for
434 several winters. By contrast, there is only a first, slightly earlier SST reemergence peak,
435 noisy evidence of a second one, and none of a third peak. Note that a clear second SST

436 anomaly reemergence peak was seen in a longer data set in a broadly similar region,
437 albeit extending to 60°N (Deser et al. 2003, their Fig. 9).

438 In the western subtropical gyre region (60°-35°W, 30°-40°N), the SSS autocorrelation
439 (Fig. 8b) has two peaks, one at month 10, 11, and 12 (October to December) and the
440 other at month 20 and 21 (August and September). However, the second peak occurs
441 closely after the minimum mixed-layer depth (in July) and much before the maximum
442 entrainment rate (Carton et al. 2018); hence it does not reflect SSS reemergence, but low-
443 frequency fluctuations or eddy noise. This is consistent with the 5°x5° results, since SSS
444 reemergence was only found in the easternmost part of the subdomain (Fig. 7). On the
445 other hand, a more robust first reemergence peak is found for the large-scale SST
446 anomalies, again consistent with the 5° x 5° box results. There is also a second, albeit
447 small, SST peak in October and November, which becomes significant when an even
448 larger domain (70°-30°W, 20°-40°N) is considered (not shown).

449 In the eastern subtropical gyre region (35°-20°W, 30-40°N), there is no clear
450 indication of a first reemergence for either SSS or SST anomalies (Fig. 8c), consistent
451 with the 5° x5° results in Fig. 7. However, there is a SSS correlation peak at lag 23
452 (December) followed by a minimum between the following May to August, and a broad
453 peak between lag 35 and 40 (December to May). Note also the SST correlation peak near
454 lag 23 (November). Although unlikely in a 24-year record, it might perhaps reveal the
455 presence of a second and, for SSS, a third reemergence since, as pointed out by a
456 reviewer, if the mixed layer is especially deep when the anomaly is formed in the first
457 winter, anomalously shallow in the second winter, and anomalously deep in the winter
458 after that, the re-entrainment of anomalous temperature or salinity anomalies into the
459 surface mixed layer would skip a year.

460 In southeastern region (50°-20°W, 20°-30°N), a first and a second SSS reemergence
461 peak are seen in November and December relative to a slow decay, and even hint of a

462 third one (larger for a February starting date, lost for an April one), albeit not significant,
463 each of them following smaller summer values, albeit noisy during the first summer (Fig.
464 8d). On the other hand, only a first SST reemergence peak is clearly seen above the
465 background of low-frequency variations. This indicates that the large-scale wintertime
466 SSS anomalies decay faster than in the northeastern corner, consistent with the smaller
467 winter mixed-layer depth and inertia.

468

469 *b. Link to subsurface salinity*

470 To link the SSS anomaly correlation peaks to the reemergence of subsurface salinity
471 anomalies, the GLORYS2V4 reanalysis was used, but only the 2005-2018 period was
472 considered because of the insufficient number of salinity profiles before many ARGO
473 floats became available. To verify whether such period would be sufficiently long to
474 detect reemergence, we first re-did the correlation analysis using our data set in the
475 2005-2016 period. Unfortunately, 12 years of 5°x5° data turned out to be insufficient to
476 reproduce many results based on 24 years, showing instead noisy correlations for both
477 SSS and SST anomalies. Hence, it was not surprising that using reanalyzed SSS or SST
478 anomalies derived from GLORYS2V4 mostly showed little evidence of reemergence and
479 often at different locations. This is consistent with the often-limited correlation between
480 the two SSS anomaly data sets, which is due to differences in both sampling and analysis
481 methods. Nonetheless, evidence of SSS reemergence was found in both data sets for
482 several of the 5°x5° boxes in the northeastern and southeastern parts of the domain
483 where the correlation between the data sets was typically ~ 0.6 , and reemergence had
484 been found in the longer 1993-2016 data.

485 To optimize the links with subsurface data, the reanalyzed SSS anomalies were
486 considered in the 2005-2018 period in two somewhat larger regions, one in the
487 southeast (35°-20°W, 20°-30°N) and the other in the northeast (30°-20°W, 45°-45°N),

488 where the maximum mixed layer depth is ~ 100 and 120 m, respectively (Fig. A1). A
489 depth-time diagram of the lag correlation with the averaged salinity anomalies in the
490 upper 20 m was constructed for both a February and a March starting date at lag ranging
491 between 0 and 24. Despite the short data duration (14 years), the results for (30° - 20° W,
492 45° - 45° N) clearly show that the SSS anomalies, which extend throughout the mixed layer
493 in late winter, are capped by the seasonal thermocline in summer at lag 3 to 6 (i.e. June to
494 September) and reappear at the surface in fall and winter when subsurface water is
495 entrained in the deepening mixed layer, peaking at lag 8 to 10 (November to the
496 following January) (Fig. 9, left). After the winter, the correlation keeps decreasing,
497 presumably because of the large low-frequency SSS fluctuations found at this location.
498 Interestingly, the subsurface salinity and SST (not shown) anomalies propagate
499 downward, reflecting the large southwestward subduction in this area (Marshall et al.
500 1993; Qiu and Huang 1995). Similar results are obtained with a February starting date,
501 or when using SSS instead of the 0-20 m salinity as basic time series. As expected from
502 the limited number of salinity profiles in the pre-ARGO period, no reemergence is seen
503 when the longer 1993-2016 reanalyzed data set is used. Similar results are obtained for
504 the (30° - 20° W, 45° - 45° N) domain, but for deeper wintertime anomalies, with the
505 reemergence of the subsurface SSS anomalies starting around October (lag 7), peaking in
506 December (lag 9), and lingering throughout winter, again consistent with the mean
507 seasonal cycle of the mixed layer depth (Fig. 9, right). In summary, this analysis
508 demonstrates, based on the two locations, that SSS reemergence can be well detected
509 using the lag seasonal correlation analysis.

510

511 *b. With advection*

512 To take advection into account, which could lead to non-local SSS reemergence by
513 displacing the deep mixed-layer water after they are capped by the seasonal thermocline,

514 we used the virtual float trajectories F described in section 2.3. As illustrated in Fig. 4,
515 they reflect the mean near-surface circulation of the subtropical gyre, except in the
516 northwestern corner east of the Grand Banks (box 47), where the mean flow results from
517 the southward flowing Labrador Current. Further east, the northern boxes are located on
518 the southern side of the confluence of the subtropical and subpolar gyres. As shown by
519 the averaged 2-year trajectories in Fig. 4, float velocity strongly varies with location
520 within the subtropical gyre, with a 12-month displacement from the first March typically
521 ranging between five and up to ten 1° grid cells. There are substantial year-to-year
522 fluctuations in the trajectories, as illustrated for 5 boxes by the mean 2-year trajectories
523 of the virtual float emitted in each year. Note the larger dispersion of the mean
524 trajectories at box 32 (65° - 60° W, 35° - 40° N), which reflects the large eddy activity in the
525 vicinity of the Gulf Stream. Along each individual 2-year virtual float trajectory F , the
526 monthly SSS anomaly (before or after quadratic detrending) is interpolated from the $1^\circ \times$
527 1° objective SSS maps, yielding the data matrix $SSS(1:24, F, R)$, where R is the number of
528 successive years providing initial conditions. Because of data gaps, R is not always equal
529 to 22, and can be as low as 17. The SSS anomalies following geostrophic advection are
530 obtained by averaging them along the floats issued from each $5^\circ \times 5^\circ$ box, yielding the
531 data matrix $SSS'(1:24, R)$, which is used to calculate the seasonal cross-correlations. The
532 same procedure is used for SST anomalies. It should be stressed that for simplicity the
533 cross-correlations and possible remote reemergence are attributed to the $5^\circ \times 5^\circ$ boxes
534 where the virtual floats were issued. However, the reemergence along individual
535 trajectories really occurs in broader regions spanned by the float trajectories, which
536 overlap neighboring $5^\circ \times 5^\circ$ boxes, with a dispersion even larger than shown in Fig. 4,
537 where only the mean trajectories for each year are represented. In other words, remote
538 reemergence takes place at a different location determined by the mean horizontal
539 currents and their daily variability. However, as the spatial scale of SST or SSS anomalies

540 is generally much larger than the water displacements before the first reemergence, both
541 local and remote reemergence could well be found for the same box.

542 As illustrated in Fig. 6 for the 40° - 45° N latitudinal band, remote SSS reemergence
543 might occur along float trajectories issued from the (50° - 45° W) box, which largely go
544 eastward (Fig. 6e, blue curves). At short lag, displacement is limited and, as expected, the
545 seasonal autocorrelation closely resembles that of the issuing box. However, the
546 correlation maximum is slightly sharper and occurs one month earlier, although the
547 maximum still occurs in October for a February starting month (not shown).
548 Nonetheless, because the maximum mixed layer depth occurs in February, remote
549 reemergence is considered as hinted at in Fig. 7b, as was the local one. Floats issued from
550 (45° - 40° W) do not appear to reemerge (Fig. 6f), despite a minimum correlation in June,
551 and there is no reemergence evidence based on other starting months. The correlations
552 based on floats issued from 40° - 35° W are very sensitive to both starting month and
553 detrending, but there is some tentative indication of possible reemergence for a
554 February starting month (not shown). Remote reemergence seems to occur in 35° - 30° W
555 (Fig. 6h), but the correlation at large lag is affected by low-frequency variability, even
556 with quadratic detrending. The same holds in 30° - 25° W and 25° - 20° W, although the
557 reemergence signature is clearest for the latter box (Fig. 6i,j). In summary, good evidence
558 of remote reemergence in 40° - 45° N only occurs for floats issued east of 35° W.
559 Interestingly, even at large lags the auto-correlations along float trajectories largely
560 resemble the local ones in the issuing boxes, suggesting that the SSS anomalies have a
561 large zonal scale.

562 In the 30° - 35° N latitudinal band (Fig. A3, blue curves), taking advection into
563 account enhances the detection of SSS reemergence for a few boxes, such as in panels (d)
564 and (f). However, as summarized in Fig. 7b, taking advection into account somewhat
565 deteriorates the detection of SSS reemergence in other areas. In particular, remote

566 reemergence is only seen in a third of the boxes in the 45°-50°N band, in part because of
567 limited data density (Fig. 2), and no SSS data availability north of 50°N when
568 interpolating SSS along the trajectories that escape the domain (8 to 9%). Also, remote
569 SSS reemergence is seldom identified for boxes west of 55°W, perhaps in part because of
570 the large dispersion of the trajectories (see Fig. 4) caused by the strong eddy activity in
571 the western North Atlantic. On the other hand, remote reemergence is more often found
572 for trajectories issued from the central part of the domain, but less often for those issued
573 at the southernmost locations.

574 Similarly, taking advection into account leads to fewer boxes with clear remote
575 SST reemergence (Fig. 7d). Remote SST reemergence is found when issued from most of
576 the northern boxes, but it is not as often clear between 40°N and 50°N. Also, remote SST
577 reemergence is not clearly detected between 20°N and 25°N, west of 40°W, and is still
578 not seen in much of the eastern subtropical gyre.

579 The reemergence along artificial float trajectories was also investigated in the
580 larger domains, thus considering anomalies along all the float trajectories issued within
581 them, although only lags up to month 24 (December) could be considered due to the
582 limited duration of the trajectories (section 2). Consistent with the 5° x 5° results,
583 advection generally degrades the detection of SSS reemergence, while only slightly
584 affecting SST reemergence. This is particularly striking in the northeastern domain (Fig.
585 10a), where the first SSS reemergence peak is negligible and the second one is narrower,
586 independent of the starting date (not shown). However, this may be due in part to the
587 larger SSS anomaly persistence along the trajectories. In the western subtropics (Fig.
588 10b), the first remote SSS reemergence peak is stronger than the local one in Fig. 8b,
589 while the second peak is smaller, still occurring too early (in October) for reemergence,
590 and no remote SST reemergence is apparent. There is no convincing indication of SSS or
591 SST reemergence along floats issued from the eastern subtropical region (Fig. 10c), but

592 note that the SSS anomalies are very persistent. Finally, the first SST and SSS
593 reemergence peaks for trajectories issued from the southeastern domain (Fig. 10d) are
594 as large as without advection, but only hint of the second SSS reemergence peak remains.
595 Hence, even for larger domains, taking advection into account mostly degrades
596 reemergence detection.

597

598 **4. Summary and discussion**

599 The Atlantic SSS fields constructed from observations by RKFD07 have been
600 extended to the 1970-2016 period. The raw SSS data are rather sparse, except along VOS
601 lines and when many Argo floats became available. The monthly SSS was gridded in
602 30°S-50°N using objective mapping at 1°x1° spatial resolution. The reemergence of SSS
603 anomalies was investigated between 20°N and 50°N during the 1993-2016 period, when
604 the sampling was improved and surface geostrophic currents derived from satellite
605 measurements became available. To do so, the objective fields were binned in 5°x5°
606 squares if at least 3 values (among 25) were available. Although the binning results in
607 rather complete data set for most boxes, it is based on raw data whose density often
608 ranges between 10 and 35% before objective mapping. Hence, the monthly SSS anomaly
609 fields have limited accuracy and are sensitive to eddy and instrumental noise. In
610 addition, there are large low-frequency SSS fluctuations that may obscure reemergence
611 in the short 24-year data set. Nonetheless, the new data set has allowed us to detect for
612 the first time SSS reemergence in observations.

613 SSS reemergence was first investigated locally in each 5°x5° box, using seasonal auto-
614 correlation functions with a February, March, or April starting month, in relation to the
615 climatological seasonal cycle of the mixed layer depth. For comparison, the local SST
616 anomaly reemergence was also investigated in the same 1993-2016 period. Although
617 one expects that the SSS and SST autocorrelations should be broadly similar when there

618 is reemergence, there were differences in the occurrence and the timing of the
619 reemergence peak. This suggests that SSS and SST are affected differently by data
620 availability, noise, and low-frequency fluctuations. In addition, SST and SSS anomalies
621 should be affected differently by anomalous advection where the climatological SST and
622 SSS gradients do not correspond, and by mean advection when their spatial scale differs.

623 The results were separated, albeit somewhat subjectively, into cases with clear
624 reemergence, hints of possible reemergence, and no reemergence (Fig. 7). Both SSS and
625 SST reemergence are clearly seen locally in most boxes of the northeastern corner,
626 where the winter mixed-layer depth is deep (de Boyer et al. 2004; Carton et al. 2008;
627 Sallée et al. 2021) and the seasonal range generally exceeds 100 m. Interestingly, the
628 correlation between the wintertime SST and SSS anomalies is generally large (up to 0.66
629 in 30°-20°W, 45°-50°N), suggesting that they were largely driven by the same
630 atmospheric fluctuations and/or similar low-frequency oceanic variability. Although the
631 winter mixed-layer is rather shallow and the seasonal range limited, SSS and SST
632 reemergence are largely seen in the southeastern part of the domain and, to a lesser
633 extend, the northwestern corner. Puzzlingly, SSS reemergence was detected or hinted at
634 in several boxes between 30°N and 40°N, west of 60°W, while no local SST reemergence
635 was seen, although it was found in Deser et al. (2003), de Coëtlogon and Frankignoul
636 (2003), and Hanawa and Sugimoto (2004) in longer data sets. On the other hand, there is
637 limited evidence of SSS reemergence in the central part of the domain, presumably
638 because of limited sampling since SST reemergence is largely found there. In the eastern
639 subtropical gyre, east of 35°W, there is no SST reemergence nor, albeit in a narrower
640 domain, SSS reemergence, as expected from a rather high correlation between SSS and
641 SST anomalies. The lack of SST reemergence in the eastern subtropical gyre is consistent
642 with previous studies (Deser et al. 2003; de Coëtlogon and Frankignoul 2003; Hanawa
643 and Sugimoto 2004; Byju et al. 2018), and it has been attributed to oceanic subduction,

644 strong oceanic heat loss, and, for the North Atlantic Madeira mode water (Sugimoto and
645 Hanawa 2005), vigorous salt-finger mixing. A small seasonal range of mixed layer depth
646 has also been invoked, but the range is actually large ~ 100 m and unlikely to be a
647 contributing factor.

648 Overall, local SSS reemergence was detected in 27 of the 57 $5^\circ \times 5^\circ$ boxes, and hinted
649 at in 9 others, while SST reemergence was detected in 31 boxes and hinted at in 11
650 others. Hence, while SST reemergence is seen more often than SSS reemergence, the
651 number of clear SST reemergence cases remains limited. This reflects in part the short
652 duration (24 years) of the investigated period, which makes the correlation analysis
653 sensitive to sampling errors and low frequency fluctuations and eddy noise.

654 To investigate longer spatial and temporal scales, and whether a second or third
655 reemergence peak could be seen, the SSS and SST anomalies were averaged over broader
656 domains, thus reducing the impact of data noise, small-scale fluctuations, and advection.
657 In the northeastern region (40° - 20° W, 40° - 50° N), a first, a second and a third SSS
658 reemergence peaks were seen, with even hints of a fourth one, resulting in a very long
659 persistence (e-folding time of about 4 years) of the large-scale SSS anomalies in the cold
660 season. As expected from the negative heat flux feedback (e.g., Frankignoul and
661 Kestenare 2002) that damps SST anomalies when they are in contact with the
662 atmosphere while SSS anomalies are little affected, the persistence of the wintertime SST
663 anomalies is smaller, as noted by Alexander et al. (2011), and only a second SST
664 reemergence peak, albeit noisy, could be seen. In the western subtropical gyre region
665 (60° - 35° W, 30° - 40° N), only a first reemergence peak was seen for the SST anomalies and,
666 less convincingly, the SSS anomalies, consistent with the $5^\circ \times 5^\circ$ box results. In the eastern
667 subtropical gyre region (35° - 20° W, 30° - 40° N), there was no first SSS or SST reemergence
668 peak, as in the $5^\circ \times 5^\circ$ boxes, but there were peaks that could reflect a second and a third
669 SSS reemergence, or be accidental in view of the lack of first reemergence. In the

670 southeastern region (50° - 20° W, 20° - 30° N), a first, a second and hints of third
671 reemergence peaks were found for the SSS anomalies, which thus decay faster than in
672 the northeast, consistent with the smaller winter mixed-layer depth. In contrast, only a
673 first SST reemergence could be clearly seen, reflecting again that wintertime SSS
674 anomalies are more persistent than SST anomalies. In longer data sets, a second SST
675 reemergence peak had been found for the main mode of North Atlantic SST variability,
676 namely the North Atlantic SST anomaly tripole (Watanabe and Kimoto 2000; Deser et al.
677 2003; de Coëtlogon and Frankignoul 2003). However, as the EOF gives substantial
678 weight to SST anomalies in both the northeastern and the southeastern domains, the
679 second reemergence may reflect the behavior of the more persistent northeastern
680 region.

681 To verify that the correlation peaks that we attributed to SSS reemergence
682 correspond to the re-surfacing of the deep wintertime salinity anomalies by entrainment
683 when the mixed layer is deepening, the GLORYS2v4 reanalysis was considered during
684 the 2005-2018 period when ARGO floats lead to a large number of salinity profiles.
685 Although in many 5° \times 5° boxes, the 2005-2016 period was often too short to show
686 consistency between the seasonal correlations obtained from our data set and the
687 reanalysis, or those obtained in the whole 1993-2016 period, there were several boxes in
688 the northeastern and southeastern domains that showed consistent reemergence peaks.
689 To optimize the relation with subsurface salinity data in these regions, averaged salinity
690 anomalies were constructed for two larger domains, (35° - 20° W, 20° - 30° N) and (30° -
691 20° W, 40° - 45° N). At both sites, the correlation between late winter surface or near-
692 surface salinity anomalies and subsurface salinity at increasing lag clearly showed that
693 the late winter salinity anomalies are indeed capped by the seasonal thermocline during
694 late spring and summer, and are then re-mixed in the surface mixed layer by
695 entrainment during its fall deepening, leading to a winter correlation peak with the

696 surface salinity in the previous winter. This confirms that SSS reemergence can indeed be
697 well detected from SSS anomaly alone when the sampling is sufficiently large.

698 To take into account advection by the ocean currents that could lead to remote
699 reemergence (rather than occurring locally), the analysis was also performed along a
700 large ensemble of 24-month virtual float trajectories based on the daily estimates of the
701 AVISO surface geostrophic currents. However, this neglects geostrophic shear, perhaps
702 leading to an overestimate of the advection during summer, as well as Ekman currents,
703 which may play a role in late autumn and winter when the mixed layer is deep. It also
704 neglects vertical advection, which may be large in regions of strong subduction or
705 obduction. This may explain why, contrary to expectations, there were fewer $5^\circ \times 5^\circ$ boxes
706 for which remote SSS and SST reemergence could be clearly identified. In particular,
707 there was much less evidence of SSS reemergence along trajectories issued in the 45° -
708 50°N band, likely because of limited data density and no SSS data availability north of
709 50°N when interpolating SSS along the trajectories that escape the domain (8 to 9%), and
710 perhaps also because of our use of surface geostrophic currents, although remote SST
711 reemergence was largely seen. Little remote SSS or SST reemergence was clearly
712 identified for anomalies issued west of 55°W , perhaps because of the larger dispersion of
713 the trajectories caused by the strong eddy activity in the western North Atlantic. On the
714 other hand, remote SSS reemergence was better seen along trajectories issued in the
715 central part of the basin than local one. Along trajectories issued from boxes between
716 20°N and 25°N , little remote SSS reemergence was detected, and clear remote SST
717 reemergence only seen west of 40°W , as in de Coëtlogon and Frankignoul (2003). This
718 may be linked to shallower mixed layers and small seasonal mixed-layer depth range
719 (Byju et al. 2018, Fig. A2) south of 20°N . Overall, remote SSS reemergence was clearly
720 seen when issued from 21 boxes instead of being seen locally in 24 boxes (in the same

721 domain). Similarly, there were fewer clear cases of remote SST reemergence (21 versus
722 29), although more cases with hints of remote SST reemergence.

723 Remote reemergence along the artificial float trajectories was also investigated for
724 the four large domains, although shorter lags could only be considered because of the
725 limited duration of the trajectories. Consistent with the analysis based of 5° x 5° boxes,
726 taking advection into account generally tended to degrade the detection of large-scale
727 SSS reemergence. However, it did not substantially affect the detection of SST
728 reemergence, presumably because of the better SST data.

729 This study has focused on the detection of SSS anomaly reemergence and persistence
730 in a purely observational data set, while the implications of our results for ocean
731 circulation remain to be explored. Unfortunately, poor data coverage prevented us from
732 considering SSS anomalies in the subpolar regions, where they critically affect the
733 subpolar gyre and the meridional overturning circulations. Better coverage will be
734 provided in the future by satellite-derived SSS products such as the weekly or monthly
735 CCI SSS (multi-mission SSS product from the climate change initiative
736 (Sea_Surface_Salinity_cci v2.31) project
737 (doi:10.5285/4ce685bff631459fb2a30faa699f3fc5), but the time series are too short at
738 present. However, such analysis could be attempted using reanalyzed products, oceanic
739 model hindcasts, and climate models, with the present results used as a benchmark for
740 validating them.

741

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748 useful comments, and the three anonymous reviewers for their constructive comments
749 that substantially improved earlier versions of the manuscript. The gridded Sea surface
750 salinity data is made freely available by the French Sea Surface Salinity Observation
751 Service (<http://sss.sedoo.fr/#GriddedProductMetadataPlace:ATLANTIC>).

752

753 **Appendix 1: Climatological mixed layer depth**

754

755 Sallée et al. (2021) have estimated the global seasonal cycle of the mixed layer depth on a
756 $0.5^\circ \times 0.5^\circ$ grid, using temperature and salinity profiles from a number of different sources
757 between 1970 and 2018, and a density threshold of 0.03 kg m^{-3} . After removing the mean
758 seasonal cycle, the SSS anomalies were binned into the $5^\circ \times 5^\circ$ North Atlantic boxes used
759 in this study, providing key information for reemergence. Figure A1 shows the maximum
760 and the minimum mixed layer depth with their month of occurrence, and Figure A2 gives
761 the range of seasonal mixed layer variations. However, as they reflect spatially averaged
762 properties, values within each box may have much larger ranges.

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764 **Appendix 1: Seasonal auto-correlation in 30° - 35° N**

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840 **Figure captions**

841

842 Figure 1. (Top) Time evolution of the number of $1^\circ \times 1^\circ$ grid points per year included in
843 the analysis as a function of year for 1970-2016 (there are on the order of 65,000 grid
844 points-months in a year) and (Bottom) their spatial distribution, in number of months
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847

848 Figure 2. Percentage of data points in each $5^\circ \times 5^\circ$ box before (left) and after (right)
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853 estimates (among 288) are indicated. Red indicates that the objective analysis provided
854 less than 3 values.

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856 Figure 4. Mean 2-year trajectory (black lines) of the virtual floats issued in March from
857 each $5^{\circ} \times 5^{\circ}$ box. The mean trajectory of the virtual floats deployed in each of the 22
858 successive 2-years are shown in different colors for five selected boxes.

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860 Figure 5. Seasonal auto-correlation starting in March for various boxes without or with
861 quadratic detrending, as indicated. The box location is given. The x-axis indicates the
862 months of the year, not the lag (for instance, months 3 and 15 indicate March). Red is for
863 SSS and blue for SST. The 10% significance level for complete data is indicated (dashed
864 line).

865

866 Figure 6. Seasonal auto-correlation following the time-varying surface geostrophic flow
867 (in blue) and estimated locally (in red) for the (40° - 45° N) boxes (location is indicated).
868 The starting month is March and a linear trend is removed, unless another month or
869 quadratic detrending (as indicated) gave better evidence of local SSS reemergence. The
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888 2005-2018 period. The 10% significance level is 0.47 until lag 9 and 0.48 until lag 21.

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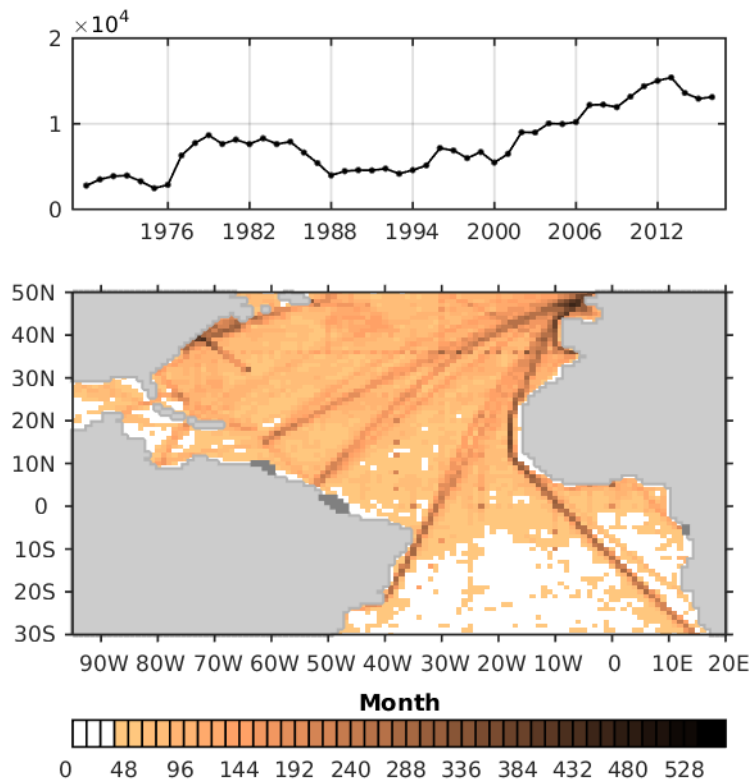
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910 **Figures**

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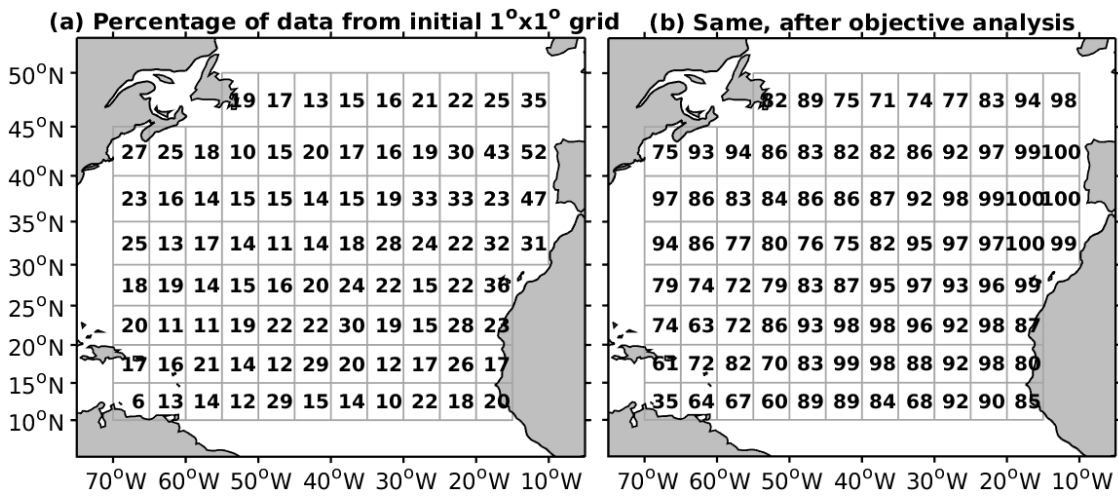
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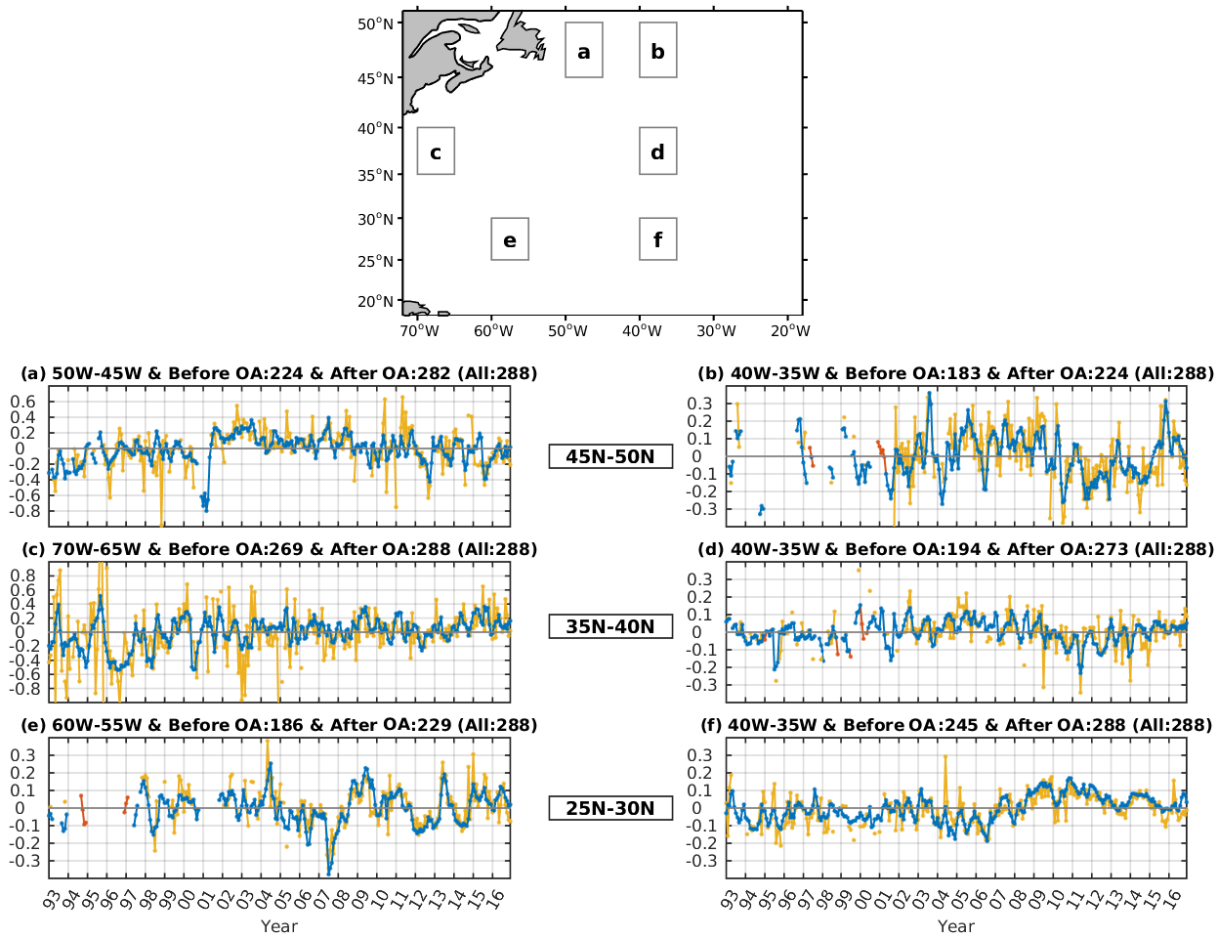
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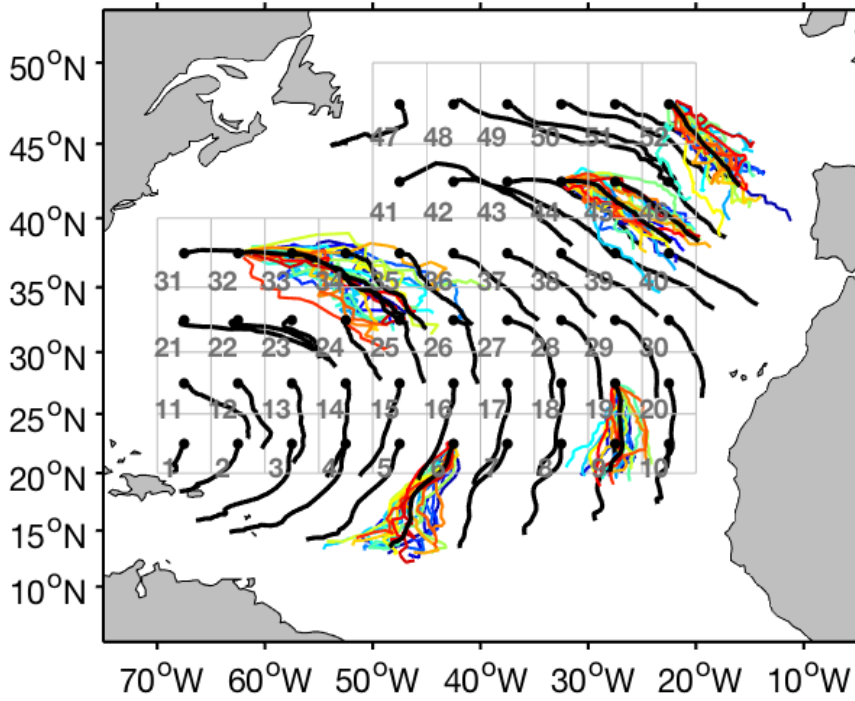
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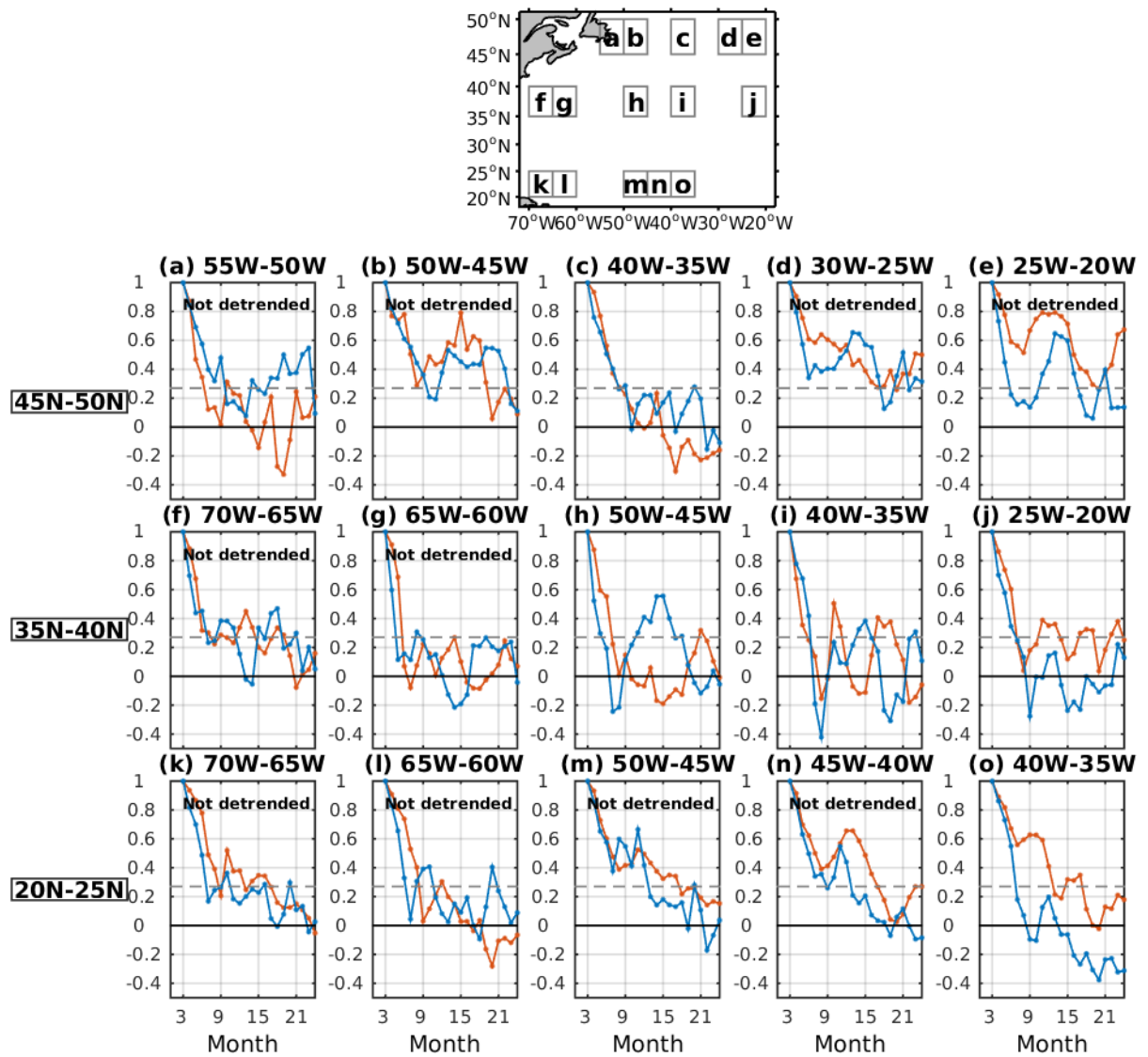
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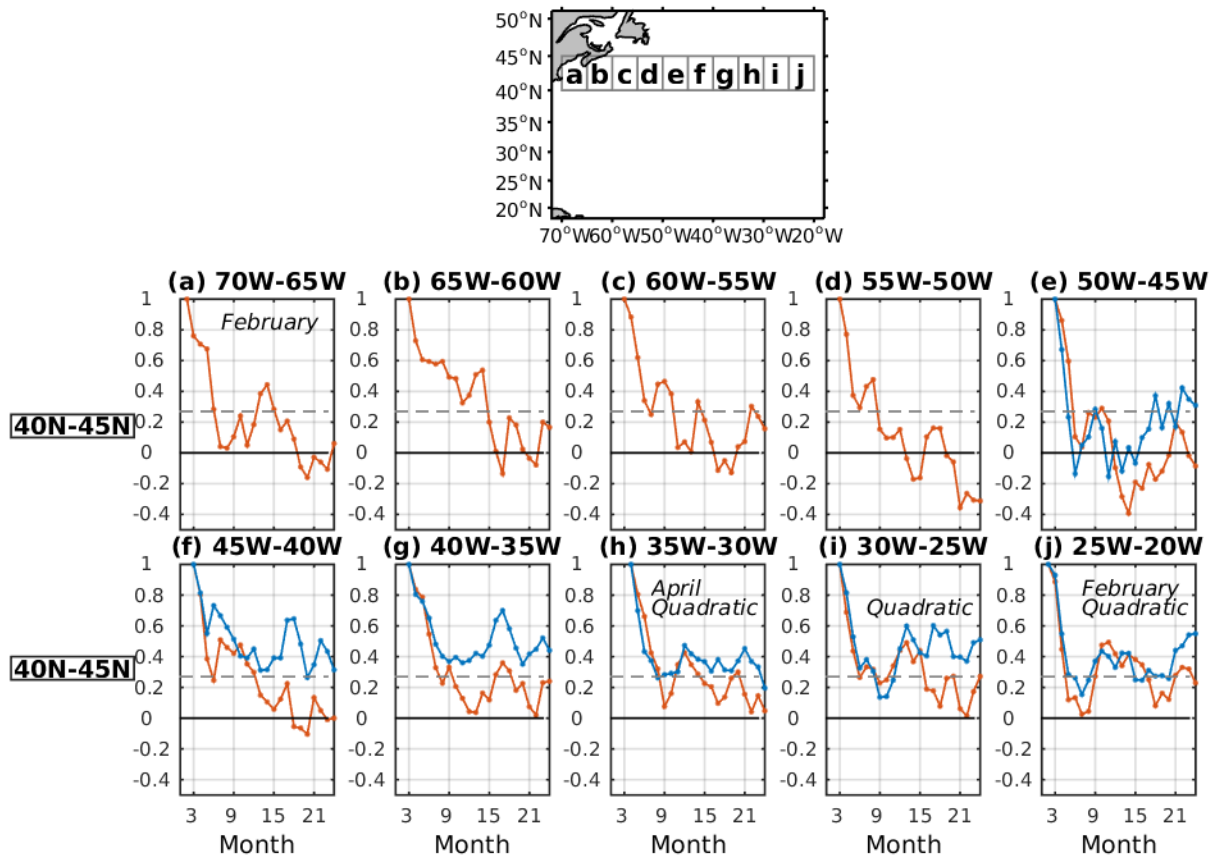
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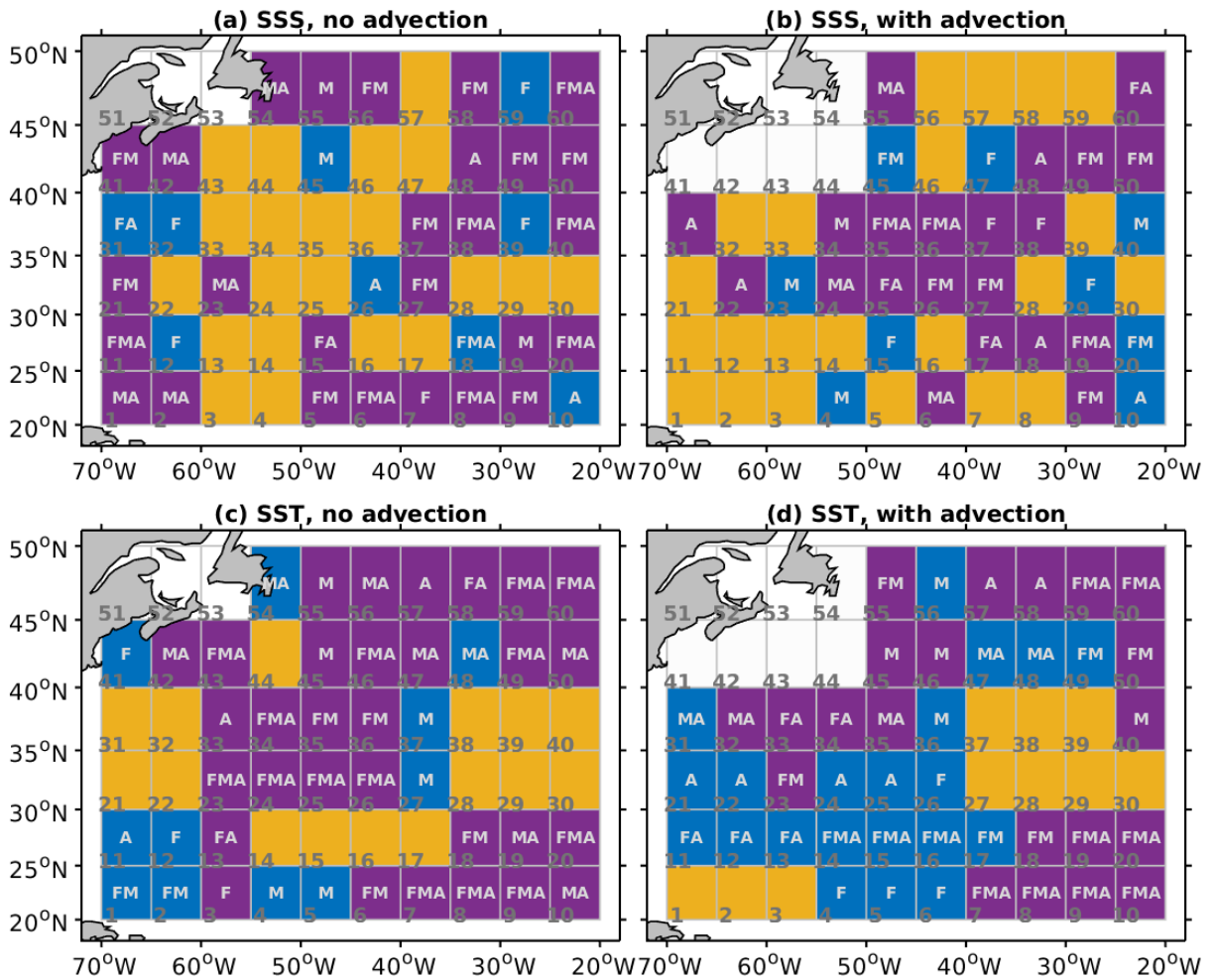
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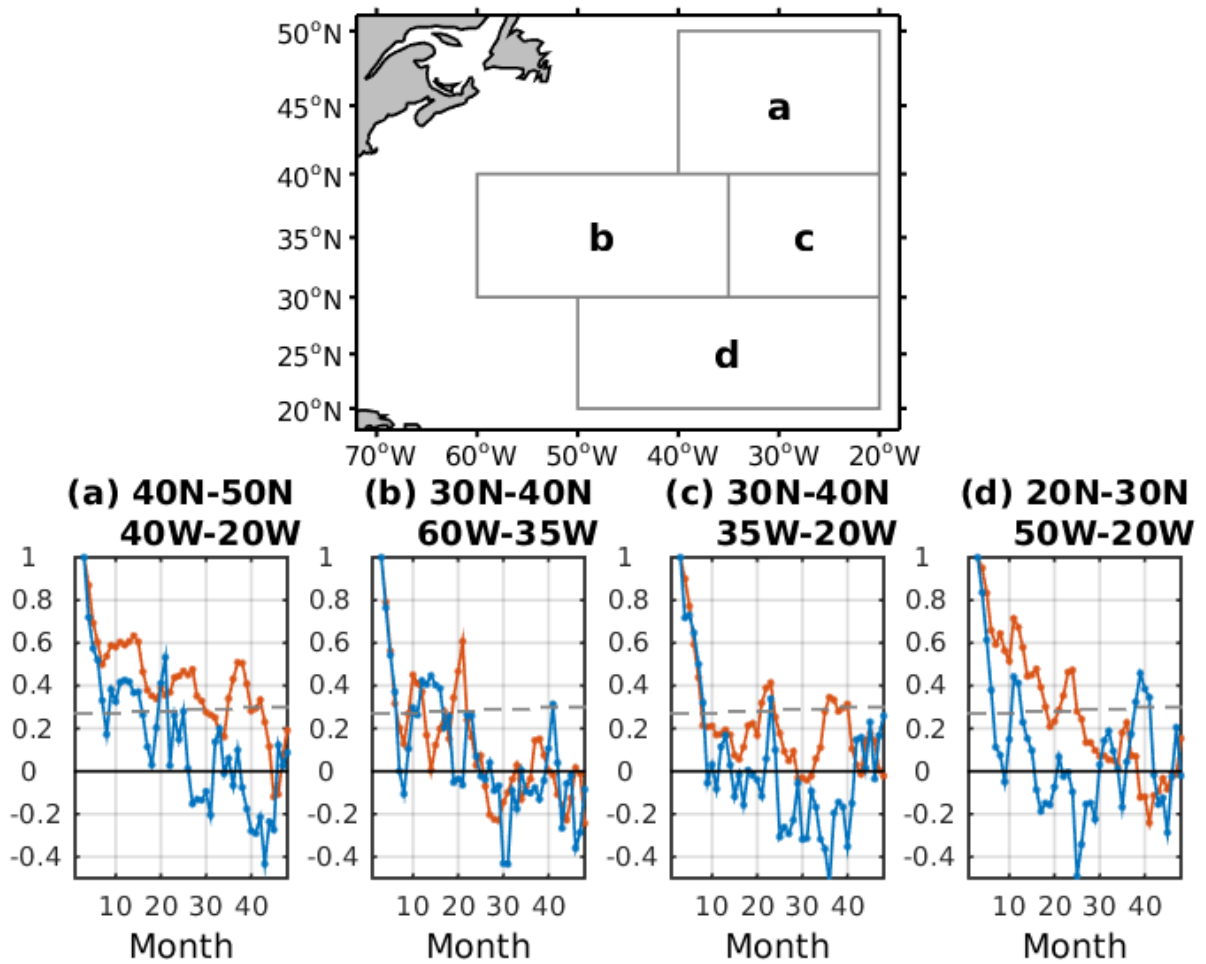
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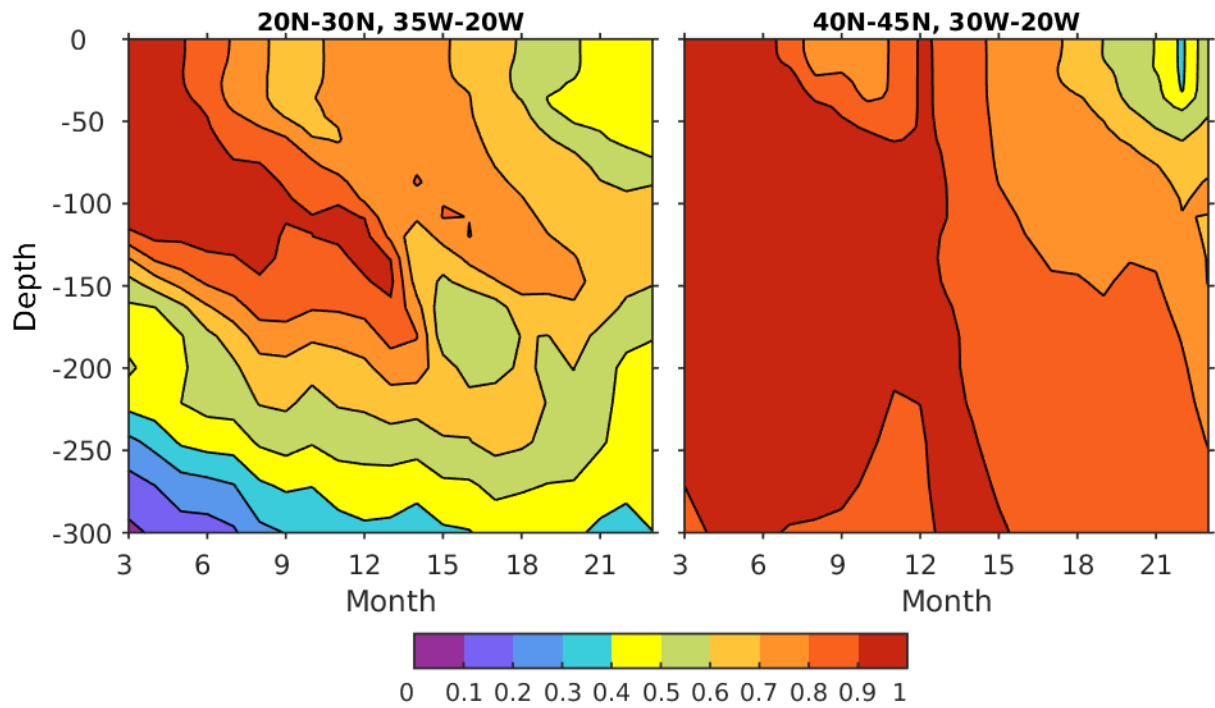
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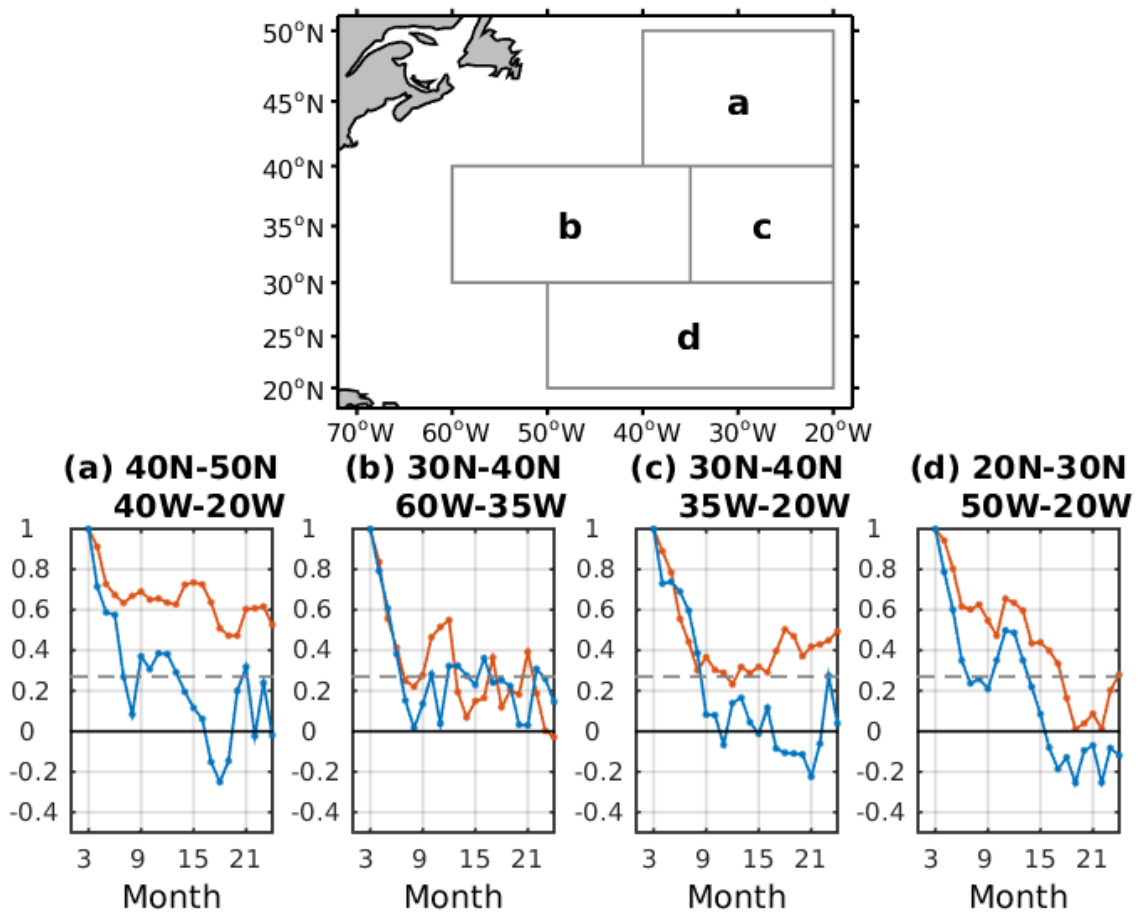


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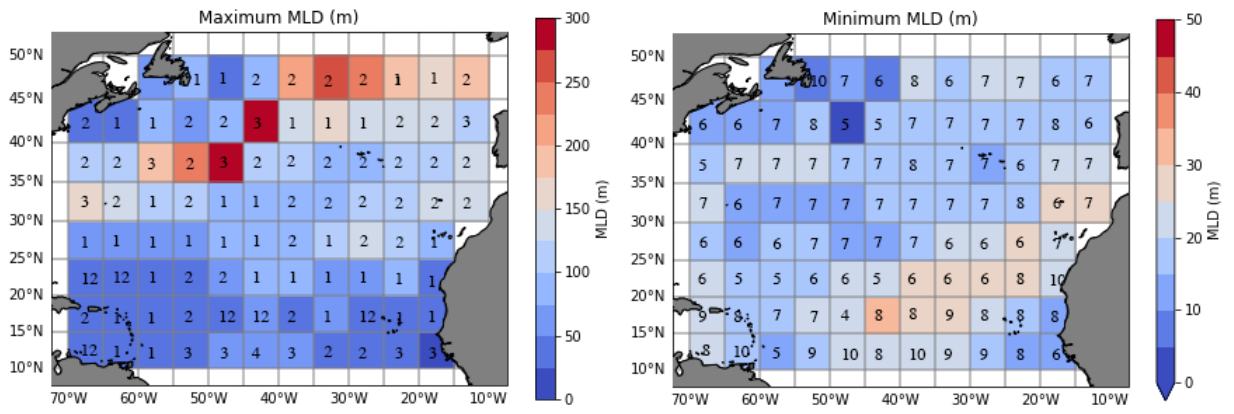
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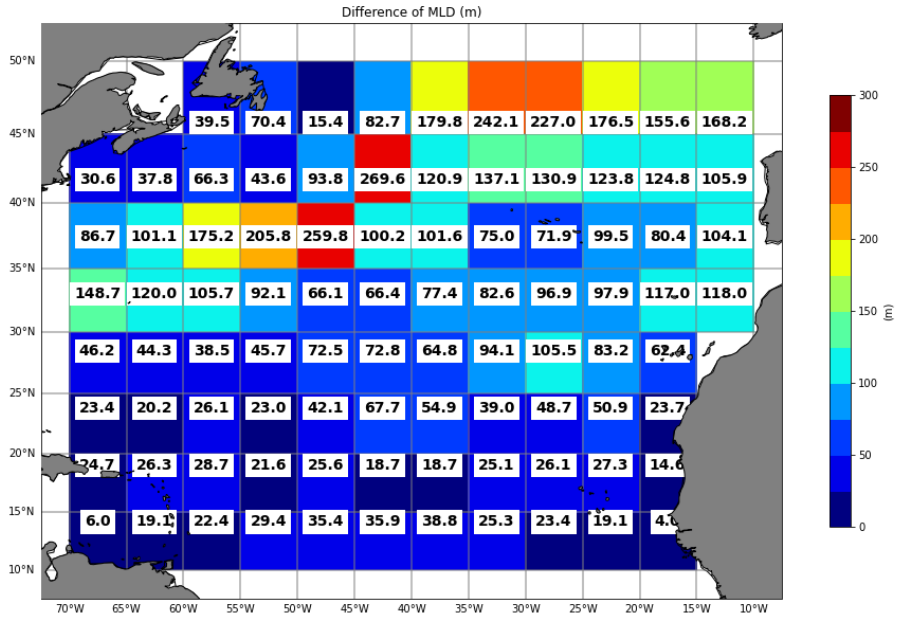
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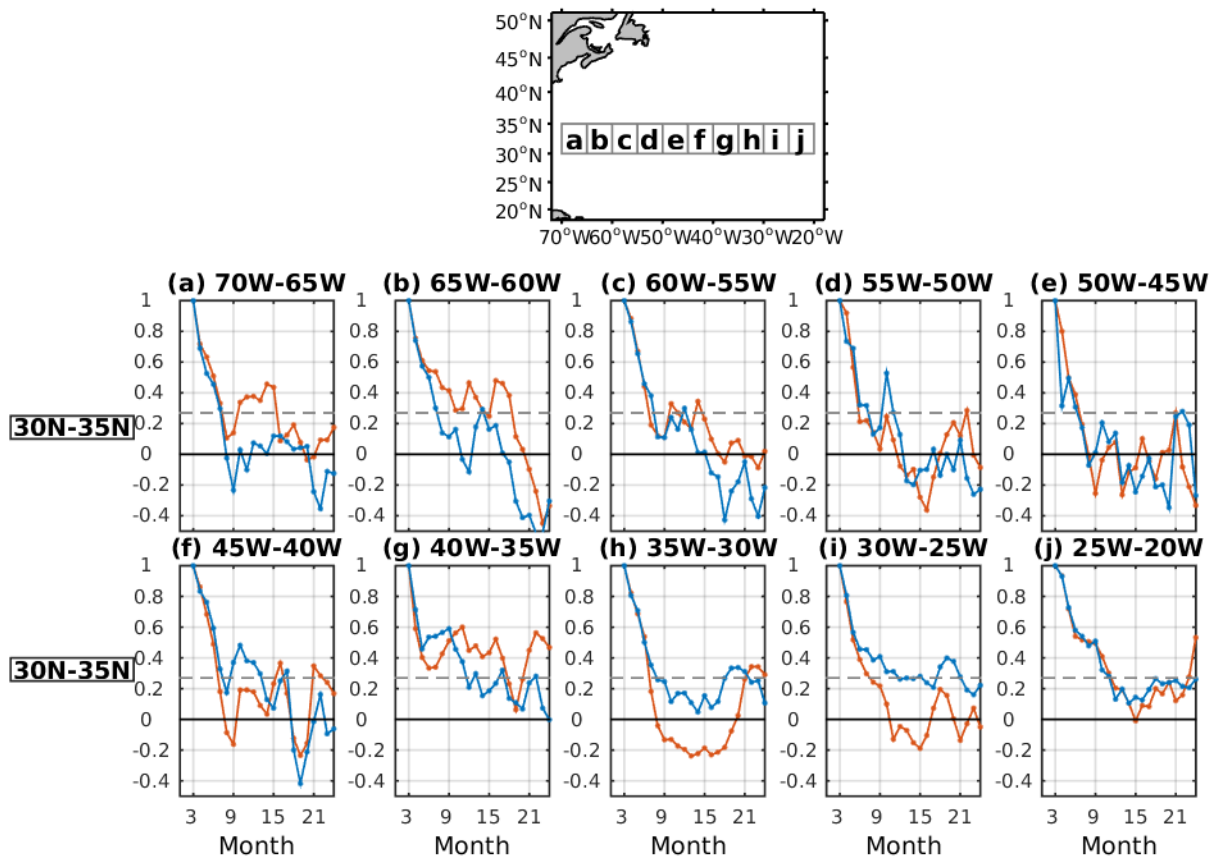


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