

Insights into decadal North Atlantic sea surface temperature and ocean heat content variability from an eddy-permitting coupled climate model

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1 **Insights into decadal North Atlantic sea surface temperature and ocean heat**
2 **content variability from an eddy-permitting coupled climate model**

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27 surface temperature, Atlantic multidecadal variability, high resolution climate
28 modelling, North Atlantic, North Atlantic subpolar gyre

29

30 **Abstract**

31 An ocean mixed layer heat budget methodology is used to investigate the physical
32 processes determining subpolar North Atlantic (SPNA) sea surface temperature (SST)
33 and ocean heat content (OHC) variability on decadal-multidecadal timescales using the
34 state-of-the-art climate model HadGEM3-GC2. New elements include development of
35 an equation for evolution of anomalous SST for interannual and longer timescales in a
36 form analogous to that for OHC, parameterization of the diffusive heat flux at the base
37 of the mixed layer and analysis of a composite AMOC event. Contributions to OHC
38 and SST variability from two sources are evaluated i) net ocean-atmosphere heat flux
39 and ii) all other processes, including advection, diffusion and entrainment for SST.
40 Anomalies in OHC tendency propagate anticlockwise around the SPNA on
41 multidecadal timescales with a clear relationship to the phase of the Atlantic meridional
42 overturning circulation (AMOC). AMOC anomalies lead SST tendencies which in turn
43 lead OHC tendencies in both the eastern and western SPNA. OHC and SST variations
44 in the SPNA on decadal timescales are dominated by AMOC variability because it
45 controls variability of advection which is shown to be the dominant term in the OHC
46 budget. Lags between OHC and SST is traced to differences between the advection
47 term for OHC and the advection-entrainment term for SST. The new results have
48 implications for interpretation of variations in Atlantic heat uptake in the CMIP6
49 climate model assessment.

50

51 **1. Introduction**

52 The North Atlantic undergoes variations in sea-surface temperature (SST) on
53 multidecadal timescales (e.g. Kerr 2000; Francombe et al. 2008; Chylek et al. 2011;
54 Vianna and Menezes 2013), with impacts on the climate of adjacent land areas (e.g.,
55 Enfield et al., 2001; Knight et al. 2006; Msadek and Frankignoul 2009; Sutton et al.
56 2012 and 2018) and beyond (Lu et al. 2006; Zhang and Delworth, 2006). These SST
57 variations are widely referred to as Atlantic Multidecadal Variability (AMV).

58 A variety of mechanisms have been proposed to drive AMV, including external
59 forcing by anthropogenic aerosols (Booth et al. 2012), and/or volcanoes (Otterå et al.
60 2010; Swingedouw et al. 2017), atmospheric forcing (Clement et al. 2015), internal
61 oceanic variability (Sévellec and Fedorov, 2013; Gastineau et al., 2018) and coupled
62 ocean-atmosphere modes of variability involving the Atlantic Meridional Overturning
63 Circulation (AMOC, Knight et al. 2005; Ortega et al. 2015). Atmospheric feedbacks
64 are also likely to play a crucial role in setting the AMV pattern (Xie, 2009). There is as
65 yet little consensus on the precise mechanism as AMV simulation varies from model to
66 model in both phenomenology and driving processes (Drews and Greatbatch, 2017;
67 Muir and Fedorov, 2017; Sévellec and Sinha 2018; Sutton et al. 2018).

68 Observational studies are hindered by the relatively short instrumental record which
69 captures only one or two AMV cycles and lacks information on other variables such as
70 the AMOC. Recent studies have instead utilised AMOC proxies, for example McCarthy
71 et al. (2015) use a sea-level based indirect proxy of the AMOC to demonstrate a link
72 between the AMOC, OHC in the top 500m and AMV from the 1920s to the 2000s.

73 The link between AMOC and upper ocean OHC is well established in modelling
74 studies (Robson et al., 2012; Zhang 2008; Zhang and Zhang, 2015). There is a strong
75 correlation between subtropical AMOC and meridional heat transport (MHT) found in

76 models (Sévellec and Huck, 2015; Moat et al. 2016) and observations (Johns et al.
77 2011). Grist et al. (2010) found, in a model based analysis for 1958-2002, that the
78 subpolar gyre OHC anomaly was more strongly correlated with the ocean heat transport
79 convergence ($r=0.75$) than with surface fluxes ($r=0.5$). Similarly, Robson et al. (2014,
80 2018) and Hodson et al. (2014) found the AMOC and its associated ocean heat transport
81 was the dominant process in the 1990s warming and the 1960s cooling of the subpolar
82 gyre. Likewise, Williams et al. (2014, 2015a), using a model which was strongly
83 relaxed to observed temperature and salinity, attributed decadal changes in subpolar
84 gyre OHC to changes in the AMOC.

85 Whatever the detailed mechanisms and drivers of the AMV, it seems likely that
86 horizontal ocean heat transport convergence and surface fluxes of heat will both play
87 important roles. However the key relationship between changes in oceanic heat
88 transport, OHC and SST is not well understood, particularly on multidecadal timescales
89 which is the focus of this paper.

90 A number of studies have attempted to identify fingerprints of changing AMOC
91 directly on the SST, thus bypassing the need to examine OHC. However, the results
92 from climate models are variable (Roberts et al. 2013; Zhang 2008) and although there
93 is now evidence of a similar pattern associated with the limited duration observational
94 record (Smeed et al. 2018), without a verified mechanism it is difficult to be confident
95 in these fingerprints.

96 A more rigorous approach was adopted by Buckley et al. (2014) where interannual
97 heat content was evaluated over the depth of the monthly maximum climatological
98 mixed layer, i.e. the portion of the upper ocean in contact with the atmosphere. Using
99 the ECCO state estimate for the period 1992-2010 they estimate that 70% of the
100 variability in mixed layer heat content is explained by local forcing (i.e. air sea heat

101 fluxes and Ekman convergence) and only 30% due to advection over large parts of the
102 North Atlantic. Their use of the monthly maximum mixed layer was an improvement
103 over previous studies which employ a spatially constant depth horizon. However, due
104 to the length of the simulation they were unable to address multidecadal time scales.

105 The Buckley et al. (2014) approach was extended to the global domain by Roberts
106 et al. (2017) who used a similar theoretical framework, including a spatially variable
107 maximum mixed layer depth (MLD) to differentiate the near-surface layer in contact
108 with the atmosphere from the rest of the ocean. Unlike Buckley et al. (2014) they used
109 observationally based gridded OHC products and surface fluxes from atmospheric
110 reanalyses with a Kalman filter based method to obtain an estimated heat budget with
111 error bounds for both the mixed layer and the rest of the ocean, evaluating ocean heat
112 transport convergence as a residual. Their results indicated that on interannual
113 timescales there are extensive regions (equator and western boundary currents and the
114 Antarctic Circumpolar Current) where ocean heat transport convergence dominates the
115 OHC variability of the mixed layer and over large parts of the rest of the ocean both
116 ocean heat transport convergence and surface heat fluxes are important. This contrasts
117 with the full depth OHC which on these timescales is dominated by ocean heat transport
118 convergence.

119 In this paper we consider temperature changes in the mixed layer, taking account of
120 its time varying depth using the SST evolution equation described by Stevenson and
121 Niiler (1983) paying particular attention to the diffusive flux at the base of the mixed
122 layer.

123 We address the following questions using a state of the art coupled climate model
124 which we demonstrate has realistic Atlantic multidecadal variability:

- 125 (1) What controls the multidecadal evolution of full depth OHC in the subpolar
 126 North Atlantic? What are the respective roles of ocean surface fluxes versus
 127 internal ocean processes? Is there a difference between the deep convection
 128 regions to the west and the region further east which is more influenced by
 129 the North Atlantic Current?
- 130 (2) What controls the multidecadal evolution of SST in the subpolar North
 131 Atlantic? Are the respective roles of surface fluxes and internal ocean
 132 processes similar and if not how do they differ?
- 133 (3) What is the relationship between changes in the deep (sub mixed layer) OHC
 134 and SST? How and why are the forcing terms different?
- 135 (4) How do both deep OHC and SST depend on the AMOC?

136 We focus on the subpolar North Atlantic (SPNA) as the AMV spatial pattern is
 137 strongly concentrated in this region (e.g. Sutton et al., 2018). In contrast, subtropical
 138 AMV is thought to be caused by relatively rapid (months to a few years) adjustment of
 139 the subtropical ocean to changes in the subpolar gyre via boundary waves (Johnson and
 140 Marshall 2002), or by atmospheric feedbacks to SPNA variability (Sutton et al. 2018).

141 The paper is organized as follows. We use a rigorous theoretical framework for
 142 comparing OHC and SST variability in Section 2. Details of the model configurations
 143 and methodology are given in Section 3. The results are presented in Section 4 and
 144 conclusions in Section 5.

145 **2 Theory**

146 **2.1 Full Depth Ocean Heat Content**

147 We define the full depth ocean heat content per unit area (Θ_{FD}) as

$$148 \quad \Theta_{FD}(\lambda, \varphi, t) = \rho_0 C_P \int_{H(\lambda, \varphi)}^0 \theta(\lambda, \varphi, z, t) dz \quad (1)$$

149 where λ and φ are longitude and latitude, respectively; t , time; z , depth (increasing
 150 upwards); θ , potential temperature, and H , local water depth. ρ_0 and C_p are a reference
 151 seawater density and specific heat capacity respectively

152 Changes in θ_{FD} at any given location can be caused by heating/cooling at the air-
 153 sea interface (Q_{NET}) or by horizontal advection and/or diffusion (considered here as one
 154 term, R_{FD}) resulting in a simple evolution equation:

$$155 \quad \frac{\partial \theta_{FD}}{\partial t} = Q_{NET} + R_{FD} \quad (2)$$

156 Observationally, $\partial \theta_{FD} / \partial t$ can be estimated from Eq. (1) using ocean temperature
 157 measurements, Q_{NET} using atmospheric reanalysis and hence R_{FD} as a residual,
 158 although for climate relevant time and space scales, each term would carry considerable
 159 uncertainty. Alternatively, a heat-conserving climate model simulation can provide
 160 exact $\partial \theta_{FD} / \partial t$ and Q_{NET} , with R_{FD} again evaluated as a residual, for comparison with
 161 observed estimates. In principle, in a climate model R_{FD} could be calculated directly
 162 rather than as a residual, but in practice this is rather difficult because diffusive as well
 163 as advective lateral transport convergences would be required, and these were not stored
 164 for the simulation used in this study.

165 Eqs. (1) and (2) could equally be evaluated over different depth horizons if $H(\lambda, \varphi)$
 166 in (1) is replaced by a fixed depth taking bottom topography into account. We examine
 167 the sensitivity of our results to choice of depth horizon in Section 4.5.

168 **2.2 Sea-surface temperature**

169 We employ the mixed layer temperature evolution equation derived by Stevenson
 170 and Niiler (1983)

$$171 \quad h \frac{\partial T_a}{\partial t} + h \mathbf{v}_a \cdot \nabla T_a + \nabla \cdot \left(\int_{-h}^0 \hat{\mathbf{v}} \hat{T} dz \right) + (T_a - T_{-h}) \left(\frac{\partial h}{\partial t} + \mathbf{v}_{-h} \cdot \nabla h + w_{-h} \right) =$$

$$172 \quad (Q_{NET} - Q_{-h}) / \rho_0 C_p \quad (3)$$

173 where h is the mixed layer depth, \mathbf{v}_a is the vertical average within the mixed layer
 174 of the horizontal velocity vector, $\hat{\mathbf{v}}$ and \hat{T} respectively are deviations of the horizontal
 175 velocity and temperature from their vertically averaged values, \mathbf{v}_{-h} , T_{-h} , w_{-h} and Q_{-h}
 176 are the horizontal velocity, temperature, vertical velocity and diffusive heat flux at the
 177 base of the mixed layer.

178 Neglecting horizontal diffusion, changes in the ocean temperature averaged over
 179 the mixed layer, T_a , at any given location can be caused either by heating/cooling at the
 180 air-sea interface, Q_{NET} , or by horizontal advection, vertical advection/diffusion of heat,
 181 and entrainment/detrainment of fluid into or out of the mixed layer:

182 Defining ξ to be the sea surface temperature and substituting $T_a = \xi - (\xi -$
 183 $T_a)$, Eq. (3) can be recast into a simpler form analogous to Eq. (2):

$$184 \quad \frac{\partial \xi}{\partial t} = \frac{Q_{NET}}{\rho_0 C_P h} + \frac{R_{ML}}{\rho_0 C_P h} \quad (4)$$

185 where

$$186 \quad \frac{R_{ML}}{\rho_0 C_P} = -h \mathbf{v}_a \cdot \nabla \xi - \nabla \cdot \left(\int_{-h}^0 \hat{\mathbf{v}} \hat{T} dz \right)$$

$$187 \quad -(T_a - T_{-h}) \left(\frac{\partial h}{\partial t} + \mathbf{v}_{-h} \cdot \nabla h + w_{-h} \right) - Q_{-h} / \rho_0 C_P + \frac{\partial(\xi - T_a)}{\partial t} \quad (5)$$

188 represents the aggregated effect of all internal ocean processes plus an error
 189 term, $\frac{\partial(\xi - T_a)}{\partial t}$ which indicates how well the SST tendency, $\frac{\partial \xi}{\partial t}$, approximates the depth
 190 averaged temperature tendency, $\frac{\partial T_a}{\partial t}$. We focus on SST because the AMV index, the
 191 main motivation of our study, is defined in terms of SST. Also, we would like to apply
 192 our method to observations in the future and T_a is not routinely available from
 193 observations, partly because mixed layer depth is not known with sufficient accuracy
 194 whereas there are many high quality SST data sets available. As for Eq. (2), each of the

195 terms in Eq. (4), with the exception of R_{ML} , can be diagnosed from climate model
 196 output, or from observations as long as the MLD is available as a function of time.
 197 However, observational data sets of the MLD are limited to monthly mean
 198 climatologies (e.g. de Boyer Montégut et al. 2004). The rate of change $\partial\xi/\partial t$ can be
 199 estimated from observed sea-surface temperature.

200 Once $\partial\xi/\partial t$ and Q_{NET}/h have been calculated, R_{ML}/h and R_{ML} can be evaluated as
 201 a residual from observations (with associated observational uncertainty), or exactly
 202 from a heat-conserving climate model.

203 ***2.3 Anomaly formulation***

204 As we are interested in decadal variations of heat content and SST, we recast Eqs.
 205 (1) and (4) in terms of anomalies from long term mean quantities. For the heat content,
 206 this is straightforward, we average Eq. (2) over sufficiently long timescales, the time
 207 derivative tends to zero and we obtain

$$208 \quad \overline{Q_{NET}} + \overline{R_{FD}} = 0 \quad (6)$$

209 where the overbar denotes a long term average. Subtracting Eq. (6) from Eq. (2) yields

$$210 \quad \frac{\partial \theta_{FD}^*}{\partial t} = Q_{NET}^* + R_{FD}^* \quad (7)$$

211 where the asterisk denotes a deviation from the long term mean value. We will refer to
 212 R_{FD}^* as the “advection” term (because lateral diffusion can be assumed to be small)
 213 and to Q_{NET}^* as the “surface flux” term. Note that, it is not always true that averaging
 214 over longer periods will result in an exact balance between $\overline{Q_{NET}}$ and $\overline{R_{FD}}$. However,
 215 for our analysis it is not a necessary condition. The only requirement is that mean values
 216 are removed from $\partial\theta_{FD}/\partial t$, Q_{NET} , and R_{FD} . This is the equivalent to detrending T and
 217 centering Q_{NET} , and R_{FD} on zero for the period of interest.

218 A similar procedure can be adopted for the SST using Eq. (4):

219
$$\left[\frac{Q_{NET}}{\rho_0 C_P h} \right] + \left[\frac{R_{ML}}{\rho_0 C_P h} \right] = 0 \quad (8)$$

220 leading to

221
$$\frac{\partial \xi^*}{\partial t} = \left[\frac{Q_{NET}}{\rho_0 C_P h} \right]^* + \left[\frac{R_{ML}}{\rho_0 C_P h} \right]^* \quad (9)$$

222 We will refer to $\left[\frac{Q_{NET}}{\rho_0 C_P h} \right]^*$ as the “unadjusted surface flux term” for SST and to $\left[\frac{R_{ML}}{\rho_0 C_P h} \right]^*$
 223 as the “unadjusted advection-diffusion-entrainment” term for reasons which will
 224 become clear shortly, however, for comparison with Eq. (7) this formulation is not very
 225 convenient. Instead we return to Eq. (4) and taking correlations between h^* and ξ^* into
 226 account (see Appendix 1) we obtain the following equation for the SST anomaly ξ^* :

227
$$\frac{\partial \xi^*}{\partial t} = Q_{NET}^* / \rho_0 C_P \bar{h} + \mathfrak{R}_{ML}^* / \rho_0 C_P \bar{h} \quad (10)$$

228 note that the denominator of the terms on the right hand side of Eq. (10) is the mean
 229 mixed layer depth, \bar{h} , not the instantaneous value, h , as in Eq. (4). Also \mathfrak{R}_{ML} is a
 230 different residual to R_{FD} .

231 The first term on the RHS of Eq. (10) represents “external” forcing of the SST by
 232 surface fluxes, whilst the second term represents trends due to “internal” processes in
 233 the ocean. These are analogous to Q_{NET}^* and R_{FD}^* in Eq. (7). The reasons for differing
 234 temporal evolution of SST and OHC are contained in Eqs. (7) and (10), in particular
 235 the difference between R_{FD}^* and \mathfrak{R}_{ML}^* . At any given point, if R_{FD}^* and \mathfrak{R}_{ML}^* were
 236 identical, $\rho_0 C_P \bar{h} \xi^*$ (and hence ξ^*) would have the same temporal evolution as θ_{FD}^* .
 237 Hence, we analyse the relationships between these terms later in order to understand
 238 differences between the time evolution of SST and OHC in the SPNA. We will refer to
 239 $Q_{NET}^* / \rho_0 C_P \bar{h}$ as the “surface flux” term for SST and to $\mathfrak{R}_{ML}^* / \rho_0 C_P \bar{h}$ as the
 240 “advection-entrainment” term.

241 **2.4 Parameterisation of diffusive vertical heat flux**

242 We will find that the terms on the right hand side of Eq. (10) are generally of
 243 opposite sign and $\frac{\partial \xi^*}{\partial t}$ is much smaller in magnitude than either, which makes it difficult
 244 to identify which term is most important. This is because the diffusive vertical heat flux,
 245 Q_{-h} , can be of the same order of magnitude as Q_{NET} in Eq. (3). We can therefore
 246 reformulate Eq. (8) as:

$$247 \quad \frac{\partial \xi^*}{\partial t} = \frac{Q_{NET}^*}{\rho_0 C_P \bar{h}} - \frac{Q_{-h}^*}{\rho_0 C_P \bar{h}} + \mathbb{R}_{ML}^* / \rho_0 C_P \bar{h} \quad (11)$$

248 Where \mathbb{R}_{ML} is yet another residual representing advection and entrainment, but
 249 excluding vertical diffusion. Q_{-h} is generally parameterised in models as a function of
 250 vertical temperature gradient $K \frac{\partial T}{\partial z}$, with K a time-variable diffusion coefficient. Here
 251 we adopt an even simpler approach and crudely parameterize it as a constant proportion
 252 of the surface heat flux anomaly $Q_{-h}^* = \lambda Q_{NET}^*$, where λ is a constant. This gives an
 253 alternative formulation for the SST tendency:

$$254 \quad \frac{\partial \xi^*}{\partial t} = \frac{(1-\lambda)Q_{NET}^*}{\rho_0 C_P \bar{h}} + \mathbb{R}_{ML}^* / \rho_0 C_P \bar{h} \quad (12)$$

255 Our motivation in this paper is to relate the SST variation to the full depth OHC
 256 variations, so we select a measure which will maximise the relationship between them.
 257 Therefore we determine the value of λ by requiring the strongest correlation between
 258 R_{FD}^* and \mathbb{R}_{ML}^* (see Section 4.4 and Appendix 2). We will refer to $\frac{(1-\lambda)Q_{NET}^*}{\rho_0 C_P \bar{h}}$ as the
 259 “adjusted surface fluxes” term for SST and to $\mathbb{R}_{ML}^* / \rho_0 C_P \bar{h}$ as the “adjusted advection-
 260 entrainment term”. We note that our use of the coefficient λ is an empirical approach:
 261 we do find large correlations between R_{FD}^* and \mathbb{R}_{ML}^* in the SPNA (up to 0.87 in the
 262 eastern SPNA and 0.63 in the western SPNA, Appendix 2). However further
 263 investigation, beyond this paper, is required to understand the full significance of λ .

264 3. Model Description and Analysis Procedure

265 ***3.1 HadGEM3-GC2 Coupled Climate Model***

266 We analyze output from a 300-year preindustrial control simulation HadGEM3-
267 GC2 (Williams et al. 2015b), a high-resolution version of the UK Met Office
268 HadGEM3 climate model, including ocean, atmosphere, sea-ice and land-surface
269 components. The ocean configuration is the Global Ocean version 5.0 (Megann et al.
270 2014) of the v3.4 NEMO model (Madec 2008) which uses the ORCA025 tripolar grid
271 ($\sim 0.25^\circ$ horizontal resolution) and 75 vertical levels. The sea ice component, also on
272 the ORCA025 grid, is version 4.1 of the Los Alamos Sea Ice Model (CICE; Hunke and
273 Lipscomb, 2010) which includes five sea-ice thickness categories and has improved
274 representation of Arctic sea ice concentration with respect to previous configurations
275 (Rae et al. 2015).

276 The atmosphere component is the Global Atmosphere version 6.0 of the Met Office
277 Unified Model (UM; Walters et al. 2011), with a horizontal resolution of N216 ($\sim 60\text{km}$
278 at mid latitudes) and 85 levels in the vertical. The land-surface model, is the Global
279 Land version 6.0 of the Joint UK Land Environment Simulator (JULES; Best et al.
280 2011), which shares the same grid as the atmospheric component.

281 This control simulation has been employed in many studies to examine a variety of
282 climate system processes. For example, the model has been used to examine
283 mechanisms of decadal variability in the Labrador Sea (Ortega et al. 2017), predictions
284 of the winter NAO (Scaife et al. 2014; Dunstone et al. 2016), and climatic trends in the
285 North Atlantic (Robson et al. 2016).

286 ***3.2 Analysis procedure***

287 Eqs. (1)-(12) were evaluated from the GC2 climate model simulation (Williams et
288 al. 2015b) using monthly mean potential temperature, MLD (defined as the depth at
289 which the potential density referenced to the surface differs from the surface density by

290 0.01 kg m⁻³) and mean net surface heat flux.

291 For each model year we take each month and calculate the average tendency terms
292 for SST and OHC for the 1 year period from that month to the same month in the next
293 year (Jan 2294 – Jan 2295, Feb 2294-Feb 2295 ... Dec 2294-Dec 2295). We then
294 calculate the mean of these twelve averaged tendency terms to obtain a consolidated
295 tendency term representative of the entire year. With this approach an exact heat budget
296 for the annual mean OHC or SST anomaly is obtained. A constant value of $\rho_0 C_P = 4.1$
297 $\times 10^6 \text{ J kg}^{-1} \text{ K}^{-1}$ was used throughout.

298 The AMOC at 26°N and 50°N was taken from the annual mean overturning stream
299 function output as a standard model diagnostic. The AMV index was calculated as the
300 annual mean SST averaged over the North Atlantic (75°W to 7.5°W, and 0° to 65°N)
301 minus the annual mean global SST normalised by the standard deviation (after Sutton
302 et al. 2018).

$$303 \quad AMV = \frac{\overline{\langle North Atlantic SST - Global SST \rangle}}{\sigma \langle North Atlantic SST - Global SST \rangle} \quad (13)$$

304 Where the overbar represents a spatial average, angled brackets represent a time
305 average and the standard deviation σ is taken over the 300-yr simulation.

306 All variables are filtered to retain periods of 10 years and longer using an 11-point
307 Parzen filter for annual means, or a 121-point filter for monthly means, Press (1986).

308 The results were essentially the same using a running mean filter.

309 **4. Results**

310 **4.1 Mean OHC and SST tendency terms**

311 Over long timescales, the mean OHC tendency is very small and surface fluxes
312 balance advection as in Eq. (6), hence it is sufficient to examine just one of these latter
313 terms in order to understand the mean state. The HadGEM3-GC2 300-year mean Q_{NET}
314 is shown in Fig. 1a. The net heat flux term shows cooling in the Gulf Stream region and

315 SPNA (north of a line connecting Florida with the Bay of Biscay), and warming in the
316 subtropics (south of this line). The cooling is considerably weaker in the central SPNA,
317 and there is a strong region of warming on the shelf region of the Grand Banks. The
318 warming in the subtropics is enhanced towards the shelf-slope regions bordering Africa
319 and South America. Eq. (6) indicates that advection has a mean pattern opposite to the
320 surface heat flux term with cooling in the subtropics and warming in the subpolar
321 regions.

322 Thus, as expected, the model shows warming in the subtropics and cooling in the
323 subpolar regions due to differential radiative heating. The ocean circulation (mainly the
324 AMOC in the North Atlantic) redistributes the excess heat in the tropics towards the
325 pole.

326 The HadGEM3-GC2 300-year mean SST tendency due to surface fluxes in the
327 North Atlantic, first term in Eq. (8), is shown in Fig. 1b. Surface fluxes introduce a
328 warming SST tendency everywhere with the exception of the western boundary regions
329 and some small isolated regions in the tropics, and Greenland and Labrador Seas. In the
330 Gulf Stream extension, North Atlantic Current and subpolar gyre regions the sign is
331 opposite to the effect of surface heat fluxes on the OHC (c.f. Fig. 1a). Also the pattern
332 is different, with maximum values over the Grand Banks shelf region, in the subtropical
333 gyre and in the western subpolar region. The prevailing positive tendencies occur
334 because of the MLD factor h in the denominator of the $\frac{Q_{net}}{\rho_0 c_p h}$ term in Eq. (8), which
335 weights the annual mean towards the summer months when the MLD is shallowest and
336 the ocean experiences heat gain from surface fluxes. Advection-diffusion-entrainment
337 opposes the warming effect of surface fluxes and hence is negative in most locations.

338 The result that in most of the North Atlantic north of 30°N, surface fluxes impose a
339 negative trend on the annual mean full depth heat content whilst also imposing a

340 positive trend on the annual mean SST is somewhat counterintuitive and bears further
341 explanation. As an illustration, Fig. 1c displays the MLD over the model year 2295 at
342 55°N, 28°W. In January, the MLD is 300m. It deepens to a maximum of 400m in
343 February before shallowing over spring (March-May) to a minimum of about 20m in
344 June. Over summer (June-August) the mixed layer remains very shallow but during the
345 autumn it deepens, reaching in excess of 100m in December. For comparison the
346 maximum winter MLD over the 300-year simulation (482.5m) is shown as a solid line.
347 Also marked are the 100m and 200m depth levels. Evidently, use of a temporally fixed
348 depth to characterise the mixed layer (e.g. Buckley et al. 2014; Roberts et al. 2017),
349 whilst mathematically simpler, is problematic. Heat content in such a fixed layer is not
350 simply related to SST in any season.

351 Surface heat flux, Q_{NET} , for each month of the year is plotted in Fig. 1d (blue). There
352 is strong (turbulent) heat loss from ocean to atmosphere between January and March
353 and again between October and December. In summer, between May and August, the
354 ocean gains heat due to increased insolation. At this example location, the seasonal
355 variation of the net surface heat flux is $\pm 200 \text{ W m}^{-2}$.

356 The red line in Fig. 1d represents the accumulated net surface heat flux (i.e. the
357 accumulated sum of the values plotted in blue). The accumulated heat flux remains
358 negative over the whole year, indicating that winter heat loss strongly outweighs
359 summer heat gain. Hence in the annual mean, surface heat flux tends to reduce OHC
360 and a negative value is found in Fig. 1a at this location.

361 The surface flux related forcing term for SST, Q_{NET}/h , is plotted in red in Fig. 1e.
362 The high values of h in winter, spring and autumn compared to summer (up to 20 times
363 higher) result in much smaller values of Q_{NET}/h in these seasons so the accumulated

364 value of Q_{NET}/h (red) is strongly positive from May to the end of the year and a positive
365 value is found in the corresponding location in Fig. 1b.

366 **4.2 Simulated AMV variability**

367 A common hypothesis for the observed temporal AMV variability is heat
368 redistribution by the AMOC. Whilst changes in the AMOC and associated changes in
369 horizontal heat transport divergence can potentially affect full depth OHC, whether and
370 by what mechanism changes in full depth OHC are translated to changes in SST are not
371 clear. In this Section, we first examine the relationship between the AMOC and AMV
372 in the HadGEM2-GC2 simulation, then use our theoretical framework to obtain insights
373 into the mechanisms.

374 Fig. 2a) shows the AMV index calculated from annual mean model output, together
375 with the AMOC anomaly at 26°N (Fig. 2b), and 50°N (Fig. 2c), with respect to its long
376 term mean, low pass filtered with a cut off period of 10 years. The AMV index shows
377 multidecadal variability reminiscent of the observations and the timescale of the
378 variability (~ 50 years) is within the range estimated from observations and multi-model
379 studies (20-70 years). There are four large AMOC excursions in the simulation period
380 (Fig. 2b-c) and these are matched with large AMV fluctuations. The spatial pattern
381 associated with the AMV (regression coefficient of the linear correlation of SST with
382 the AMV index) is shown in Fig. 2d. The pattern approximately matches that obtained
383 from observations (e.g. Sutton et al. 2018, see also Kushnir (1994)) but the region of
384 low regression in the western subtropics (between Florida and Cape Hatteras) is larger
385 than that seen in observations and in addition the Greenland Sea shows the opposite
386 sign regression coefficient. However, the HadGEM3-GC2 control simulation has fixed
387 atmospheric aerosol and CO_2 concentrations, whereas the real-world AMV may be
388 influenced by changing concentrations of anthropogenic aerosols or greenhouse gases.

389 Hence, even if the model was perfect, we might not expect or demand exact agreement.
390 On the other hand, the current generation of climate models shows a range of AMV
391 timescales and spatial patterns, hence some of the results presented in this study may
392 be model dependent and it will be important to compare them across a range of models
393 in future.

394 Correlation analysis shows a lagged relationship between AMOC and AMV with a
395 maximum correlation coefficient of 0.56 (26°N) and 0.52 (50°N) with the AMOC
396 leading by ~5 years and ~9 years (Fig. 3a). The thicker black and red lines indicate
397 significance at the 95% level. Both time series were detrended and autocorrelations
398 were considered in determining the degrees of freedom for significance testing (Emery
399 and Thomson 1997). Although significant correlations are found, they do not account
400 for all the AMV variance and many other processes could contribute to the AMV
401 variability including sub-polar gyre variability independent of the AMOC, atmospheric
402 teleconnections from the tropics and variability of the northern hemisphere cryosphere
403 including sea ice and snow cover.

404 The time series of the AMOC at 26°N (Fig. 3b) and 50°N (Fig. 3c) are divided into
405 events (labelled A to D) where each event spans a full AMOC cycle. We subdivide each
406 event into four phases corresponding to decreasing and increasing AMOC during
407 periods of negative and positive AMOC anomalies respectively. Thus, each event has
408 a full cycle of the AMOC during which the AMOC anomaly reduces to a minimum
409 (phase 1 - red), increases from the minimum to zero (phase 2 - blue), increases to a
410 maximum value (phase 3 - cyan) and then decreases to zero (phase 4 - magenta). The
411 year numbers of these events (based on the AMOC excursions, not the matching AMV
412 excursions) are listed in Tables 1 and 2. The duration of the events varies between 12
413 and 65 years and individual phases vary from 3 to 26 years.

414 In the next section, we will investigate the processes controlling the OHC and SST
415 trends in the different phases of the AMOC cycle. We will concentrate on SST and
416 OHC changes during the four events, focusing both on the full time series, and on a
417 composite of all four events.

418 **4.3 OHC trends during different phases of the AMOC**

419 Figure 4 a-d shows OHC trend composites based on the AMOC at 26°N (upper
420 panels) in the North Atlantic for each phase in turn of a composite of all four events A-
421 D (annual mean trends averaged over the duration of each phase of all four events -
422 Table 1 lists the model years included in each phase). During phase 1 (AMOC anomaly
423 < 0 and reducing) there is a negative heat content trend in the SPNA coupled with
424 increasing OHC in the subtropical gyre (STG) and in the Nordic Seas (Fig. 4a). There
425 is a dipole pattern in the intergyre region (Cape Hatteras to the Bay of Biscay) with
426 positive trends in the west and negative in the east. In phases 2-4 we see positive OHC
427 trends spreading first into the eastern and northern SPNA (Fig. 4b) and later into the
428 western SPNA (Fig. 4c-d). Negative trends appear in the western part of the intergyre
429 region in phase 2, but there is a return to positive trends in phases 3 and 4. The STG
430 (south of 40°N) shows somewhat complicated behaviour, with mainly positive trends
431 in phases 1 and 4, and opposite signed north-south dipoles in phases 2 and 3. The Nordic
432 Seas as a whole vary coherently, with OHC increasing in phases 1 and 4, and decreasing
433 in phases 2 and 3. The OHC trend composites based on the AMOC at 50°N (panels e-
434 h) show strong similarity with those based on the AMOC at 26°N. Phase 1 at 26°N (Fig.
435 4a) and at 50°N (Fig. 4e) look very similar for example as do phases 2-4. Of particular
436 note is the fact that in the SPNA, in phase 4, when the AMOC is reducing, the OHC
437 shows a warming tendency.

438 The SST trend composites based on the AMOC at 26°N show some similarities to
439 the corresponding OHC composites in the SPNA, intergyre and STG regions, but also
440 substantial differences (compare Figs. 4a-d with i-l). For example in phase 3, the
441 patterns are broadly similar with extensive warming over the whole SPNA and the
442 eastern SPNA (Fig. 4c, k) whereas in phase 4 the western SPNA has strongly increasing
443 OHC (Fig. 4d), but the SST is weakly increasing (Fig. 4l). In contrast to the OHC trends,
444 the peak SST warming occurs in phases 2 and 3, not in phase 4. In the SPNA, SST trend
445 composites based on the AMOC at 50°N show a phase lag compared to those based on
446 the AMOC at 26°N. Phases 2, 3 and 4 of the 50°N based composites (Figs. 4n, o, p) are
447 very similar to phases 1, 2 and 3 respectively of the 26°N based composites (Figs. 4i, j,
448 k). The SST phases at 26°N bear some similarity to the observation based normalised
449 SST trends presented in Fig. 2 of Caesar et al. (2018). The sequence established for the
450 composite event is essentially seen in the individual events (not shown).

451 Figure 5 shows the two terms, Q_{NET}^* and R_{FD}^* , which determine the full depth heat
452 content tendency. As the AMOC increases from a minimum (Fig. 5a), there is a positive
453 heat flux anomaly in the north western subtropical gyre with the exception of the Gulf
454 Stream which has a negative surface heat flux signature. Elsewhere in the subtropical
455 and subpolar gyres, the heat fluxes are rather weak except over the East and West
456 Greenland boundary current and in the Norwegian Sea where there is anomalous heat
457 input. Subsequently there is widespread heat uptake in both SPNA and subtropical
458 regions (Fig. 5b). Phases 3 and 4 (Figs. 5c, d) then reverse the sequence, with phase 3
459 a negative version of phase 1 and phase 4 a negative version of phase 2. It is remarkable
460 that there is strong heat gain (loss) due to surface fluxes in the SPNA in phase 2 (phase
461 4) when the AMOC is increasing (decreasing). The composites based on the AMOC at

462 50°N (Fig. 5e-h) are very similar in pattern to those based on the AMOC at 26°N, the
463 main differences being in the magnitude of the anomalous fluxes.

464 In phases 1 and 2, the advection anomaly term, R_{FD}^* , is very similar to the surface
465 heat flux anomalies but opposite in sign, and the net tendency is a small residual
466 between the terms (compare Figs. 5i, j with Figs. 5a, b). Hence it is difficult to pick out
467 by eye which term is the larger. However in phases 3 and 4, we see larger differences
468 in the patterns and in the SPNA in particular it is possible to discern which term is
469 dominant. In phase 3 in the western SPNA, surface fluxes appear to be the larger term
470 whereas in the eastern SPNA advection dominates (compare Fig. 5k with Fig. 5c). In
471 phase 4 on the other hand it appears that advection is the dominant term throughout the
472 SPNA. As with the surface fluxes, composites of R_{FD}^* based on the AMOC at 50°N
473 differ slightly in magnitude from those based on the AMOC at 26°N, but the spatial
474 patterns obtained are very similar.

475 **4.4 SST trends during different phases of the AMOC**

476 We now examine the contributions to the net SST tendency which was shown in
477 Fig. 4i-p, focussing on the advection-diffusion-entrainment related term $\left[\frac{R_{ML}}{\rho_0 C_P h}\right]^*$. From
478 Eq. (9) we plot $\left[\frac{R_{ML}}{\rho_0 C_P h}\right]^*$ for each phase in Figs. 6a-d. The term shows interesting spatial
479 structure particularly around the Labrador and Irminger Seas (areas of deep convection
480 in the model, Ortega et al. 2017). The Gulf Stream and its extension in particular shows
481 systematic changes in sign and magnitude with a warming signal in phases 1 and 4 and
482 a cooling signal in phases 2 and 3 reminiscent of the advection term in the OHC
483 equation (Fig 5e-h) The surface flux related term $\left[\frac{Q_{NET}}{\rho_0 C_P h}\right]^*$ (not shown) is essentially
484 similar in pattern, but of negative amplitude. These two terms are much larger than the

485 net tendency which is the residual between two very large and opposing terms, hence
486 this decomposition yields little insight into the relative role of each term.

487 Turning to the anomaly formulation in Eq. (10) we now plot $\mathfrak{R}_{ML}^*/\rho_0 C_P \bar{h}$ for each
488 phase (Fig. 6e-h). We discern a different temporal evolution, without a strong signal in
489 the convection regions but not so clearly reminiscent of the OHC advection especially
490 in the Arctic and the East and West Greenland currents where the shallow mixed layer
491 results in uniformly large values. The magnitude of the term ($\pm 0.5 \text{ W m}^{-3}$) is still much
492 larger than the net tendency term (Figs. 4i-p) and hence $\mathfrak{R}_{ML}^*/\rho_0 C_P \bar{h}$ and
493 $Q_{NET}^*/\rho_0 C_P \bar{h}$ still nearly cancel. Thus we still obtain little insight into the controlling
494 process.

495 Finally we turn to Eq. (12) and evaluate $\mathbb{R}_{ML}^*/\rho_0 C_P \bar{h}$ using $\lambda=0.99$ (this choice of
496 λ is justified in Appendix 2, we note that it is obtained by searching for the maximum
497 correlation between $\mathbb{R}_{ML}^*/\rho_0 C_P \bar{h}$ and R_{FD}). By doing this we obtain magnitudes which
498 are of the same order of magnitude as the net tendency. We therefore adopt this
499 decomposition in the following analysis.

500 **4.5 Eastern and western subpolar North Atlantic**

501 There is a tendency for both OHC and SST to show different responses in the
502 western compared to the eastern SPNA (see Fig. 4 for region definitions). For example,
503 for the composites based on the AMOC at 26°N (Fig. 4), in phase 1 there is a more
504 negative OHC tendency in the eastern SPNA than in the western SPNA; in phase 2 the
505 tendencies are of opposite sign; and in phase 3 there is a stronger positive tendency in
506 the eastern SPNA than the west. Accordingly, we investigate the spatially averaged
507 response in each region separately.

508 OHC and SST spatially averaged over the eastern and western SPNA and the
509 AMOC at 26°N and 50°N are plotted in Fig. 7. Both regions show a lagged relationship

510 between the AMOC at both latitudes (black, magenta, Fig. 7c) and the OHC (red, Fig.
511 7a-b). At 26°N the AMOC leads western SPNA OHC by 15 years and at 50°N by 18
512 years (see Table 3). The corresponding lead times for the eastern SPNA are 10 years
513 and 12 years. This is consistent with our earlier finding that OHC tendencies tend to
514 propagate anticlockwise around the SPNA (Fig. 4). The SST (blue, Fig. 7) is also
515 related to the AMOC, but the lag is smaller compared to the OHC (5 years and 7 years
516 at 26°N and 50°N respectively) and it does not vary between the eastern and western
517 SPNA.

518 In order to explore the possibility that the OHC variability may depend on the depth
519 horizon over which it is evaluated, we evaluate the OHC, Eq. (1) from the surface to
520 depth horizons of 100m, 200m, 500m, 1000m and the full ocean depth (Fig. 8 – for this
521 figure (only) we use monthly data in order to accurately characterise the lags between
522 different depth horizons). In both eastern and western SPNA (Fig. 8a, b), the variability
523 of the OHC is qualitatively similar no matter which depth horizon is employed:
524 correlations of the OHC at 1000m with the OHC at shallower depths yields r^2 values
525 between 0.63 (100m) to 0.94 (500m) in the west and 0.83 (100m) to 0.93 east (500m).
526 However, the variability for deeper depth horizons are lagged with respect to shallower
527 ones (Fig. 8c, d), particularly marked in the western SPNA where the correlation also
528 drops more rapidly with depth. Nevertheless, a robust result is that SST leads heat
529 content, irrespective of the depth horizon to which it is evaluated (Fig. 8 c-d). This is
530 quantified in Table 4 which shows the maximum correlation, and the lag at which the
531 maximum occurs, of each heat content evaluation with the SST. In the western SPNA,
532 the lag narrows from 45 months for full depth to only 3 months for 100m depth, but a
533 lag always remains. In the east, the SST and the OHC become almost simultaneous for
534 depths shallower than 200m and the correlation becomes very close to unity. In

535 summary, for depth horizons greater than 200m the maximum correlation between
536 OHC and SST never reaches unity and a substantial lag (1.5 to 3.5 years) occurs.

537 **4.6 Balance between surface fluxes and advection**

538 **4.6.1 OHC**

539 Having discussed the variation in OHC we now examine the processes controlling
540 its rate of change via Eq. (7). Figs. 9a, b show Q_{NET}^* , and R_{FD}^* averaged over the
541 western and eastern SPNA respectively whilst Figs. 9c, d show similar plots for $\frac{\partial \theta_{FD}^*}{\partial t}$.
542 The rate of change of OHC (red) displays decadal timescale shifts from positive to
543 negative values, during which OHC rises and falls respectively. The events noted earlier
544 (Table 1) are visible as longer than average periods of increasing OHC (e.g. years 2120-
545 2160, 2290-2330 and 2390-2410). This rate of change is caused by the interplay
546 between the surface fluxes (Q_{NET} in black) and advection (R_{FD} in blue), which tend to
547 oppose to each other, but not always.

548 The term with the larger absolute magnitude will drive the sign of the OHC
549 tendency. If the other term is of opposite sign then it will act as a brake whereas if it is
550 of the same sign then the two terms act in concert. For example in year 2240 the
551 absolute magnitude of the surface heat flux (Q_{NET}^*) is larger than that of advection, the
552 two terms act in concert, the net rate of change is positive and the anomalous heat
553 content rises. In contrast, in year 2400, the absolute magnitude of the surface heat flux
554 is less than that of advection and it is of opposite sign, the rate of change is positive and
555 heat content rises with advection driving and heat fluxes acting as a brake.

556 In Fig. 9a the surface flux term often leads advection by a few years, $r=0.5$ at 6.5
557 years, implying that in the western SPNA surface fluxes control the evolution of the
558 full depth OHC. However Q_{NET} and R_{FD} are significantly anticorrelated and correlated
559 respectively with the AMOC at 26°N with the AMOC leading or simultaneous (Table

560 3). This implies that it is the AMOC which is the main driver of the heat content. Further
561 support for this conclusion will be given in Section 4.6 which considers the time
562 evolution of a composite AMOC cycle.

563 In the eastern SPNA, the opposite pattern occurs (Fig. 9b). Firstly, the decadal
564 variability of advection (R_{FD} in blue), 6.1 W m^{-2} , is much larger in magnitude than that
565 of surface fluxes, 3.9 W m^{-2} , unlike the western SPNA where the variability is of
566 roughly equal amplitude (both $\sim 4.3 \text{ W m}^{-2}$). In addition, advection tends to lead surface
567 fluxes by a few years, $r=0.3$ at 11 years (disregarding a peak at 2.5 years which is
568 statistically insignificant), suggesting advection is the controlling process in this region.
569 Once again, The AMOC is significantly related to both terms (Table 3).

570 4.6.2 SST

571 Moving on to the processes controlling the SST, we have already noted that in order
572 to make progress we need to use Eq. (12) with a parameterized heat flux (Q_h) at the
573 base of the mixed layer. This is further illustrated by Figs. 10a which shows the relative
574 contributions of surface fluxes ($\left[\frac{Q_{NET}}{\rho_0 C_P h}\right]^*$) and other processes ($\left[\frac{R_{ML}}{\rho_0 C_P h}\right]^*$) in the western
575 SPNA from Eq. (9): these are very different compared to the OHC terms Q_{NET} and R_{FD}
576 (note that the net tendency terms for SST are plotted in Figs. 10g, h). There is no
577 discernible lag between the two terms, they are coincident in time, are of opposite sign
578 and very small differences in magnitude between them determine the sign of the rate of
579 change of SST. Similar considerations apply to the eastern SPNA (Fig. 10b).

580 Using Eq. (10), we again find a very high degree of compensation between the surface
581 flux and advection terms (Fig. 10c, d), although now the surface flux related term for
582 the SST, $Q_{NET}^*/\rho_0 C_P \bar{h}$, has almost exactly the same variation as for the surface flux
583 term for the OHC, Q_{NET} , (compare the black line in Fig. 10c with the black line in Fig.

584 9a. The small differences arise because here we are applying a spatial average and \bar{h}
585 varies spatially, though not with time.

586 Finally we parameterize the diffusive heat flux Eq. (11) and (12) at the base of the
587 mixed layer. The simple parameterization results in a separation of the surface heat flux
588 and advection-entrainment term (Fig. 10e, f). This decomposition allows us to draw
589 similar conclusions for the SST as we drew for the OHC, namely that in the western
590 SPNA, both surface heat flux and advection-diffusion-entrainment play major roles in
591 setting the net SST tendency. By contrast in the eastern SPNA, the advection-
592 entrainment term is the clear driver of SST variations on decadal timescales.

593 **4.6.3 Relationship between OHC and SST tendency terms**

594 A strong relationship emerges between the rates of change of full depth OHC
595 ($\partial\text{OHC}/\partial t$) and rates of change of SST ($\partial\text{SST}/\partial t$) (Fig. 11a). Maximum positive
596 correlations are found at lags of 18 months (west) and 3 months (east). As well as these
597 positive correlations, negative correlations are found when the $\partial\text{OHC}/\partial t$ leads $\partial\text{SST}/\partial t$
598 by 63 months (west) and 67 months (east).

599 As mentioned in the previous subsection, the adjusted surface flux related term for
600 the SST, $(1 - \lambda)Q_{NET}^*/\rho_0 C_P \bar{h}$, has very similar variation as for the surface flux term
601 for the OHC, Q_{NET} , small differences arising because \bar{h} varies spatially. This similarity
602 is illustrated in Fig. 11b. The two surface flux related terms vary simultaneously and
603 the maximum correlation is unity.

604 By parameterizing the heat flux at the base of the mixed layer, we obtain strong
605 lagged correlations of the advection-entrainment term, $\mathbb{R}_{ML}^*/\rho_0 C_P \bar{h}$ with R_{FD}^* . In the
606 western SPNA $\mathbb{R}_{ML}^*/\rho_0 C_P \bar{h}$ leads R_{FD}^* by ~ 3 years ($r=0.62$) whilst in the eastern
607 SPNA $\mathbb{R}_{ML}^*/\rho_0 C_P \bar{h}$ is almost simultaneous with R_{FD}^* ($r=0.78$). Additionally, both

608 terms, $\mathbb{R}_{ML}^* / \rho_0 C_P \bar{h}$ and \mathbb{R}_{FD}^* , have a significant correlation with the AMOC at 26°N
609 in both regions of the SPNA (Table 3).

610 **4.7 Drivers of net tendencies in OHC and SST**

611 We obtain further insights into the controls on SST and OHC variation by forming
612 a composite AMOC anomaly cycle based on all four individual events. In order to do
613 this we take each phase in turn and assign identical timings for the start and end points
614 of the phase. Thus for phase 1 the start year of each event is set to time zero and the end
615 year is set to $\pi/2$. For example phase 3 of event C spans years 2275-2288, including 14
616 years, whereas event D spans 2385-2395 for phase 1, a total of 11 years. Thus both 2275
617 and 2385 are assigned a time of π and 2288 and 2395 are assigned a time of $3\pi/2$ and all
618 intermediate values are interpolated onto a regular grid with spacing $\pi/50$. In this way
619 all four events and all four phases can be stretched onto a common timeframe and
620 averaged to form a composite AMOC anomaly at 26°N and associated anomalies of
621 SST (ξ^*) and OHC (θ_{FD}^*) in the western and eastern SPNA (plotted as a function of
622 phase, φ , in Fig. 12a, b). By our definition, the composite AMOC anomaly (black line)
623 is zero at phase values $\varphi=0$ and $\varphi=2\pi$. In between these values the AMOC is negative
624 between $\varphi=0$ and $\varphi=\pi$, and positive between $\varphi=\pi$ and $\varphi=2\pi$. Local extrema occur near
625 $\varphi=\pi/2$ and $\varphi=3\pi/2$ and the anomaly is near zero at $\varphi=\pi$. The minimum value is ~ -0.9
626 Sv and the maximum slightly larger at ~ 1.0 Sv. SST anomaly (dark blue) closely
627 follows the AMOC anomaly in both western and eastern SPNA. The minima coincide
628 in phase at $\varphi=\pi/2$, but there is a slight phase lag between the respective maxima close
629 to $\varphi=3\pi/2$. Minimum (maximum) SST anomaly is -0.28K ($+0.23\text{K}$) in the western
630 SPNA and -0.37K ($+0.35\text{K}$) in the eastern SPNA. The big contrast occurs with OHC
631 (red), which is shifted by a quarter cycle in the western SPNA and a little less (\sim one

632 eighth of a cycle) in the eastern SPNA, consistent with the lagged correlations presented
633 in Table 3.

634 Going further, we can form composites of all the quantities in Eqs. (9)-(12). Fig.
635 12c shows composites of the rate of change of heat content ($\frac{\partial \theta_{FD}^*}{\partial t}$) in the western SPNA
636 (light blue line) together with the surface heat flux (Q_{NET}^* , red) and advection (R_{FD}^* ,
637 dark blue) terms, with the AMOC anomaly (black) at 26°N superimposed for reference.
638 Rate of change of heat content is negative (i.e. heat content is falling) in phases 1 and
639 2, rises steeply to positive values in phase 3, and declines more slowly in phase 4.
640 Advection closely matches the net tendency (dark and light blue curves) during phases
641 1-3, but is significantly higher in phase 4. The surface flux term is positive in phases 1-
642 3, weakly opposing the advection term, and rises slightly. In the middle of phase 3, as
643 the heat content peaks, the surface flux term declines steeply, transitioning to negative
644 values in phase 4. Overall it can be seen that the net tendency is largely driven by
645 advection, but in phase 4 there is strong damping by surface fluxes. A similar
646 conclusion can be drawn for the ocean heat content in the eastern SPNA (Fig. 11b). In
647 the western SPNA, the advection term is very clearly related to the AMOC anomaly
648 with a lag of approximately $\Delta\phi=\pi/4$ (Fig. 12c) whereas in the eastern SPNA the
649 advection co-varies with the AMOC anomaly (Fig. 12d). We thus conclude that the
650 AMOC is main driver of large-amplitude decadal variations in OHC.

651 The SST tendency behaves in a broadly similar way (Fig. 12e, f where the net
652 tendency, $\frac{\partial \xi^*}{\partial t}$, is in light blue, the surface flux related term, $\frac{(1-\lambda)Q_{NET}^*}{\rho_0 C_P \bar{h}}$, is red and the
653 advection-entrainment term, $\mathbb{R}_{ML}^*/\rho_0 C_P \bar{h}$, is dark blue and the AMOC anomaly at
654 26°N (black) is again overplotted for reference) but there are some subtle differences.
655 In the western SPNA we see the larger contrast compared to OHC (Fig. 12e). The net
656 tendency (light blue) peaks earlier than the net OHC tendency in the same region (Fig

657 12c) and because both quantities have essentially the same surface flux forcing (red) it
658 must be the advection-entrainment term in the mixed layer which is responsible (dark
659 blue). Of interest is the fact that both the net tendency and the advection-entrainment
660 term lead the AMOC and the surface flux term leads the net tendency term. Thus surface
661 fluxes seem to exert some control on the SST in the western SPNA. In the eastern
662 SPNA, the SST and OHC tendency behave very similarly (Fig. 12f) and in particular
663 in both cases, the surface flux term is of opposite sign to the SST suggesting the surface
664 flux term is chiefly having a damping effect. The results strongly suggest that advection
665 is the dominant process controlling the evolution of the OHC in the both the western
666 and the eastern SPNA and additionally, advection-entrainment is the process
667 controlling SST in the eastern SPNA. In the western SPNA, there is a disconnect
668 between the full depth advection and the advection-entrainment in the mixed layer,
669 resulting in an SST peak substantially before the heat content peak. In the eastern
670 SPNA, by contrast the full depth and mixed layer tendencies work in tandem and there
671 is little difference in the timing of the peaks. This explains why there is a lag between
672 OHC peaks in the western and eastern SPNA, but no lag between the SST peaks.

673 The OHC advection term follows the AMOC according to expectations but surface
674 fluxes release the extra heat input to the atmosphere when the AMOC is rising but the
675 AMOC anomaly is still negative (i.e. in phase 2 of the composite event). It is only when
676 the AMOC anomaly becomes positive that the heat content begins to rise. When the
677 AMOC is falling in phase 4, advection falls too, but OHC increases because the
678 opposing contribution of surface fluxes falls faster. A period of decreasing OHC
679 follows when surface fluxes begin to rise at about the time that the AMOC is halfway
680 between its peak and zero (particularly marked in the western SPNA).

681 As already noted, the net SST tendency in Figs. 12e leads the AMOC anomaly at
682 26°N in the western SPNA. Since the advection-entrainment term also lags the SST
683 tendency, but the surface flux term leads all three, this suggests that surface fluxes in
684 the western SPNA are at least partly responsible for the large AMOC variations seen in
685 the model. But the surface fluxes are partially set by the AMOC through its (eventual)
686 control of the SST (via subtropics and the eastern SPNA) emphasising the coupled
687 nature of the AMOC variability.

688 **4.8 Drivers of OHC and SST variations**

689 In this section we summarize the driving terms which characterize the AMOC
690 cycle (Fig. 13). Recalling from Section 4.5 that the term with the larger absolute
691 magnitude (either surface flux related or advection (-entrainment) related) drives the
692 sign of the OHC tendency. If the other term is of opposite sign then it will act as a brake;
693 if it is of the same sign then the two terms act in concert. In Fig. 13a the net OHC
694 tendency for the composite AMOC event is shown in black. We then divide the cycle
695 into regimes depending on which term is dominant (I.e. either $|R_{FD}| > |Q_{NET}|$ or more
696 rarely $|Q_{NET}| > |R_{FD}|$). For each regime the corresponding terms are averaged over the
697 duration of the regime and a constant value plotted in order to quantitatively depict the
698 interplay between the forcing terms during each regime. These regimes do not in
699 general line up with the AMOC phases (p1-p4), for example midway between phase 1
700 at $\varphi \sim \pi/4$ to partway through phase 3 ($\varphi \sim 1.1\pi$) advection (blue) is the driving term with
701 an average value of approximately -3.0 W m^{-2} and it is opposed by surface fluxes (red)
702 with an average value of approximately $+1.0 \text{ W m}^{-2}$. In the subsequent regime, for a
703 brief period surface fluxes dominate as the advection term transitions from negative to
704 positive values as does the net tendency itself. From here to the peak net tendency
705 ($\varphi \sim 1.2\pi$ to $\varphi \sim 1.4\pi$) the two terms act in concert after which surface fluxes transition to

706 negative values. Advection remains the dominant term in this regime, but receives
707 substantial opposition from surface fluxes.

708 The situation in the eastern SPNA (Fig. 13b) is similar, but the cycle is shifted to
709 earlier times with respect to the west. As with the west, there is a shift from negative to
710 positive forcing by advection halfway along the period when the net tendency increases
711 ($\varphi \sim 0.9\pi$) and a shift from positive to negative surface flux forcing close to the time of
712 peak net tendency ($\varphi \sim 1.3\pi$). In addition, there is an extended regime where surface
713 fluxes are the dominant term ($\varphi \sim 1.7\pi$ to $\varphi \sim 2.0\pi$) which is not seen in the west. Despite
714 this, advection is clearly the dominant term over most of the cycle for both eastern (66%
715 of the time) and western SPNA (88% of the time). The equivalent plots for the SST are
716 shown in Figs. 13c,d. These are quite similar to the OHC plots, especially for the eastern
717 SPNA, but it is noteworthy that surface fluxes play a more important role especially in
718 the west where there is a long period from $\varphi \sim 0.6\pi$ to $\varphi \sim 1.4\pi$ during which surface fluxes
719 dominate, albeit sometimes narrowly. In both east and west, surface fluxes dominate
720 from $\varphi \sim 1.7\pi$ to $\varphi \sim 2.0\pi$. Overall advection dominates only 53% of the time in the
721 western SPNA and 61% of the time in the eastern SPNA. Unlike the composite terms
722 in Figs. 12e, f) the results shown in Figs. 13c, d) are not very sensitive to whether or
723 not we use the unadjusted (Equ 10) or adjusted tendency terms (Equ 12).

724 **5 Conclusions**

725 We have developed a novel combined approach to the mixed layer and full depth
726 ocean heat budgets and used it to investigate sea-surface temperature (SST) and ocean
727 heat content (OHC) variability on decadal to multidecadal timescales in the subpolar
728 North Atlantic (SPNA), the main centre of action of the Atlantic Multidecadal
729 Variability (AMV). Our analysis has employed a state-of-the-art coupled climate
730 model, HadGEM3-GC2, in which the simulated AMV index and spatial pattern is very

731 similar to observed estimates. The new elements of the approach are development of
732 an equation for evolution of anomalous SST and a parameterization of the diffusive
733 heat flux at the base of the mixed layer.

734 The results of our analysis show that both OHC and SST tendencies are the result
735 of a competition between two terms representing the effects of surface fluxes and
736 advection for OHC (advection-entrainment for SST). These terms have different forms
737 in the OHC and SST equations, because additional terms related to entrainment appear
738 in the SST equation but not in the OHC equation. Hence, the relationship between OHC
739 and SST becomes an investigation into how and why the surface fluxes and advection
740 related terms differ between the OHC and SST equations.

741 The main conclusions are listed below:

- 742 • Anomalies in the OHC tendency propagate around the SPNA on decadal
743 timescales with a clear relationship to the phase of the AMOC.
- 744 • In the SPNA, AMOC anomalies lead SST anomalies, which in turn lead OHC
745 anomalies. This result does not depend on the depth used for calculation of
746 OHC and is common to both eastern and western SPNA.
- 747 • OHC variations in the SPNA on decadal timescales are largely dominated
748 by AMOC variability because it controls variability of advection which is
749 shown to be the dominant term in the OHC budget. Surface heat fluxes
750 modulate the OHC variability, particularly as OHC peaks and declines.
751 Surface heat flux plays a larger role in SST variability.
- 752 • The advection term covaries with the AMOC in the eastern SPNA, but lags
753 the AMOC in the western SPNA, leading to the anticlockwise propagation
754 of OHC anomalies around the SPNA.

- 755 • The lag between OHC and SST is traced to differences between the
756 advection term for OHC and the advection-entrainment term for SST. The
757 latter leads the former particularly in the western SPNA.
- 758 • In the western SPNA, surface fluxes and SST appear to precede and cause
759 AMOC changes, whereas in the east AMOC changes cause the changes in
760 SST and surface fluxes.

761 The main implication of our study is that deep OHC changes are not associated
762 with immediate changes in SST in HadGEM3-GC2, indeed changes in SST precede
763 OHC deep changes. There is also a very clear difference in the dominant process
764 between the eastern and western SPNA. In the former region, advection is
765 dominant, whereas in the latter surface fluxes dominate. Whilst our study
766 confirms the important role of the AMOC in the decadal variability of the North
767 Atlantic SST, this role cannot be simplified as an increasing AMOC leading to
768 increasing heat content leading to increasing SST, which is a common assumption
769 underlying numerous studies of contemporary and palaeo variability of the North
770 Atlantic (e.g. Chen and Tung 2018). For example, in this study using HadGEM3-
771 GC2 the SPNA OHC rarely immediately increases as AMOC increases (Phase 2 in
772 Fig. 12), because the advection term must first switch sign from negative to
773 positive (Fig 13a, b). On the other hand the SST can and does begin rising quite
774 soon after the AMOC starts increasing, because the surface flux term is already
775 driving an increasing SST at this time and reduced opposition to this term from
776 advection reinforces this trend.

777 In the western SPNA in particular it seems that surface fluxes drive both the
778 subsequent evolution of the advection-entrainment term, and ultimately the
779 AMOC. The detailed mechanism by which surface fluxes can influence the

780 advection still need to be determined, but may be related to the projection of short
 781 (seasonal-interannual) timescale correlations between MLD and temperature
 782 onto the decadal timescale (See appendix 1, Eq. (A9)).

783 The diagnostic framework developed here is eminently suitable for use with
 784 observations and multi-model ensembles. For observations, however, great care must
 785 be taken in analysis of errors as rates of change of both OHC and SST consist of a fine
 786 balance (i.e. a small residual) between large competing terms of opposite sign. In
 787 addition, decadal scale observational analysis would require high-quality mixed layer
 788 depth observations, that are still not available globally. Finally, we note that the new
 789 framework can be usefully applied to the CMIP6 model ensemble in order to establish
 790 the robustness of the results, and to reveal individual model deficiencies that could help
 791 usefully constrain climate change projections.

792

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799

800 **Appendix 1 Derivation of SST Anomaly Equation**

801 In this section we derive Equations (9)-(12). Returning to Eq. (3)

$$802 \quad h \frac{\partial T_a}{\partial t} + h \mathbf{v}_a \cdot \nabla T_a + \nabla \cdot \left(\int_{-h}^0 \hat{\mathbf{v}} \hat{T} dz \right) + (T_a - T_{-h}) \left(\frac{\partial h}{\partial t} + \mathbf{v}_{-h} \cdot \nabla h + w_{-h} \right) =$$

$$803 \quad (Q_{NET} - Q_{-h}) / \rho_0 C_P \quad (A1)$$

804 We first isolate the time derivative terms

$$805 \quad h \frac{\partial T_a}{\partial t} + h \mathbf{v}_a \cdot \nabla T_a + \nabla \cdot \left(\int_{-h}^0 \hat{\mathbf{v}} \hat{T} dz \right) + (T_a - T_{-h})(\mathbf{v}_{-h} \cdot \nabla h + w_{-h}) + (T_a -$$

$$806 \quad T_{-h}) \frac{\partial h}{\partial t} = (Q_{NET} - Q_{-h}) / \rho_0 C_P \quad (A2)$$

807 then aggregate terms

$$808 \quad h \frac{\partial T_a}{\partial t} - X + (T_a - T_{-h}) \frac{\partial h}{\partial t} = (Q_{NET} - Q_{-h}) / \rho_0 C_P \quad (A3)$$

809 where

$$810 \quad X = h \mathbf{v}_a \cdot \nabla T_a + \nabla \cdot \left(\int_{-h}^0 \hat{\mathbf{v}} \hat{T} dz \right) + (T_a - T_{-h})(\mathbf{v}_{-h} \cdot \nabla h + w_{-h}) \quad (A4)$$

811 decompose h and T_a , X , T_{-h} , Q_{NET} , and Q_{-h} into mean and anomaly components,

812 denoted by an overbar and an asterisk respectively, in Eq. (A3)

$$813 \quad (\bar{h} + h^*) \frac{\partial T_a^*}{\partial t} - \bar{X} - X^* + (\bar{T}_a + T_a^* - \bar{T}_{-h} - T_{-h}^*) \frac{\partial h^*}{\partial t} = (\bar{Q}_{NET} + Q_{NET}^* -$$

$$814 \quad \bar{Q}_{-h} - Q_{-h}^*) / \rho_0 C_P \quad (A5)$$

815 take the mean of Eq. (A5)

$$816 \quad \overline{h^* \frac{\partial T_a^*}{\partial t}} - \bar{X} + \left(\overline{T_a^* \frac{\partial h^*}{\partial t}} - \overline{T_{-h}^* \frac{\partial h^*}{\partial t}} \right) = (\bar{Q}_{NET} - \bar{Q}_{-h}) / \rho_0 C_P \quad (A6)$$

817 now subtract Eq. (A6) from Eq. (A5)

$$818 \quad \bar{h} \frac{\partial \xi^*}{\partial t} = (Q_{NET}^* - Q_{-h}^*) / \rho_0 C_P + X^* - (\bar{T}_a - \bar{T}_{-h}) \frac{\partial h^*}{\partial t} - (T_a^* - T_{-h}^*) \frac{\partial h^*}{\partial t} +$$

$$819 \quad \overline{(T_a^* - T_{-h}^*) \frac{\partial h^*}{\partial t}} - \left(\overline{h^* \frac{\partial T_a^*}{\partial t}} - \overline{h^* \frac{\partial T_{-h}^*}{\partial t}} \right) + \bar{h} \frac{\partial (\xi^* - T_a^*)}{\partial t} \quad (A7)$$

820 consolidate terms, parameterize $Q_{-h}^* = \lambda Q_{NET}^*$ and divide by \bar{h}

$$821 \quad \frac{\partial \xi^*}{\partial t} = (1 - \lambda) Q_{NET}^* / \rho_0 C_P \bar{h} + \mathfrak{R}_{ML}^* / \bar{h} \quad (A8)$$

822 Where

$$823 \quad \mathfrak{R}_{ML}^* = X^* - (\bar{T}_a - \bar{T}_{-h}) \frac{\partial h^*}{\partial t} - (T_a^* - T_{-h}^*) \frac{\partial h^*}{\partial t} + \overline{(T_a^* - T_{-h}^*) \frac{\partial h^*}{\partial t}} - \left(\overline{h^* \frac{\partial T_a^*}{\partial t}} -$$

$$824 \quad \overline{h^* \frac{\partial T_{-h}^*}{\partial t}} \right) + \bar{h} \frac{\partial (\xi^* - T_a^*)}{\partial t} \quad (A9)$$

825

826 **Appendix 2 Optimal Value for Diffusive Heat Flux Fraction λ**

827 As explained in Section 4.4 we obtain an optimal value for λ by ensuring that the
828 resulting mixed layer advection entrainment term \mathfrak{R}_{ML}^* has a maximum correlation
829 with the full depth advection term R_{FD} . Figure A2.1(a) illustrates this correlation for
830 the western (black) and eastern (red) SPNA for values of λ between 0.91 and 1.0. It is
831 remarkable that such a maximum correlation with non-negligible value exists, ~ 0.63
832 for the western and ~ 0.88 for the eastern SPNA. Corresponding lags are shown in Fig
833 A2.1(b) and indicate that the mixed layer term precedes the full depth term by three
834 years in the western SPNA and that the two terms are simultaneous in the eastern
835 SPNA. For the purposes of this paper we choose a compromise value of $\lambda=0.99$.

836

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1033 **Tables**

event identifier	phase 1	phase 2	phase 3	phase 4
A (33)	2148-2151 (4)	2119-2130 (12)	2131-2140 (10)	2141-2147 (7)
B (26)	2201-2203 (3)	2204-2207 (4)	2208-2217 (10)	2218-2226 (9)
C (56)	2239-2259 (21)	2260-2274 (15)	2275-2288 (14)	2289-2294 (6)
D (65)	2345-2366 (22)	2367-2384 (18)	2385-2395 (11)	2396-2409 (14)

1034 Table 1. Time periods of major AMOC events at 26°N and their Phases in the
 1035 HadGEM3-GC2 control simulation. The duration in years of each event is in brackets.
 1036 The events are shown in Fig. 3b.

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event identifier	phase 1	phase 2	phase 3	phase 4
A (34)	2146-2150 (5)	2116-2127 (12)	2128-2134 (7)	2135-2145 (11)
B (22)	2200-2206 (7)	2207-2211 (5)	2212-2215 (4)	2216-2221 (6)
C (60)	2238-2258 (21)	2259-2272 (14)	2272-2282 (11)	2283-2296 (14)
D (68)	2339-2356 (18)	2357-2377 (21)	2378-2395 (18)	2396-2406 (11)

1038 Table 2. Time periods of major AMOC events at 50°N and their phases in the
 1039 HadGEM3-GC2 control simulation. The duration in years of each event is in brackets.
 1040 The events are shown in Fig. 3c.

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	West				East			
	26 N		50 N		26N		50 N	
	lag (years)	r	Lag (years)	r	lag (years)	r	lag (years)	r
OHC	-15	0.60	-18	0.49	-10	0.76	-12	0.52
SST	-5	0.66	-7	0.76	-5	0.74	-7	0.72
dOHC	-2	0.35	-3	0.54	+3	0.49	0	0.57
dSST	+6	0.24	0	0.40	+5	0.34	+1	0.52
Q _{NET}	-11	-0.55	-16	-0.50	-8	-0.64	-11	-0.57
RFD	-4	0.74	-6	0.57	0	0.64	-1	0.58
Q _{NET} /hbar	-11	-0.55	-16	-0.50	-8	-0.64	-11	-0.57
RML/hbar	-3	0.34	-16	0.31	0	0.44	0	0.57

1047 - AMOC leads +AMOC lags

1048 Table 3 Correlation coefficients for lagged regressions between the AMOC and OHC,
1049 SST and associated terms for the eastern and western SPNA. The maximum correlation
1050 (r), and the lag at which the maximum occurs (years) is shown.

1051

OHC Depth (m)	West		East	
	Lag (months)	r	Lag (months)	r
100	-3	0.94	0	0.98
200	-6	0.92	0	0.97
500	-15	0.83	-3	0.95
1000	-26	0.74	-10	0.88
Full depth	-45	0.61	-19	0.75

1052 Table 4 Correlation coefficients for lagged regressions between the OHC and SST for
1053 the eastern and western SPNA shown in Fig. 8. The maximum correlation (r), and the
1054 lag at which the maximum occurs (months) is shown.

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1062 **Figure Captions**

1063 Fig. 1. a) HadGEM3-GC2 control simulation 300-year mean full depth OHC tendency
1064 component due to net surface heat flux (W m^{-2}) b) as a) for SST tendency (K month^{-1})
1065 A negative surface net heat flux indicates a loss of heat from ocean to atmosphere. c)
1066 seasonal MLD variation (m) during model year 2295 at 24.8°W , 55.4°N . Horizontal
1067 lines represent depth horizons of 100 m, 200 m, and the maximum MLD of 482.5 m at
1068 this location (d) Q_{NET} (blue) and accumulated Q_{NET} (red) (W m^{-2}) at 24.8°W , 55.4°N ,
1069 e) Q_{NET}/h (blue) and accumulated Q_{NET}/h (red) (W m^{-3}) at 24.8°W , 55.4°N .

1070 Fig. 2. a) The HadGEM3-GC2 AMV index time series and AMOC anomalies (both 10-
1071 year low pass filtered) at b) 26°N and c) 50°N . d) SST pattern associated with the AMV,
1072 represented by the regression slope between AMV index and 10-year low pass filtered
1073 SST anomalies at each grid point over 300 model years. Dots indicate values which are
1074 significant at the 95% level.

1075 Fig. 3. a) Lagged correlation between the AMOC anomaly (Sv) and the AMV (both 10-
1076 year low pass filtered) indicating the AMV lags the AMOC at 26°N (black) and 50°N
1077 (red). Thick lines indicate correlations are significant at the 95% level. AMOC anomaly
1078 at b) 26°N and c) 50°N . Events spanning a full AMOC cycle are indicated by letters A-
1079 D. Colours represent four different phases of the AMOC in each event: phase 1 (red),
1080 phase 2 (blue), phase 3 (cyan), and phase 4 (magenta).

1081 Fig. 4. Composites of (a-d) net OHC tendency (W m^{-2}) on AMOC phase at 26°N , phases
1082 1-4. (e-h) same as (a-d) at 50°N . (i-l) net SST tendency (K month^{-1}) on AMOC phase
1083 at 26°N , phases 1-4. (m-p) same as (i-l) for 50°N . The timings and durations of the
1084 phases and events are shown in Fig. 3b, c. Thick black lines define the western and
1085 eastern SPNA used in this analysis.

1086 Fig. 5. Composites of (a-d) Q_{NET}^* ($W m^{-2}$) on AMOC phase at $26^\circ N$, phases 1-4. (e-h)
 1087 same as (a-d) at $50^\circ N$. (i-l) R_{FD}^* ($W m^{-2}$) on AMOC phase at $26^\circ N$, phases 1-4. (m-p)
 1088 same as (i-l) for $50^\circ N$. The timings and durations of the phases and events are shown
 1089 in Fig. 3b, c. Thick black lines define the western and eastern SPNA used in this
 1090 analysis.

1091 Fig. 6. Composites on each phase 1-4 of the AMOC at $26^\circ N$. (a-d) $\left[\frac{R_{ML}}{\rho_0 C_P \bar{h}}\right]^*$ ($W m^{-2}$). (e-
 1092 h) $\Re_{ML}^* / \rho_0 C_P \bar{h}$. (i-l) $\mathbb{R}_{ML}^* / \rho_0 C_P \bar{h}$ ($\lambda = 0.99$) The timings and durations of the phases
 1093 and events are shown in Fig. 3b, c). Thick black lines define the western and eastern
 1094 SPNA used in this analysis.

1095 Fig. 7. Full depth OHC (red), SST (blue) anomalies in (a) western (b) eastern SPNA.
 1096 AMOC anomalies (c) at $26^\circ N$ (black) and AMOC at $50^\circ N$ (magenta). All variables are
 1097 10 year lowpass filtered.

1098 Fig. 8. Variation in OHC anomaly ($J m^{-2}$) evaluated from the surface to various depths
 1099 (100m, 200m, 500m, 1000m, full depth) and their relationship with SST anomaly in a)
 1100 western b) eastern SPNA. SST has been scaled and offset for comparison with the OHC.
 1101 c-d) Correlation coefficient between OHC and SST for depths between 100m and
 1102 1000m, and lags between -20 and 20 years. Negative lag indicate SST leading OHC.
 1103 All variables are 10 year lowpass filtered.

1104 Fig 9. Terms in the OHC Eq. (2): Q_{NET}^* (black), and R_{FD}^* (blue) averaged over a)
 1105 western and b) eastern SPNA. (c, d) $\frac{\partial \theta_{FD}^*}{\partial t}$ averaged over western and eastern SPNA.
 1106 All variables are 10 year lowpass filtered.

1107 Fig. 10. Terms in the SST Eqs. (9)-(12): $\left[\frac{Q_{NET}}{\rho_0 C_P \bar{h}}\right]^*$ (black) and $\left[\frac{R_{ML}}{\rho_0 C_P \bar{h}}\right]^*$ (blue) for (a)
 1108 western and (b) eastern SPNA. (c, d) $\frac{Q_{NET}^*}{\rho_0 C_P \bar{h}}$ (black) and $\Re_{ML}^* / \rho_0 C_P \bar{h}$ (blue) for western

1109 and eastern SPNA. (e, f) $(1 - \lambda)Q_{NET}^*/\rho_0C_P\bar{h}$ (black) and $\mathbb{R}_{ML}^*/\rho_0C_P\bar{h}$ (blue) for
 1110 western and eastern SPNA. (g, h) $\frac{\partial \xi^*}{\partial t}$ for western and eastern SPNA.

1111 Fig. 11. Correlation coefficient between processes in the western (black) and eastern
 1112 (red) SPNA at different lags. Thick lines indicate regressions of 95% significance. All
 1113 variables are 10 year lowpass filtered. (a) $\frac{\partial \theta_{FD}^*}{\partial t}$ vs $\frac{\partial \xi^*}{\partial t}$ (b) Q_{NET}^* vs $\frac{(1-\lambda)Q_{NET}^*}{\rho_0C_P\bar{h}}$ (c)
 1114 R_{FD}^* vs $\mathbb{R}_{ML}^*/\rho_0C_P\bar{h}$. Negative lag indicates that the second term leads the first (e.g
 1115 in the west $\frac{\partial \xi^*}{\partial t}$ leads $\frac{\partial \theta_{FD}^*}{\partial t}$ in a).

1116 Fig 12 SST anomaly, ξ^* , and full depth OHC anomaly, θ_{FD}^* , in red and blue
 1117 respectively, for composite AMOC event averaged over the a) western and b) eastern
 1118 SPNA. $\frac{\partial \theta_{FD}^*}{\partial t}$ (cyan), net surface heat flux anomaly, Q_{NET}^* (red), and anomalous
 1119 advection, R_{FD}^* (blue) for composite AMOC event averaged over the c) western and
 1120 d) eastern SPNA. $\frac{\partial \xi^*}{\partial t}$ (cyan), adjusted surface flux anomaly related term $\frac{(1-\lambda)Q_{NET}^*}{\rho_0C_P\bar{h}}$
 1121 (red) and adjusted advection-entrainment term $\mathbb{R}_{ML}^*/\rho_0C_P\bar{h}$ (blue) for composite
 1122 AMOC event averaged over e) western and f) eastern SPNA. The AMOC anomaly for
 1123 the composite event is plotted as a black curve in all panels.

1124 Fig 13 (a) net OHC tendency (black) in the western SPNA for the composite AMOC
 1125 event. Average surface flux (red) and advection (blue) for heat budget regimes. (b) as
 1126 (a) for the eastern SPNA (c) net SST tendency (black) in the western SPNA for the
 1127 composite AMOC event. Average surface heat flux (red) and advection (blue) terms
 1128 for SST equation regimes. (d) as (c) for the eastern SPNA.

1129 Fig A2.1 (a) maximum correlation coefficient, r , between R_{FD}^* and $\mathbb{R}_{ML}^*/\rho_0C_P\bar{h}$ for
 1130 the western (black) and eastern (red) SPNA as a function of the parameter λ in Eq. (12)

1131 (b) lag at which the maximum correlation occurs (years) for western (black) and eastern

1132 (red) SPNA. Negative lag means $\mathbb{R}_{ML}^* / \rho_0 C_P \bar{h}$ precedes \mathbb{R}_{FD}^* .

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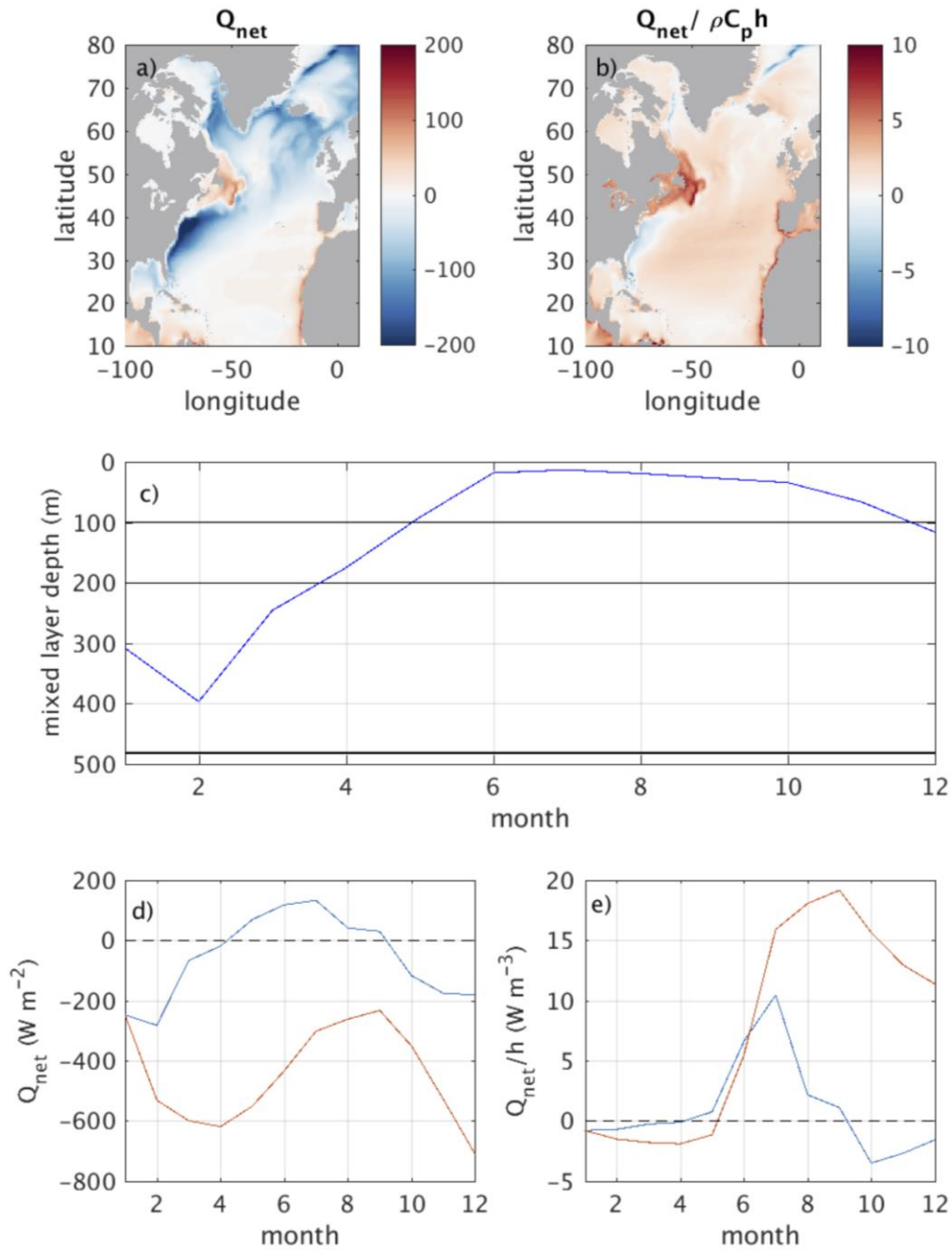


Fig. 1. a) HadGEM3-GC2 control simulation 300-year mean full depth OHC tendency component due to net surface heat flux ($W m^{-2}$) b) as a) for SST tendency ($K month^{-1}$) A negative surface net heat flux indicates a loss of heat from ocean to atmosphere. c) seasonal MLD variation (m) during model year 2295 at $24.8^\circ W, 55.4^\circ N$. Horizontal lines represent depth horizons of 100 m, 200 m, and the maximum MLD of 482.5 m at this location (d) Q_{NET} (blue) and accumulated Q_{NET} (red) ($W m^{-2}$) at $24.8^\circ W, 55.4^\circ N$, e) Q_{NET}/h (blue) and accumulated Q_{NET}/h (red) ($W m^{-3}$) at $24.8^\circ W, 55.4^\circ N$.

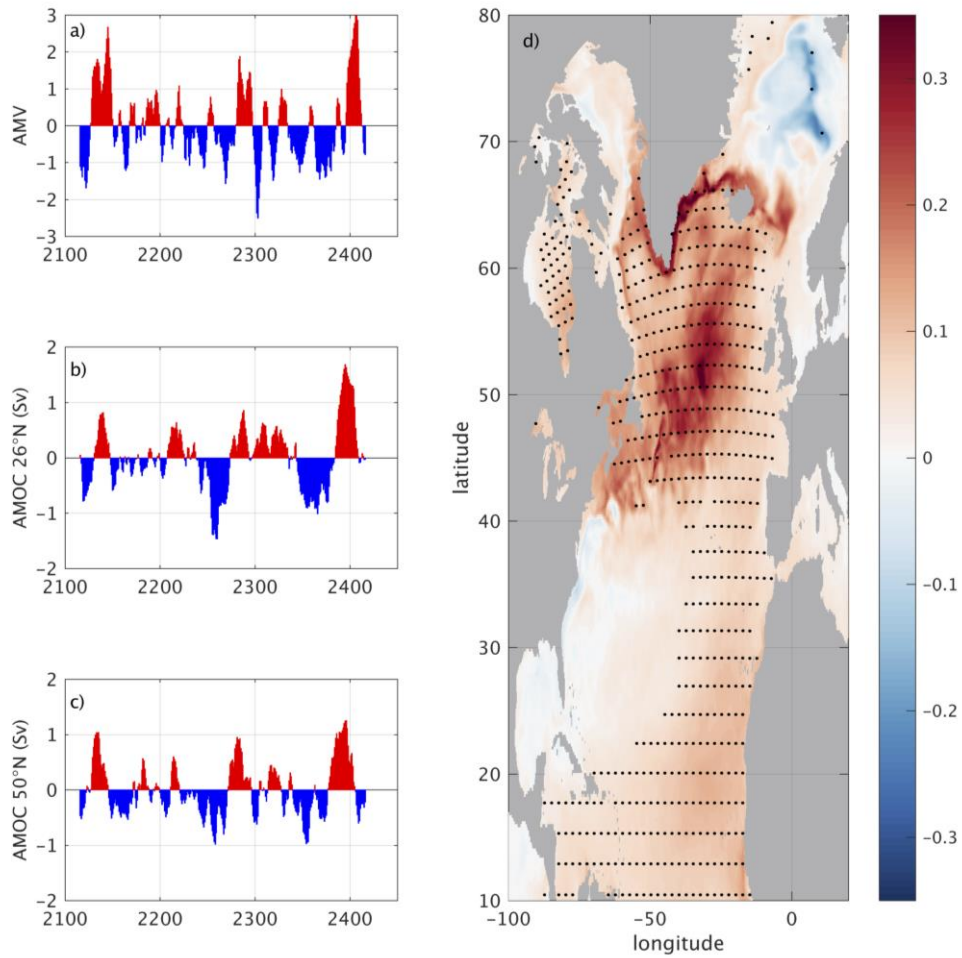


Fig. 2. a) The HadGEM3-GC2 AMV index time series and AMOC anomalies (both 10-year low pass filtered) at b) 26°N and c) 50°N. d) SST pattern associated with the AMV, represented by the regression slope between AMV index and 10-year low pass filtered SST anomalies at each grid point over 300 model years. Dots indicate values which are significant at the 95% level.

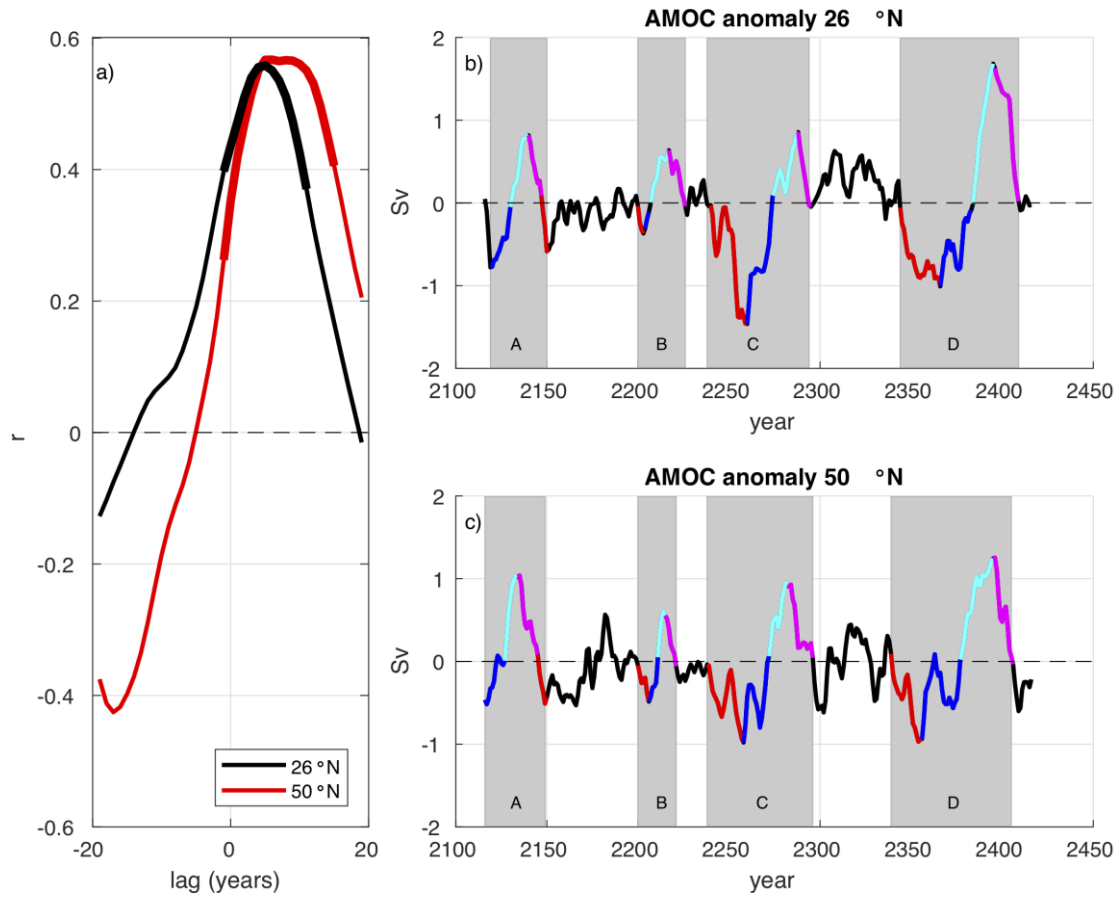


Fig. 3. a) Lagged correlation between the AMOC anomaly (Sv) and the AMV (both 10-year low pass filtered) indicating the AMV lags the AMOC at 26°N (black) and 50°N (red). Thick lines indicate correlations are significant at the 95% level. AMOC anomaly at b) 26°N and c) 50°N. Events spanning a full AMOC cycle are indicated by letters A-D. Colours represent four different phases of the AMOC in each event: phase 1 (red), phase 2 (blue), phase 3 (cyan), and phase 4 (magenta).

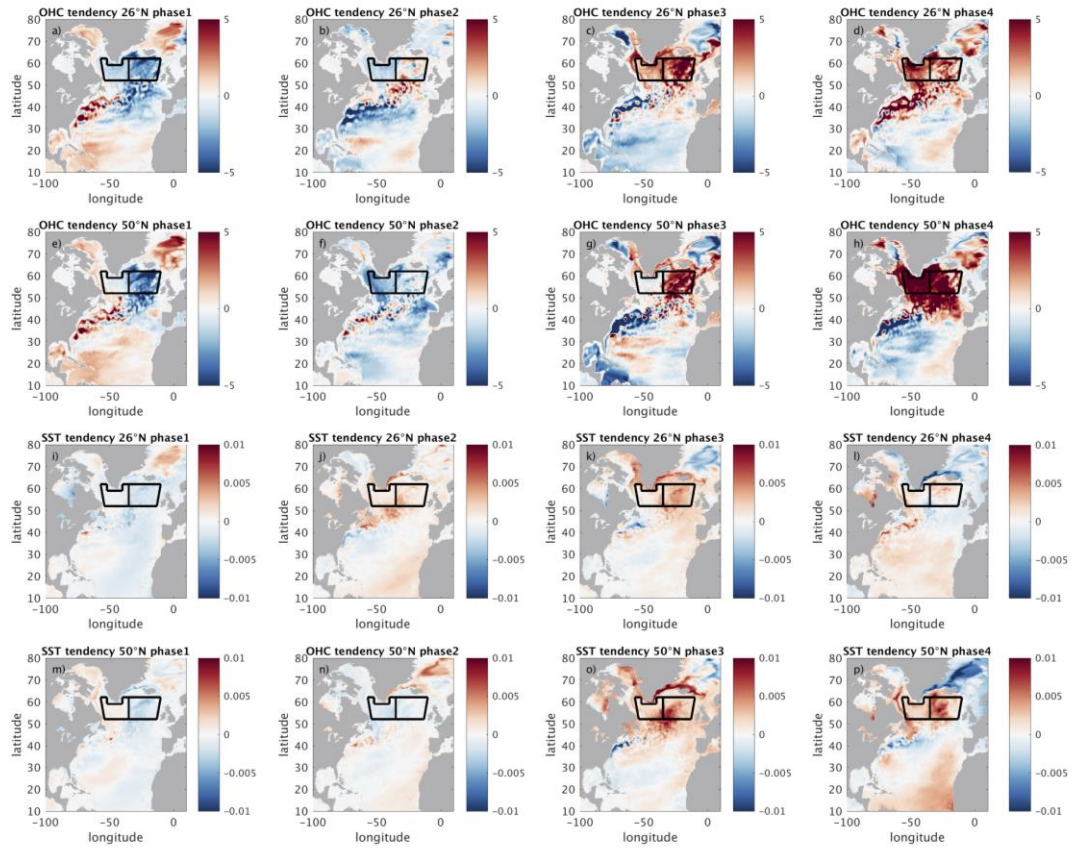


Fig. 4. Composites of (a-d) net OHC tendency (W m^{-2}) on AMOC phase at 26°N , phases 1-4. (e-h) same as (a-d) at 50°N . (i-l) net SST tendency (K month^{-1}) on AMOC phase at 26°N , phases 1-4. (m-p) same as (i-l) for 50°N . The timings and durations of the phases and events are shown in Fig. 3b, c. Thick black lines define the western and eastern SPNA used in this analysis.

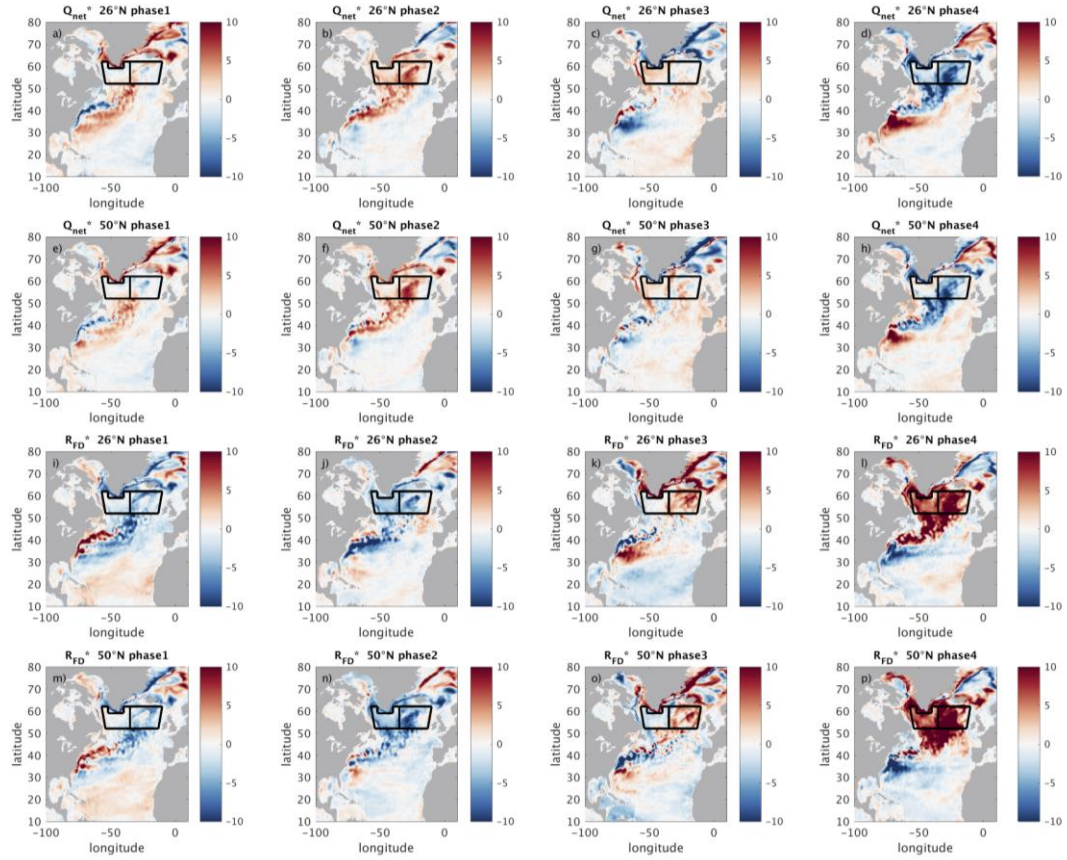


Fig. 5. Composites of (a-d) Q_{NET}^* ($W m^{-2}$) on AMOC phase at $26^\circ N$, phases 1-4. (e-h) same as (a-d) at $50^\circ N$. (i-l) R_{FD}^* ($W m^{-2}$) on AMOC phase at $26^\circ N$, phases 1-4. (m-p) same as (i-l) for $50^\circ N$. The timings and durations of the phases and events are shown in Fig. 3b, c. Thick black lines define the western and eastern SPNA used in this analysis.

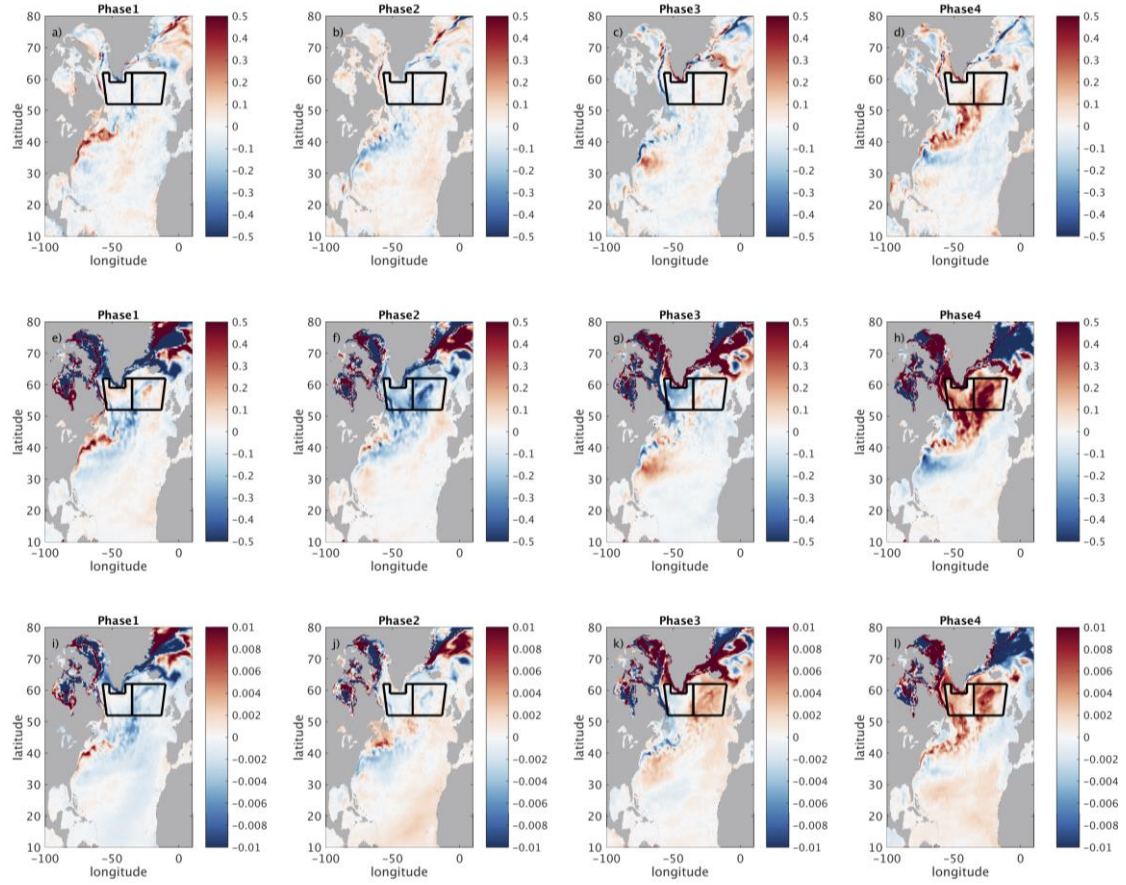


Fig. 6. Composites on each phase 1-4 of the AMOC at 26°N. (a-d) $\left[\frac{R_{ML}}{\rho_0 C_P \bar{h}}\right]^*$ (W m^{-2}). (e-h) $\mathfrak{R}_{ML}^* / \rho_0 C_P \bar{h}$. (i-l) $\mathfrak{R}_{ML}^* / \rho_0 C_P \bar{h}$ ($\lambda = 0.99$) The timings and durations of the phases and events are shown in Fig. 3b, c). Thick black lines define the western and eastern SPNA used in this analysis.

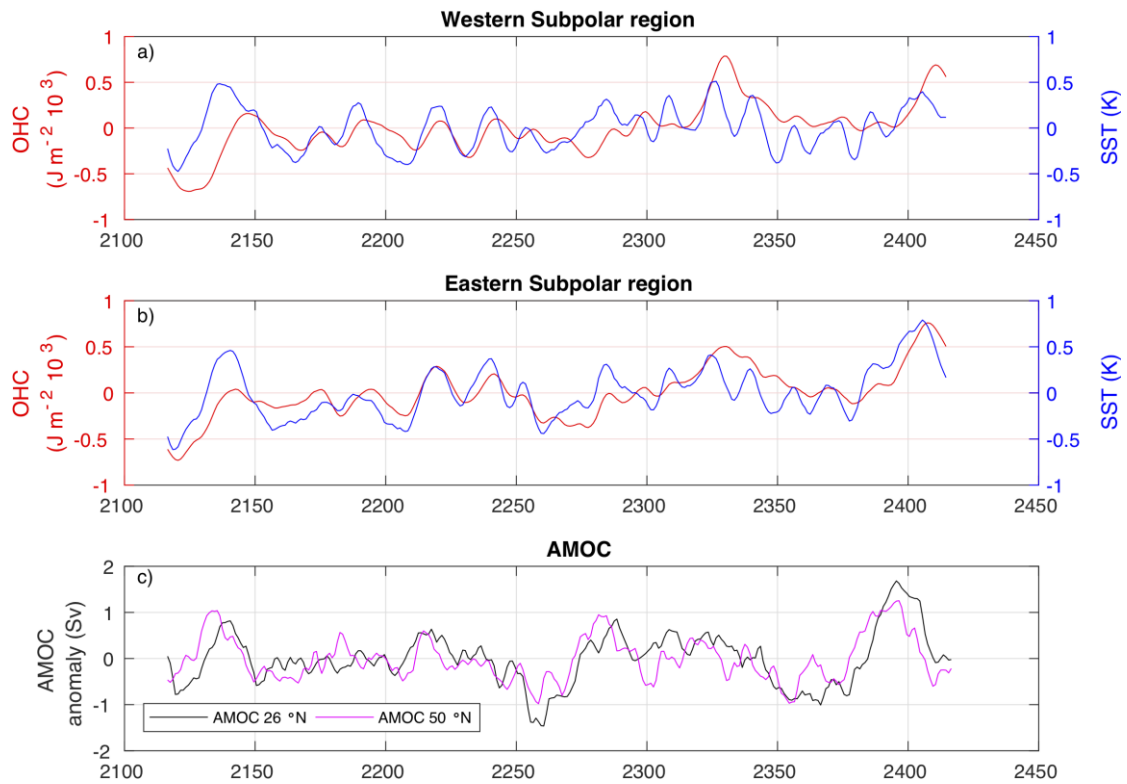


Fig. 7. Full depth OHC (red), SST (blue) anomalies in (a) western (b) eastern SPNA. AMOC anomalies (c) at 26°N (black) and AMOC at 50°N (magenta). All variables are 10 year lowpass filtered.

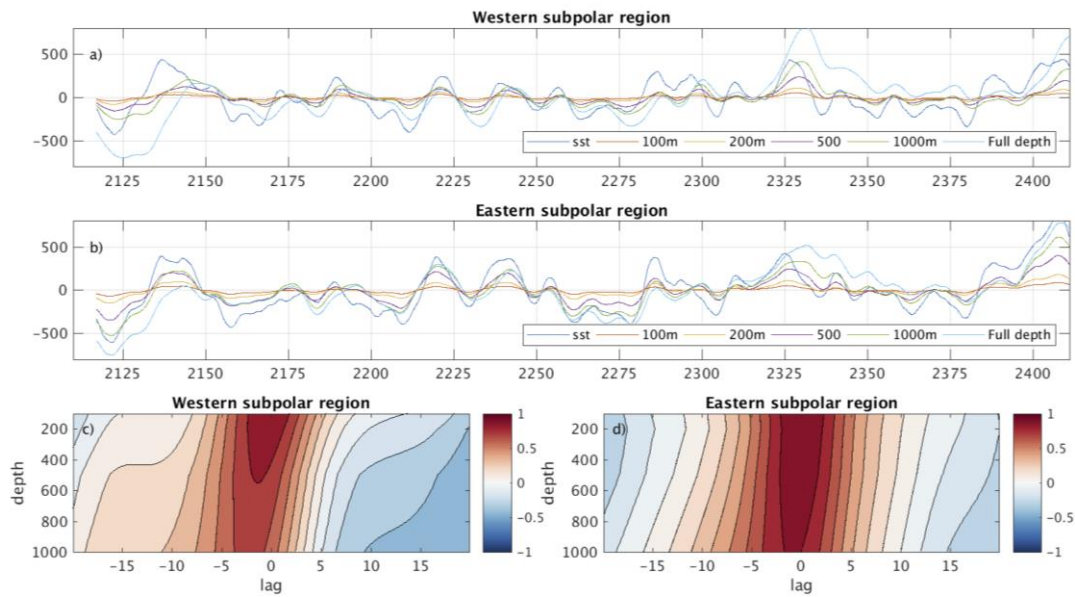


Fig. 8. Variation in OHC anomaly (J m^{-2}) evaluated from the surface to various depths (100m, 200m, 500m, 1000m, full depth) and their relationship with SST anomaly in a) western b) eastern SPNA. SST has been scaled and offset for comparison with the OHC. c-d) Correlation coefficient between OHC and SST for depths between 100m and 1000m, and lags between -20 and 20 years. Negative lag indicate SST leading OHC. All variables are 10 year lowpass filtered.

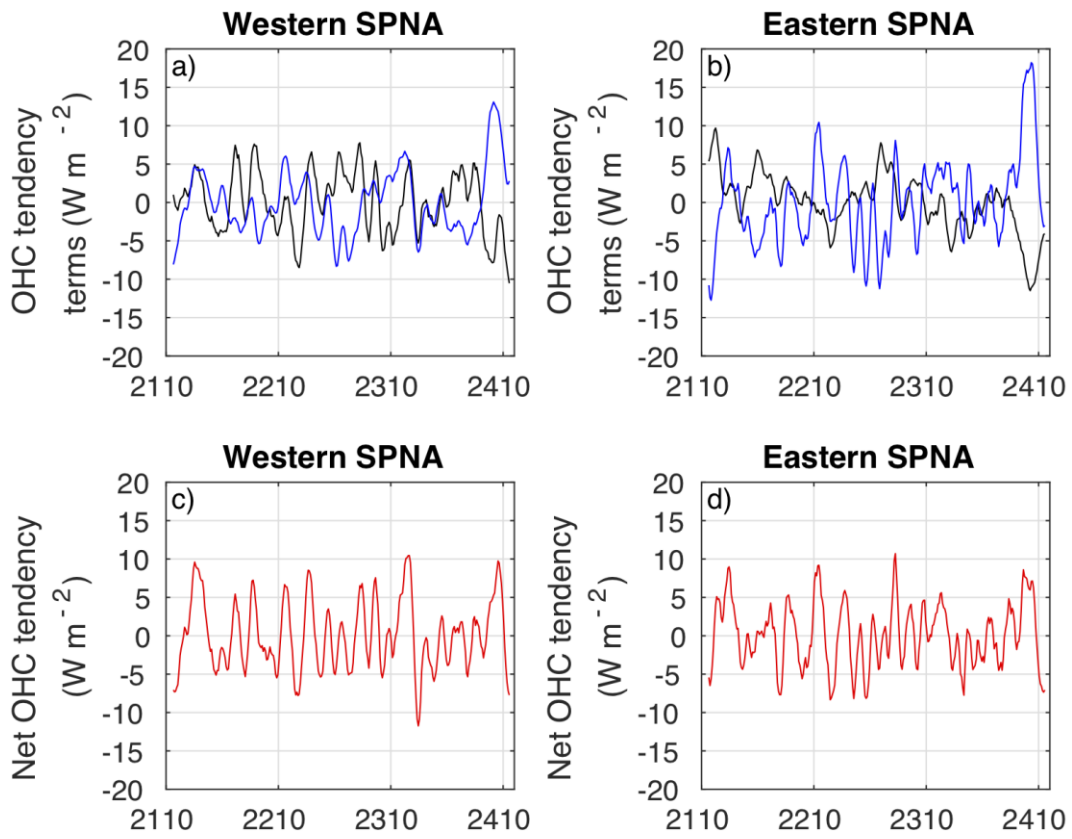


Fig 9. Terms in the OHC Eq. (2): Q_{NET}^* (black), and R_{FD}^* (blue) averaged over a) western and b) eastern SPNA. (c, d) $\frac{\partial \theta_{FD}^*}{\partial t}$ averaged over western and eastern SPNA. All variables are 10 year lowpass filtered.

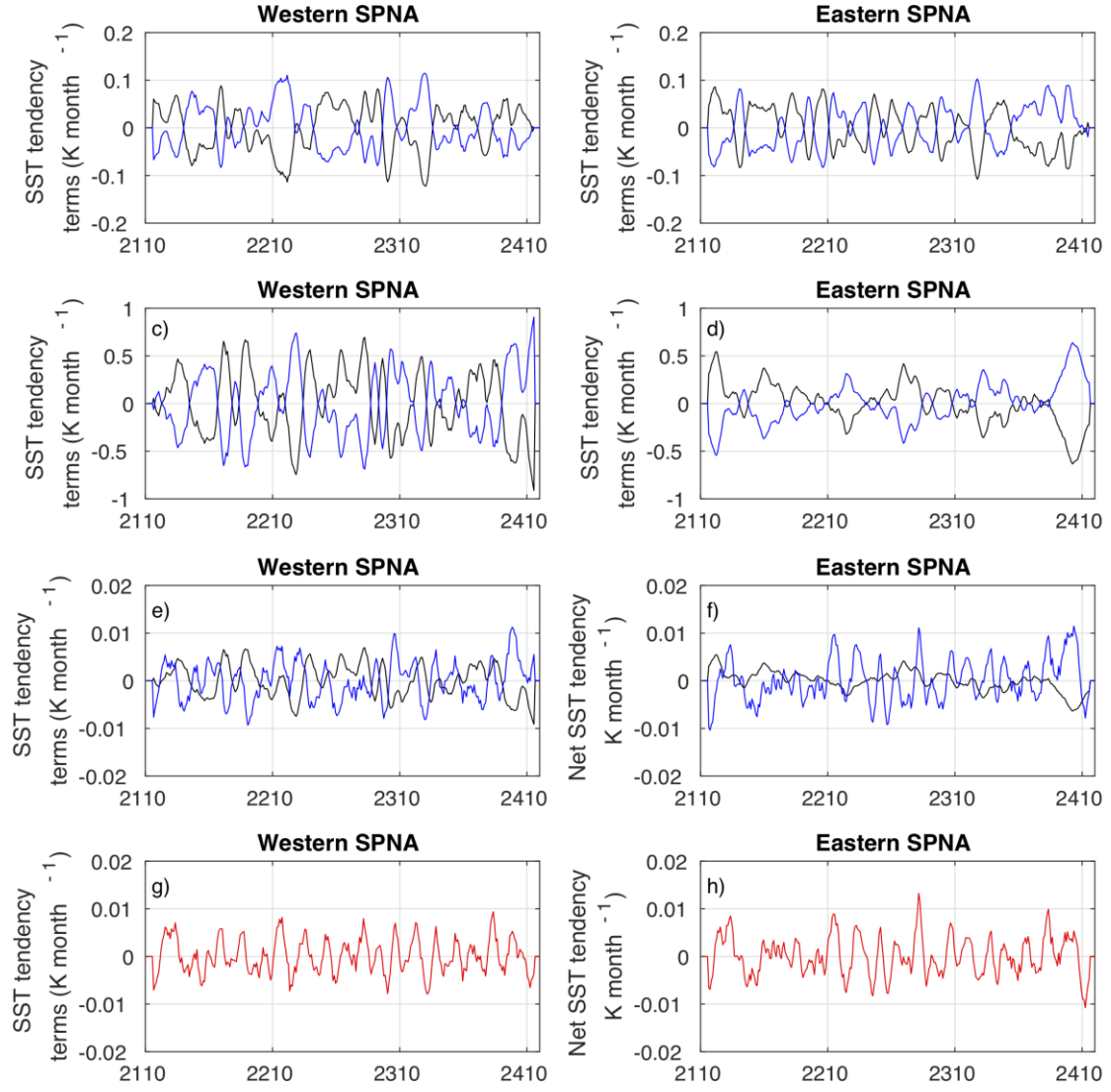


Fig. 10. Terms in the SST Eqs. (9)-(12): $\left[\frac{Q_{NET}}{\rho_0 C_P h}\right]^*$ (black) and $\left[\frac{R_{ML}}{\rho_0 C_P h}\right]^*$ (blue) for (a) western and (b) eastern SPNA. (c, d) $\frac{Q_{NET}^*}{\rho_0 C_P \bar{h}}$ (black) and $\mathfrak{R}_{ML}^*/\rho_0 C_P \bar{h}$ (blue) for western and eastern SPNA. (e, f) $(1 - \lambda)Q_{NET}^*/\rho_0 C_P \bar{h}$ (black) and $\mathfrak{R}_{ML}^*/\rho_0 C_P \bar{h}$ (blue) for western and eastern SPNA. (g, h) $\frac{\partial \xi^*}{\partial t}$ for western and eastern SPNA.

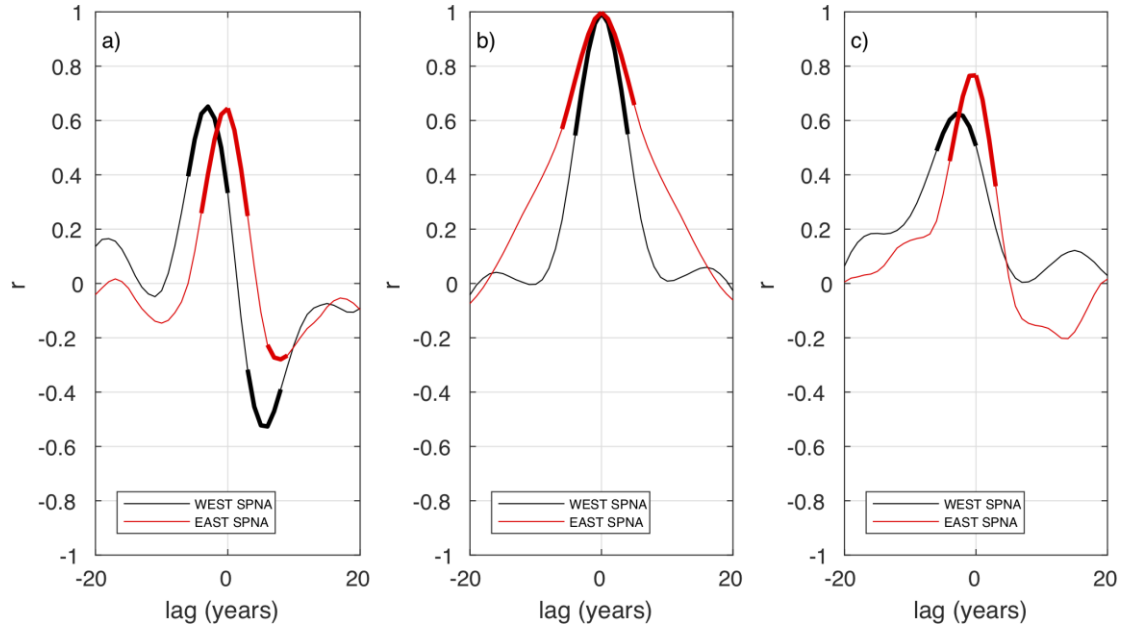


Fig. 11. Correlation coefficient between processes in the western (black) and eastern (red) SPNA at different lags. Thick lines indicate regressions of 95% significance. All variables are 10 year lowpass filtered. (a) $\frac{\partial \theta_{FD}^*}{\partial t}$ vs $\frac{\partial \xi^*}{\partial t}$ (b) Q_{NET}^* vs $\frac{(1-\lambda)Q_{NET}^*}{\rho_0 C_P \bar{h}}$ (c) R_{FD}^* vs $\mathbb{R}_{ML}^* / \rho_0 C_P \bar{h}$. Negative lag indicates that the second term leads the first (e.g in the west $\frac{\partial \xi^*}{\partial t}$ leads $\frac{\partial \theta_{FD}^*}{\partial t}$ in a).

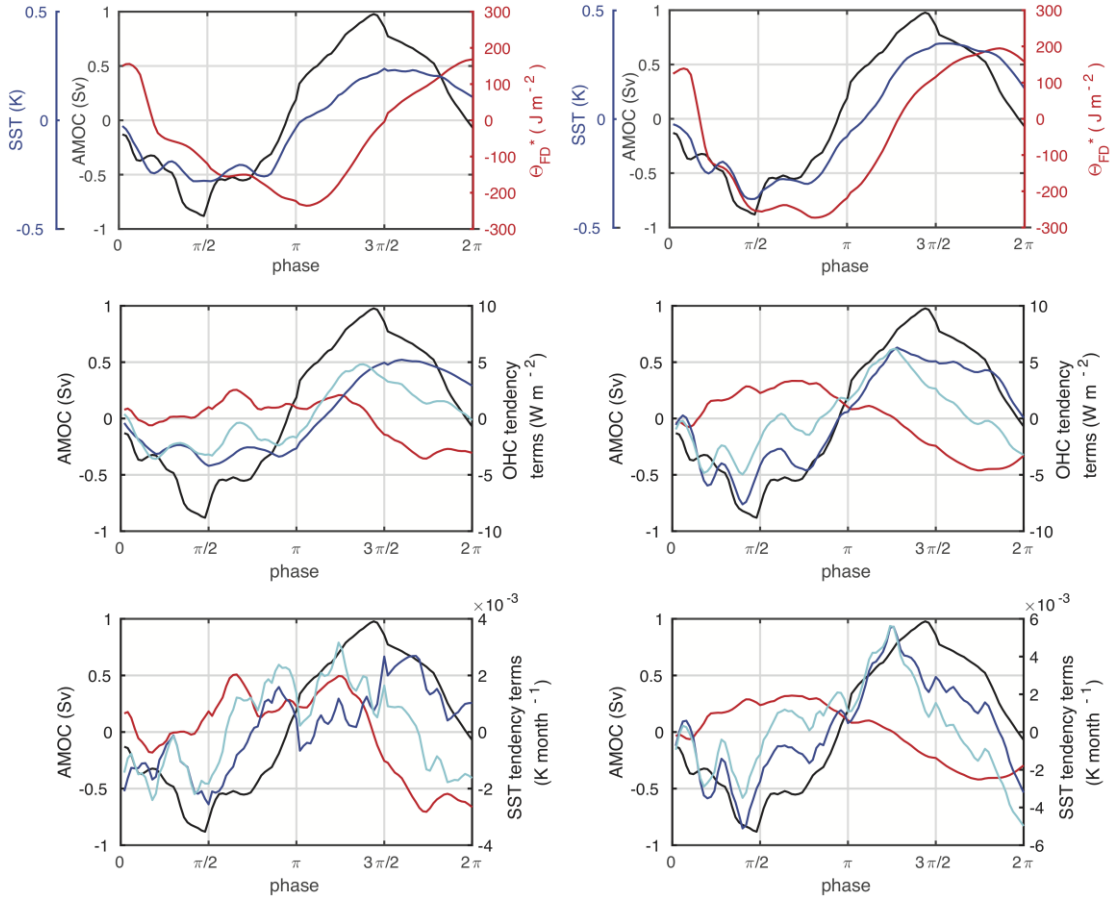


Fig 12 SST anomaly, ξ^* , and full depth OHC anomaly, θ_{FD}^* , in red and blue respectively, for composite AMOC event averaged over the a) western and b) eastern SPNA. $\frac{\partial \theta_{FD}^*}{\partial t}$ (cyan), net surface heat flux anomaly, Q_{NET}^* (red), and anomalous advection, R_{FD}^* (blue) for composite AMOC event averaged over the c) western and d) eastern SPNA. $\frac{\partial \xi^*}{\partial t}$ (cyan), adjusted surface flux anomaly related term $\frac{(1-\lambda)Q_{NET}^*}{\rho_0 C_P \bar{h}}$ (red) and adjusted advection-entrainment term $\mathbb{R}_{ML}^*/\rho_0 C_P \bar{h}$ (blue) for composite AMOC event averaged over e) western and f) eastern SPNA. The AMOC anomaly for the composite event is plotted as a black curve in all panels.

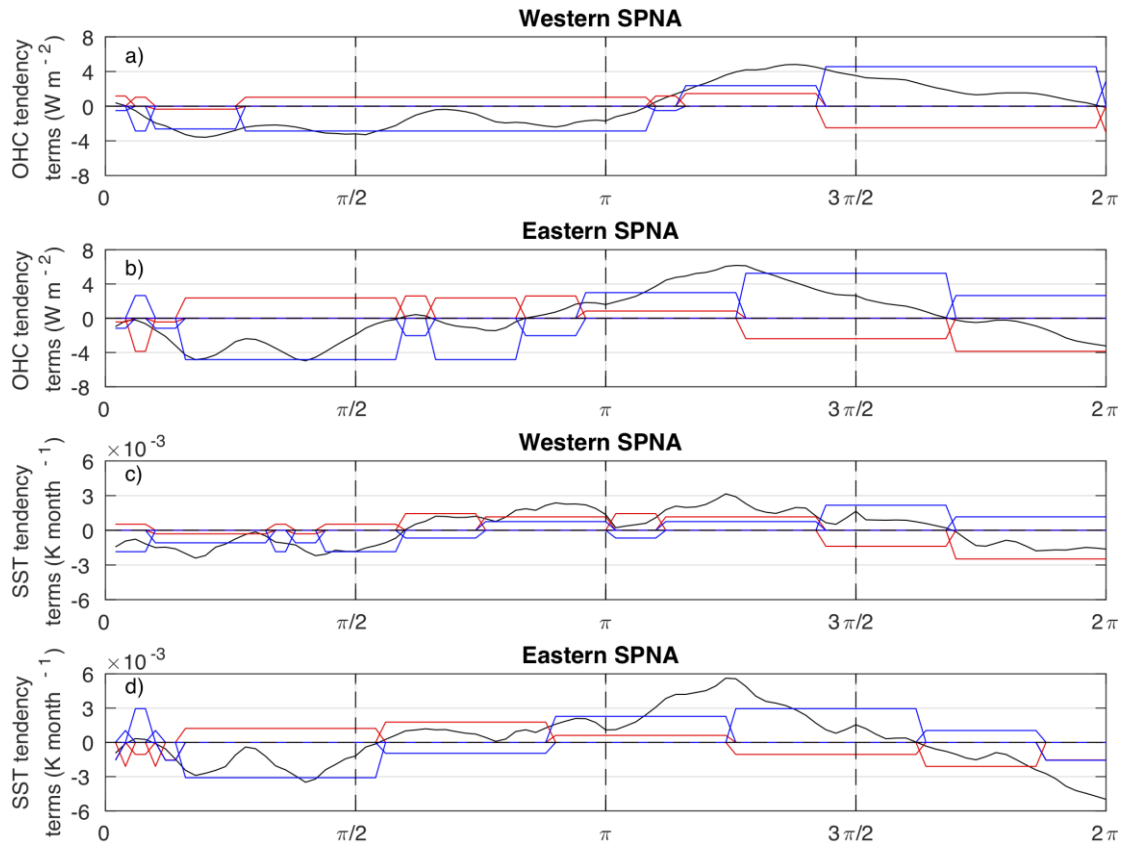


Fig 13 (a) net OHC tendency (black) in the western SPNA for the composite AMOC event. Average surface flux (red) and advection (blue) for heat budget regimes. (b) as (a) for the eastern SPNA (c) net SST tendency (black) in the western SPNA for the composite AMOC event. Average surface heat flux (red) and advection (blue) terms for SST equation regimes. (d) as (c) for the eastern SPNA.

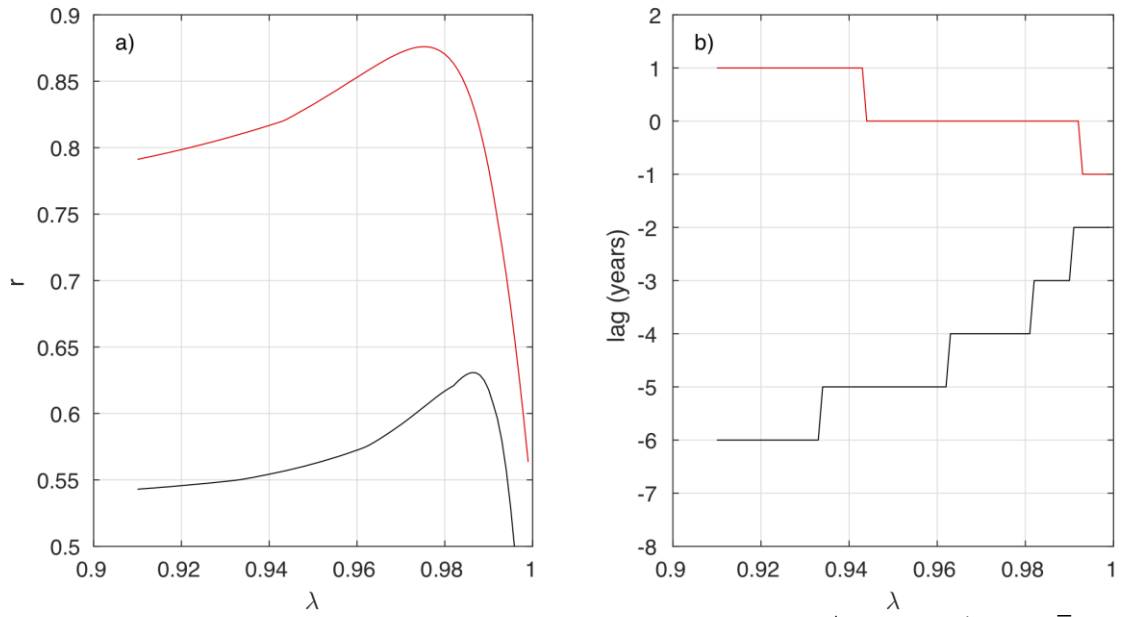


Fig A2.1 (a) maximum correlation coefficient, r , between R_{FD}^* and $\mathbb{R}_{ML}^*/\rho_0 C_P \bar{h}$ for the western (black) and eastern (red) SPNA as a function of the parameter λ in Eq. (12) (b) lag at which the maximum correlation occurs (years) for western (black) and eastern (red) SPNA. Negative lag means $\mathbb{R}_{ML}^*/\rho_0 C_P \bar{h}$ precedes R_{FD}^* .