

1 **Overturning in the Subpolar North Atlantic Program: a new international ocean**

2 **oAbserving system**

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45 **A new ocean observing system has been launched in the North Atlantic in order to**
46 **understand the linkage between the meridional overturning circulation and deep water**
47 **formation.**

48

49 **ABSTRACT**

50 For decades oceanographers have understood the Atlantic Meridional Overturning Circulation
51 (AMOC) to be primarily driven by changes in the production of deep water formation in the
52 subpolar and subarctic North Atlantic. Indeed, current IPCC projections of an AMOC slowdown
53 in the 21st century based on climate models are attributed to the inhibition of deep convection
54 in the North Atlantic. However, observational evidence for this linkage has been elusive: there
55 has been no clear demonstration of AMOC variability in response to changes in deep water
56 formation. The motivation for understanding this linkage is compelling since the overturning
57 circulation has been shown to sequester heat and anthropogenic carbon in the deep ocean.
58 Furthermore, AMOC variability is expected to impact this sequestration as well as have
59 consequences for regional and global climates through its effect on the poleward transport of
60 warm water. Motivated by the need for a mechanistic understanding of the AMOC, an
61 international community has assembled an observing system, Overturning in the Subpolar
62 North Atlantic (OSNAP), to provide a continuous record of the trans-basin fluxes of heat, mass
63 and freshwater and to link that record to convective activity and water mass transformation at
64 high latitudes. OSNAP, in conjunction with the RAPID/MOCHA array at 26⁰N and other
65 observational elements, will provide a comprehensive measure of the three-dimensional AMOC
66 and an understanding of what drives its variability. The OSNAP observing system was fully
67 deployed in the summer of 2014 and the first OSNAP data products are expected in the fall of
68 2017.

69 INTRODUCTION AND BACKGROUND

70 The ocean's Meridional Overturning Circulation (MOC) is a key component of the global climate
71 system (IPCC AR5 2013). The MOC, characterized in the Atlantic (the AMOC) by a northward
72 flux of warm upper-ocean waters and a compensating southward flux of cool deep waters,
73 plays a fundamental role in establishing the mean climate state and its variability on
74 interannual to longer time scales (Buckley and Marshall 2016; Jackson et al. 2015). Coupled
75 with the winter release of locally stored heat, the heat advected northward as part of the upper
76 AMOC limb (Rhines et al. 2008) keeps the northern hemisphere generally, and western Europe
77 in particular, warmer than they would be otherwise. Variations in AMOC strength are believed
78 to influence North Atlantic sea surface temperatures (Knight et al. 2005; Delworth et al. 2007;
79 Robson et al. 2012; Yeager et al. 2012), leading to impacts on rainfall over the African Sahel,
80 India and Brazil; Atlantic hurricane activity; and summer climate over Europe and North
81 America (Knight et al. 2006; Zhang and Delworth 2006; Sutton and Hodson 2005; Smith et al.
82 2010). Finally, variability of the inflow of warm Atlantic waters into high latitudes has been
83 linked to the decline of Arctic sea-ice (Serreze et al. 2007) and mass loss from the Greenland
84 Ice Sheet (Rignot and Kanagaratnam 2006; Holland et al. 2008; Straneo et al. 2010), both of
85 which have profound consequences for climate variability.

86

87 Though less studied than its impact on climate, the AMOC's role in the ocean carbon cycle has
88 emerged as a recent concern. The North Atlantic is a strong sink for atmospheric CO₂
89 (Takahashi et al. 2009; Khatiwala et al. 2013), accounting for ~40% of the annual mean global
90 air-sea CO₂ flux, with nearly half of that flux occurring north of 50°N. Furthermore, modeling
91 (Halloran et al. 2015; Li et al. 2016) and observational (Sabine et al. 2004) studies show that
92 the North Atlantic plays a crucial role in the uptake of anthropogenic carbon. The AMOC is

93 believed to play a strong role in creating this carbon sink (Pérez et al. 2013): in addition to
94 transporting anthropogenic carbon northward from the subtropical gyre (Rosón et al. 2003),
95 as these northward-flowing surface waters cool they absorb additional CO₂ that is carried to
96 depth when deep waters form (Steinfeldt et al. 2009). The carbon flux in the subpolar North
97 Atlantic is also driven by a strong, annual cycle of net community production (Kortzinger et al.
98 2008). AMOC variability can potentially impact this productivity if there is a disruption to the
99 northward flow of nutrients (Palter and Lozier 2008) or to the supply of nutrients to the
100 surface by convection and mixing. Thus, AMOC variability, through its direct impact on CO₂
101 uptake via transport and overturning and indirectly through its effect on ocean primary
102 productivity, has the potential to alter the ocean's role as a major sink for carbon in the
103 subpolar North Atlantic.

104

105 With such a profound array of implications, it is no surprise that a mechanistic understanding
106 of AMOC variability is a high priority for the climate science community. Hypotheses
107 concerning what drives the overturning fall into two categories (Visbeck 2007; Kuhlbrodt et al
108 2007); is the AMOC “pushed” by buoyancy forcing at high latitudes, or is it “pulled” by vertical
109 mixing supported by wind and tidal forcing? While both mechanisms contribute to the long-
110 term equilibrium state of the AMOC, it is generally believed that overturning variability on
111 interannual to millennial time scales are linked to changes in buoyancy forcing and the
112 associated changes in the formation of dense water masses at high latitudes in the North
113 Atlantic. Below, we provide a brief review of that linkage in the modeling and observational
114 context.

115

116 ***Linkage between convection and AMOC variability: climate models***

117 Current IPCC projections of AMOC slowdown in the 21st century based on an ensemble of
118 climate models (see IPCC AR5 2013, Figures 12-35) are widely attributed to the inhibition of
119 deep convection at high latitudes in the North Atlantic. Similarly, simulations using 20th
120 century coupled ocean-sea ice models also find that AMOC intensification is connected to
121 increased deep water formation in the subpolar North Atlantic (Danabasoglu et al. 2016). This
122 link between AMOC strength and North Atlantic water mass production was made explicit in a
123 study of climate models where a freshwater anomaly was spread uniformly over the subpolar
124 domain (Stouffer et al. 2006). These “hosing” experiments yielded AMOC decreases, with
125 concomitant decreases in surface air and water temperatures in the high-latitude North
126 Atlantic. However, the adequacy of coarse resolution models to simulate the ocean’s dynamical
127 response to freshwater sources has been called into question in the past few years. For
128 example, Condrón and Winsor (2011) argue that the climatic response to anomalous
129 freshwater input needs to be studied with models that resolve the dynamics of narrow, coastal
130 flows into and around the North Atlantic basin. Similarly, although a growing number of model
131 simulations suggest that present day and projected ice loss from the Greenland Ice Sheet may
132 affect the AMOC, the nature and magnitude of the prescribed freshwater fluxes may not
133 appropriately describe how and where Greenland meltwater enters the ocean (Straneo and
134 Heimbach 2013). Clearly, observational studies are needed to guide and constrain modelling
135 efforts aimed at understanding the mechanistic link between convective activity and AMOC
136 variability.

137

138 ***Linkage between convection and AMOC variability: observations***

139 Dense water formation in the Nordic Seas and in the North Atlantic subpolar gyre (NASPG)
140 produces the water masses in the AMOC lower limb (Figure 1). The deepest constituents of the

141 lower limb originate as dense intermediate waters formed in the Nordic Seas. These waters,
142 referred to collectively as overflow waters (OW), flow over the shallow sills of the Greenland-
143 Scotland Ridge (GSR) into the North Atlantic: to the east of Iceland is the Iceland-Scotland
144 Overflow Water (ISOW), which has traditionally been thought to follow the topography around
145 the Reykjanes Ridge to the Irminger Basin where it joins the deeper, denser Denmark Strait
146 Overflow Water (DSOW). The shallowest component of the AMOC lower limb is the
147 intermediate water produced by deep convection within the NASPG itself. Though this water
148 mass is referred to as Labrador Sea Water (LSW), it is the product of the cumulative
149 transformation of subtropical waters as they flow around the NASPG.

150

151 No conclusive observational evidence for a link between dense water formation in the
152 Labrador Sea and AMOC variability has emerged to date (Lozier 2012). The product of that
153 dense water formation - Labrador Sea Water - is exported out of the basin via a deep western
154 boundary current. As such, that boundary current has been closely monitored over the past
155 two decades. Measurements of that boundary current east of the Grand Banks at 43°N during
156 1993 to 1995 and then again from 1999 to 2001 showed that transport in the LSW density
157 range was remarkably steady despite the fact that LSW production was considerably weaker
158 during the latter time period (Clarke et al. 1998; Meinen et al. 2000; Schott et al. 2006; Lazier et
159 al. 2002). Similarly, Dengler et al. (2006) found a strengthening of the Deep Labrador Current
160 at 53°N over the time period of a well-documented decrease in convection. Finally, Pickart et
161 al. (1999) showed that, equatorward of the Grand Banks, the Deep Western Boundary Current
162 (DWBC) appears weaker when it advects a larger fraction of LSW. As with LSW, there has been
163 no conclusive observational evidence linking the formation of Nordic Seas overflow waters
164 with AMOC variability (Jochumsen et al. 2012; Hansen and Østerhus 2007).

165

166 One possible reason for the lack for a clear connection between convection and AMOC
167 variability is that not all of the export pathways of dense waters have been monitored. The
168 DWBC has traditionally been considered the sole conduit for the lower limb of the AMOC.
169 However, this assumption has been challenged by observational and modeling studies that
170 reveal the importance of interior, as well as boundary, pathways (e.g., Bower et al. 2009;
171 Holliday et al. 2009; Stramma et al. 2004; Xu et al. 2010; Lozier et al. 2013).

172

173 Secondly, a direct link between LSW formation and the AMOC has been called into question as
174 more has been learned about the constraints on the spreading of this water away from
175 formation sites (Send and Marshall 1995; Spall and Pickart 2001; Spall 2004; Straneo 2006;
176 Deshayes et al. 2009). Essentially, the compilation of studies over the past decade yields a
177 description of LSW production whereby the properties and transport variability within the
178 DWBC are not a sole function of deep water formation. Instead, boundary current transport,
179 property gradients between the interior and the boundary current and the strength of the eddy
180 field all play a role in setting the exit transport and properties. Finally, the linkage between
181 AMOC variability and deep water formation can be impacted by wind-driven changes in the
182 basin. Since the density field near the basin boundaries sets the overall shear of the basinwide
183 geostrophic circulation, wind-forced changes in that density field can modify AMOC strength
184 (Hirschi and Marotzke 2007).

185

186 In summary, while modeling studies have suggested a linkage between deep water mass
187 formation and AMOC variability, observations to date have been spatially or temporally
188 compromised and therefore insufficient to either support or rule out this connection.

189

190 ***Current observational efforts to assess AMOC variability in the North Atlantic***

191 The UK-US RAPID/MOCHA program at 26°N successfully measures the AMOC in the subtropical
192 North Atlantic via a trans-basin observing system (Cunningham et al. 2007; Kanzow et al. 2007;
193 McCarthy et al. 2015). While this array has fundamentally altered the community's view of the
194 AMOC, modeling studies over the past few years have suggested that AMOC fluctuations on
195 interannual time scales are coherent only over limited meridional distances. In particular, a
196 break point in coherence may occur at the subpolar/subtropical gyre boundary in the North
197 Atlantic (Bingham et al. 2007; Baehr et al. 2009). Furthermore, a recent modeling study has
198 suggested that the low-frequency variability at the RAPID/MOCHA array appears to be an
199 integrated response to buoyancy forcing over the subpolar gyre (Pillar et al. 2016). Thus, a
200 measure of the overturning in the subpolar basin contemporaneous with a measure of the
201 buoyancy forcing in that basin likely offers the best possibility of understanding the
202 mechanisms that underpin AMOC variability. Finally, though it might be expected that the
203 plethora of measurements from the North Atlantic would be sufficient to constrain a measure
204 of the AMOC within the context of an ocean general circulation model, recent studies
205 (Cunningham and Marsh 2010; Karspeck et al. 2015) reveal that there is currently no
206 consensus on the strength or variability of the AMOC in assimilation/reanalysis products.

207

208 **OSNAP OBJECTIVES**

209 Given the imperative of understanding AMOC variability and based on recommendations of the
210 ocean science community (US CLIVAR report 2007; Cunningham et al. 2010), an international
211 team of oceanographers has developed an observing system for sustained trans-basin
212 measurements in the subpolar North Atlantic, called Overturning in the Subpolar North

213 Atlantic Program (OSNAP). OSNAP, deployed in the summer of 2014, is measuring the full-
214 depth mass fluxes associated with the AMOC, as well as meridional heat and freshwater fluxes.

215

216 The specific objectives of the OSNAP program are to:

217 1. Quantify the subpolar AMOC and its intra-seasonal to interannual variability via overturning
218 metrics, including associated fluxes of heat and freshwater.

219 2. Determine the pathways of overflow waters in the NASPG to investigate the connectivity of
220 the deep boundary current system.

221 3. Relate AMOC variability to deep water mass variability and basin-scale wind forcing.

222 4. Determine the nature and degree of the subpolar-subtropical AMOC connectivity.

223 5. Determine from OSNAP observations the configuration of an optimally efficient long-term
224 AMOC monitoring system in the NASPG. Such a determination will include the use of numerical
225 model results, satellite altimetry, Argo data and other NASPG observations as needed.

226

227 **OSNAP DESIGN**

228 OSNAP is a trans-basin observing system (Figures 2 and 3a) that consists of two legs: one leg
229 extends from southern Labrador to southwestern Greenland and the other from southeastern
230 Greenland to the coast of Scotland. The two legs are situated to capitalize on a number of
231 existing long-term observational efforts in the subpolar North Atlantic: the Canadian repeat
232 AR7W program in the Labrador Sea; the German Labrador Sea western boundary mooring
233 array at 53°N; repeat A1E/AR7E hydrographic sections across the Irminger and Iceland Basins
234 (approximately coincident with OSNAP East); the western part of the biennial OVIDE line in the
235 Irminger Sea and over the Reykjanes Ridge (Mercier et al. 2015); and the Ellett line (Holliday et
236 al. 2015) in the Rockall region. Importantly, two of the four moorings that form the US Global

237 OOI (Ocean Observatories Initiative) Irminger Sea node were placed along the OSNAP line
238 (Figure 3b) in August of 2014, thereby enhancing the ability of the OSNAP array to capture the
239 full breadth of the deep currents in this basin. OSNAP also complements a new Canadian
240 program in the Labrador Sea (VITALS: Ventilation Interactions and Transports Across the
241 Labrador Sea) focused on carbon and oxygen cycles. VITALS will provide information on gas
242 uptake and water mass formation north of the OSNAP West line, complementing the water
243 mass information provided by the annual survey of the AR7W line (Yashayaev 2007).

244
245 Mooring arrays have been deployed at the continental boundaries and on the eastern and
246 western flanks of the Reykjanes Ridge (Figure 4). The OSNAP Reykjanes Ridge moorings are
247 complemented by those from the French Reykjanes Ridge Experiments (RREX; Figure 3c), an
248 observational and modeling effort designed to study the processes controlling the dynamical
249 connections between the two sides of the Reykjanes Ridge. Additional full-depth moorings
250 containing T/S sensors have been placed at key locations to estimate geostrophic transports
251 (Figure 4). Additionally, in the eastern basin, a suite of gliders is measuring properties across
252 the Rockall-Hatton Basin and westward into the Iceland basin (Figures 3a and 4b). Finally,
253 acoustically tracked deep floats (RAFOS) have been released on the OSNAP lines to study the
254 connectivity of overflow water pathways between moored arrays and to aid the interpretation
255 of the Eulerian measurements (Figure 3a).

256
257 The effectiveness of the proposed OSNAP design has been tested using a series of OSSE
258 (Observing System Simulation Experiment) where basin-width integrated fluxes calculated
259 from subsampled model fields are compared to the model “truth” or reference fluxes. OSNAP
260 OSSE were conducted using ORCA025, an intermediate resolution, or eddy-permitting,

261 configuration of the Nucleus for European Modeling of the Ocean (NEMO; Madec 2008). The
262 OSSE mean overturning transports for 1990-2004 are within one standard deviation of the
263 mean transports for the model truth, calculated over the same time period: for OSNAP West
264 the model truth mean transport in density space is 7.65 ± 1.68 Sv, while the OSSE mean
265 transport is 7.78 ± 1.73 Sv; for OSNAP East the model truth mean transport is 13.65 ± 1.56 Sv,
266 while the OSSE mean transport is 12.97 ± 2.56 Sv. Furthermore, the proposed design does an
267 impressive job of capturing the overturning variability, with a correlation of 0.89 (0.85)
268 between the OSSE and the reference time series for OSNAP West (East). Comparisons of heat
269 and freshwater fluxes are also favorable: for OSNAP West, the total heat flux is 0.10 ± 0.02 PW
270 for both the model truth and the OSSE ($R= 0.94$), and the total freshwater flux relative to the
271 section mean salinity is -0.17 ± 0.04 Sv for the OSSE and -0.16 ± 0.04 for the model truth ($R=$
272 0.90); for OSNAP East, the total heat flux is 0.36 ± 0.04 PW for the model truth and 0.33 ± 0.05
273 PW for the OSSE ($R= 0.83$), and the total freshwater flux relative to the section mean salinity is
274 -0.14 ± 0.05 Sv for both the model truth and the OSSE ($R= 0.98$). All correlation coefficients in
275 parentheses above denote agreement between the model truth and the OSSE time series.
276 Readers are referred to the OSNAP technical report ([http://www.o-](http://www.osnap.org/observations/technical-report/)
277 [snap.org/observations/technical-report/](http://www.osnap.org/observations/technical-report/)) for details on the calculation methodology and for
278 information on steps we are currently taking to improve our estimates.

279

280 **PROGRESS TO DATE**

281 Due to cost considerations, some of the OSNAP arrays are on a one-year replacement schedule;
282 others on a two-year schedule. Thus, the complete suite of data necessary to produce time
283 series of the volume, heat and freshwater fluxes across the OSNAP line will not be available
284 until September of 2016. However, in addition to these basin integral measures, the OSNAP

285 program will produce, and indeed is already producing, observations of the circulation and
286 property fields across the subpolar gyre. Data that have been collected to date, discussed
287 below, reveal the rich spatial and temporal variability of those fields. The OSNAP observational
288 program is complemented by modeling, theoretical and data analyses efforts that aim to 1)
289 place the observations in a broader spatial and temporal context and 2) link the observations
290 to forcing mechanisms. Preliminary efforts toward this end are also discussed below. Please
291 note that the sections below do not constitute a preliminary look at the comprehensive
292 measurements that will result from the entire suite of OSNAP data, namely the volume, heat
293 and freshwater transports. Rather, the sections below illustrate the wide variety of
294 investigations possible under the OSNAP program.

295

296 ***First look at the OSNAP cross-section velocity field***

297 The OSNAP line was first surveyed with a Conductivity-Temperature-Depth (CTD) section in
298 June-July 2014 on *RRS James Clark Ross*, providing the first modern, quasi-synoptic,
299 hydrographic and biogeochemical section from North America to Europe at subpolar latitudes
300 (King and Holliday 2015; see Keike and Yashayaev (2015) for a review of other hydrographic
301 surveys in the subpolar basin). The cross-section geostrophic velocity field from the survey
302 illustrates the complexity of the circulation in this region (Figure 5, derived from CTD profiles,
303 the thermal wind equation, and a reference velocity from lowered ADCP, following the method
304 in Holliday et al. 2009). The warm North Atlantic Current (NAC) can be seen as two major
305 shallow and surface-intensified currents in the Iceland Basin, plus a jet in the western Rockall
306 Trough, and the cooler Irminger Current on the west side of the Reykjanes Ridge. Between the
307 major currents there are transient eddies and more persistent topographically steered
308 recirculation features. In the Irminger and Labrador Seas the fast gyre boundary currents can

309 be seen tight against the continental slopes of Greenland and Canada. In the western gyre the
310 boundary currents are deep-reaching features, linking the surface circulation to the cold, deep
311 overflow waters (< 3.0 °C). In contrast, from the western side of the Reykjanes Ridge across to
312 Rockall, the upper ocean is often moving in a direction opposing that of the deepest layers. In
313 the Iceland Basin the multiple current cores of overflow waters lie under a thick layer of
314 slowly-circulating LSW and are also subject to recirculation (e.g., southward cores at ~ 2300
315 and ~ 2450 km, and recirculation at ~ 2400 and ~ 2600 km in Figure 5). The OSNAP moorings
316 and Lagrangian observations of overflow pathways will help put these synoptic observations
317 into context, as well as reveal variability on time scales shorter than the time it takes to
318 complete a synoptic survey.

319

320 ***Hydrography across the Irminger and Labrador Seas: signatures of strong convection***

321 The deployment of the OSNAP array in the summer of 2014 was auspiciously timed, as
322 revealed by a hydrographic survey along the OSNAP line in the Irminger Sea in the summer of
323 2015 (de Steur 2015). The survey revealed a large body of water with high dissolved oxygen
324 content and low salinity that fills the central part of the basin at upper to intermediate depths
325 (Figure 6a). Year-round observations from a profiling mooring in the Irminger gyre confirm
326 that this water was formed locally in the strong winter of 2014/2015 when mixed layer depths
327 reached down to 1400 m (de Jong and de Steur 2016). The first time series from the OOI
328 Irminger Sea global node (Figure 6b) shows the sharp increase in oxygen concentration as
329 convection deepens the mixed layer from November to December. These observations confirm
330 the role of the Irminger Sea as a convective basin in addition to the Labrador Sea as suggested
331 earlier by Pickart et al. (2003). In the Labrador Sea strong convection also took place in the
332 winter of 2014/2015 (Yashayaev and Loder 2016, in review). In addition to this signature of

333 deep convection, the survey also shows the familiar features of the warm and saline Irminger
334 Current on the eastern and western boundaries of the basin, as well as the cold, dense and
335 oxygen rich DSOW carried along the East Greenland slope by the DWBC. A new feature,
336 however, is the signature of stirring between the interior waters (high in oxygen) and
337 boundary current water (low in oxygen) that appears over the western flank of the Mid-
338 Atlantic Ridge. Interestingly, deep convection and enhanced mesoscale eddy exchange, may
339 well be related; a connection that will be investigated in detail with OSNAP data.

340

341 The evolution of convection in the Labrador basin during the winter of 2014/2015 will be
342 revealed once data from the OSNAP West arrays (on a two-year schedule) are retrieved. The
343 analysis of that data will be advantaged by the fact that there have been sustained observations
344 in the basin interior (see K1 in Figure 3a) and in the boundary current off the Labrador coast
345 since 1997 (see German boundary array in Figure 3a; Fischer et al. 2004), well before the
346 deployment of the OSNAP array in the summer of 2014. Observations from both sites allow for
347 the study of how convectively transformed waters from the Labrador Sea are exported to the
348 boundary current, as well as a study of water mass transformation within the boundary
349 current itself. The simultaneous observations at K1 and K9 since 2009 have offered an
350 interesting contrast. As seen in Figure 7a, the 2013/2014 winter was characterized by a
351 positive North Atlantic Oscillation (NAO) index that has persisted to present
352 (www.cpc.ncep.noaa.gov). An increase in surface buoyancy loss over the Labrador Sea during
353 this positive NAO index period goes along with an abrupt change in mixed-layer depths in
354 excess of 1500m in the boundary current (at K9; see location in Figure 3a) and in the central
355 Labrador Sea (at K1), a situation last documented in the 2007/2008 winter (Kieke and
356 Yashayaev 2015). While the 2013/2014 response is similar at both sites (though stronger in

357 the interior, at K1), the boundary current response to the 2011/2012 NAO forcing is decidedly
358 weaker. Though it has been pointed out that the NAO index does not optimally indicate
359 buoyancy forcing changes in the Labrador Sea (e.g. Grist et al. 2015), these observations alone
360 highlight the fact that the dynamical link between deep convection in the Labrador Sea and the
361 export of newly formed deep waters in the boundary current remains unresolved. Results from
362 the OSNAP array will enable an investigation of the link between deep mixing, the net water
363 mass formation and the dynamics of the export.

364

365 ***Glider observations in the eastern subpolar region***

366 Some areas across the OSNAP line have been monitored or at least intermittently measured for
367 years, e.g., the waters of the DWBC off the Labrador coast. However, in other areas there are
368 only sparse historical observations, particularly of the flow field, a prime example of which is
369 the Rockall Plateau. Though these observations have been too few to estimate the circulation in
370 this region, ocean model simulations indicate that 2-5 Sv of northward flow should be found
371 here, a sizeable contribution to the total northward flow across the OSNAP East line. However,
372 because the plateau is shallow, no Argo floats are deployed across or drift over the plateau, and
373 because of fishing activities moorings are unlikely to survive. Thus, gliders were chosen to
374 provide property, transport and flux measurements across the plateau. Ten OSNAP glider
375 sections were realized between 21°W and 15°W from July 2014 to November 2015 of which
376 three are shown in Figure 8. Data from past glider missions and real-time data from current
377 missions may be viewed at <http://velocity.sams.ac.uk/gliders/>.

378

379 A remarkable feature of these measurements is the signature of intense vertical mixing that
380 occurred in the 2014/2015 winter. This mixing deepened the mixed layer to 700 m (Figure

381 8b) and resulted in the formation of anomalously large volumes of Subpolar Mode Water
382 (SPMW) in the density range $\sigma_\theta = 27.3$ to 27.4. In a recent paper, Grist et al. (2015) show how
383 excess formation of Subpolar Mode Water (SPMW) in winter (2013-2014) relates to extreme
384 North American temperatures and record-breaking precipitation over the UK during that
385 winter. This volume of SPMW in the density range of $\sigma_\theta = 27.3$ to 27.4 is capped by seasonal
386 stratification (Figure 8a). In the following winter of 2014-2015 (Figure 8b) intense vertical
387 mixing deepens the mixed layer to 700m. By the following summer Figure 8c) the SPMW is
388 again capped by seasonal stratification and there is a larger, denser, volume of SPMW than the
389 previous year. These first observations confirm that the OSNAP glider across the Rockall
390 Plateau is well placed to observe the evolution of SPMW and to quantify ocean-atmosphere
391 dynamic exchanges.

392

393 Gliders are also being employed to enhance the OSNAP data coverage in the eddy-rich region of
394 the Iceland Basin where the NAC flows northward across the section, often in multiple
395 branches (Figure 5). One glider, deployed on the OSNAP-East line in June 2015 and recovered
396 in November 2015, accomplished 519 profiles with a depth range between 0-1000 m while
397 patrolling between moorings M3 and M4 (green line, Figure 3a). A replacement glider,
398 deployed in November 2015, has executed 370 profiles as of March 2016 and is expected to
399 operate until July 2016 when it will be recovered and replaced.

400

401 Between July and November 2015, a strong anticyclonic eddy was sampled by a glider between
402 the M3 and M4 moorings (Figure 9). An anticyclonic eddy is often present in this region, and is
403 a feature of the long-term (20-year) mean Absolute Dynamic Topography (ADT; the altimeter
404 ADT products were produced by Ssalto/Duacs and distributed by Aviso, with support from Cnes <

405 <http://www.aviso.altimetry.fr/duacs/>). Despite rotational currents that affected its path, the glider
406 successfully produced a hydrographic section that shows relatively warm, salty and high
407 oxygen waters for the eddy core, indicating that the water trapped in the eddy is probably
408 recently ventilated water from the NAC. The eddy moved northeastward by the time of the
409 second glider deployment, revealing the relatively smooth front separating the warm, salty and
410 low oxygen water in the east from the relatively cold, fresh and high oxygen water in the west.
411 The high-resolution sections of temperature, salinity, and geostrophic velocity across this
412 region provided by the gliders will lead to increased accuracy in estimates of heat and
413 freshwater flux over that available from the mooring observations and Argo data alone.

414

415 ***Complementary model and data-based analyses***

416 In order to quantify the transformation of the warm waters of the AMOC upper limb that flow
417 northward across the OSNAP line into cooler waters that return southward at depth across the
418 line, information is needed on the surface fluxes of heat and fresh water responsible for the
419 transformation. A Regional Thermohaline Inverse Method (RTHIM), which extends the Walin
420 (1982) water mass transformation framework to two water mass coordinates (Groeskamp et
421 al. 2014), quantifies this transformation using surface fluxes from climate reanalysis and
422 observations from Argo floats and satellite altimetry. Importantly, RTHIM provides an estimate
423 of the volume fluxes (AMOC) independent of the OSNAP array observations. RTHIM has been
424 successfully validated against a numerical simulation of the subpolar/Arctic region using a 1°
425 ORCA model and further validation, including more realistic boundary currents and mesoscale
426 eddies, is underway. The method's strength is that it allows for a determination of the relative
427 importance of interior mixing and surface fluxes to the transformation of water masses in the
428 subpolar/Arctic region. Given that surface flux observations in the Arctic are sparse, we plan

429 to use several reanalysis products, recently evaluated in Lindsay et al. (2014), to derive a set of
430 RTHIM solutions and uncertainties. When applied to the observations, this technique will
431 provide a proxy measure of the AMOC over a longer time span leading up to OSNAP, helping us
432 place the variability observed by the array in a broader temporal context.

433 To better understand, and ultimately predict, interannual and decadal variability in the AMOC,
434 a quantification of its sensitivity to changes in surface forcing is needed. This quantification is
435 most efficiently accomplished using an adjoint modelling approach, which provides the linear
436 sensitivity of the AMOC at a single latitude to changes in surface forcing over the globe, for all
437 forcing lead times (Pillar et al. 2016). Sensitivity distributions of the AMOC at 25°N and 50°N to
438 surface heat flux anomalies throughout the Atlantic basin are compared in Figure 10b-e for
439 forcing at lead times of 3 and 8 years. Differences in these sensitivity distributions indicate key
440 regions and lead times at which surface heat flux anomalies may force a notable deviation
441 between the response of the AMOC observed at the RAPID/MOCHA and OSNAP monitoring
442 arrays.

443

444 To further illustrate this point, we show the sensitivity of the AMOC at 25°N (blue) and 50°N
445 (green) to surface heat flux anomalies integrated over the subpolar gyre, as a function of
446 forcing lead time (up to 15 years), in Figure 10a. Examination of this spatially-integrated
447 sensitivity is useful for approximating the AMOC response to regional heat flux anomalies of
448 the same sign, such as those associated with the NAO (e.g., Eden and Jung 2001). At 25°N, the
449 AMOC response to NAO-type heat fluxes over the subpolar gyre oscillates in sign on decadal
450 timescales (Czeschel et al. 2010). In contrast, at 50°N, the AMOC response to the same forcing
451 notably diminishes for forcing lead times exceeding 5 years, due to large cancellation in the
452 integral associated with smaller scale structures in the sensitivity distributions (Figure 10c).

453 These results highlight the need to further explore the full spatial structure of AMOC sensitivity
454 and better constrain variations in surface buoyancy forcing, supporting the expectation that
455 subpolar monitoring under OSNAP will be invaluable in helping us to understand - and
456 possibly predict - low frequency variability in the AMOC at the RAPID/MOCHA array.

457

458 **ANTICIPATED OSNAP DATA PRODUCTS AND TIMELINE**

459 OSNAP data products will parallel those of the RAPID/MOCHA program, namely, time series of
460 the overturning circulation as well as the depth and zonally-integrated heat and freshwater
461 fluxes. The OSNAP overturning metric will be reported in both depth and density coordinates.
462 The OSNAP PIs are committed to a timely delivery of OSNAP products. The earliest expected
463 delivery of the first OSNAP products is one year following the retrieval of all data necessary for
464 the calculations, i.e., early fall of 2017. Please see www.o-snap.org for further information on
465 OSNAP, including cruise reports, blogs and technical information on all OSNAP arrays.

466

467 **SUMMARY**

468 For decades oceanographers have assumed the AMOC to be highly susceptible to changes in
469 the production of deep waters at high latitudes in the North Atlantic. A new ocean observing
470 system is now in place that will test that assumption. Early results from the OSNAP
471 observational program reveal the complexity of the velocity field across the section and the
472 dramatic increase in convective activity during the 2014/2015 winter. Early results from the
473 gliders that survey the eastern portion of the OSNAP line have illustrated the importance of
474 these measurements for estimating meridional heat fluxes and for studying the evolution of
475 subpolar mode waters. Finally, numerical modeling data has been used to demonstrate the
476 efficacy of a proxy AMOC measure based on a broader set of observational data and an adjoint

477 modelling approach has shown that measurements in the OSNAP region will aid our
478 mechanistic understanding of the low-frequency variability of the AMOC in the subtropical
479 North Atlantic.

480

481 Finally, we note that while a primary motivation for studying AMOC variability comes from its
482 potential impact on the climate system, as mentioned above, additional motivation for the
483 measure of the heat, mass and freshwater fluxes in the subpolar North Atlantic arises from
484 their potential impact on marine biogeochemistry and the cryosphere. Thus, we hope that this
485 observing system can serve the interests of the broader climate community.

486

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500

501

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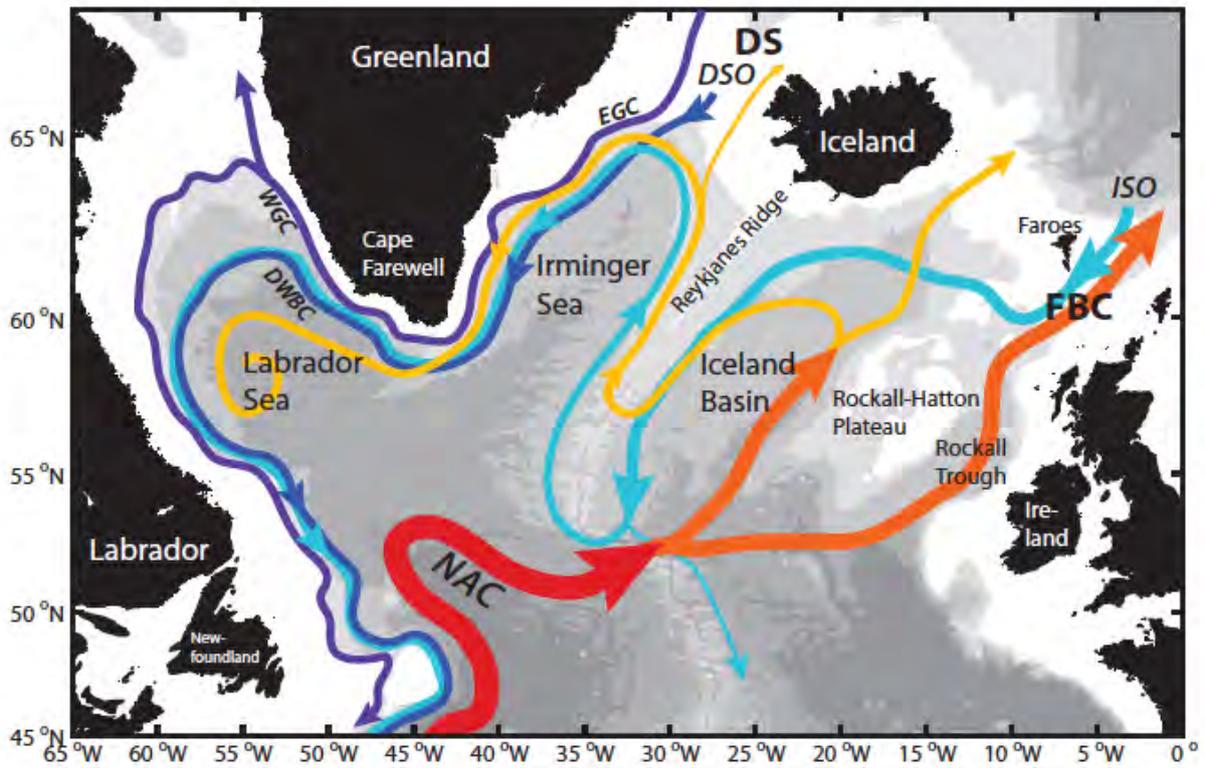


Figure 1. Schematic of the major warm (red to yellow) and cold (blue to purple) water pathways in the North Atlantic subpolar gyre (credit: H. Furey, WHOI). Acronyms not in the text: Denmark Strait (DS); Faroe Bank Channel (FBC); East and West Greenland Currents (EGC, WGC); North Atlantic Current (NAC); DSO (Denmark Straits Overflow); ISO (Iceland-Scotland Overflow).

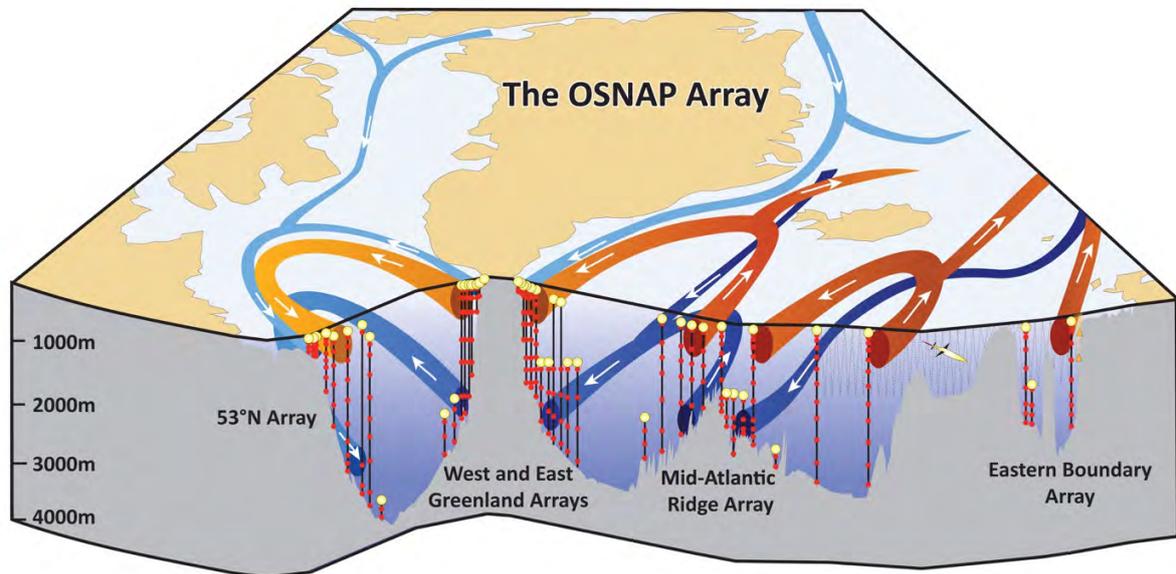


Figure 2. Schematic of the OSNAP array. The vertical black lines denote the OSNAP moorings with the red dots denoting instrumentation at depth. The thin gray lines indicate the glider survey. The red arrows show pathways for the warm, and salty waters of subtropical origin; the light blue arrows show the pathways for the fresh and cold surface waters of polar origin; and the dark blue arrows show the pathways at depth for waters formed via convections in the high latitude North Atlantic and Arctic.

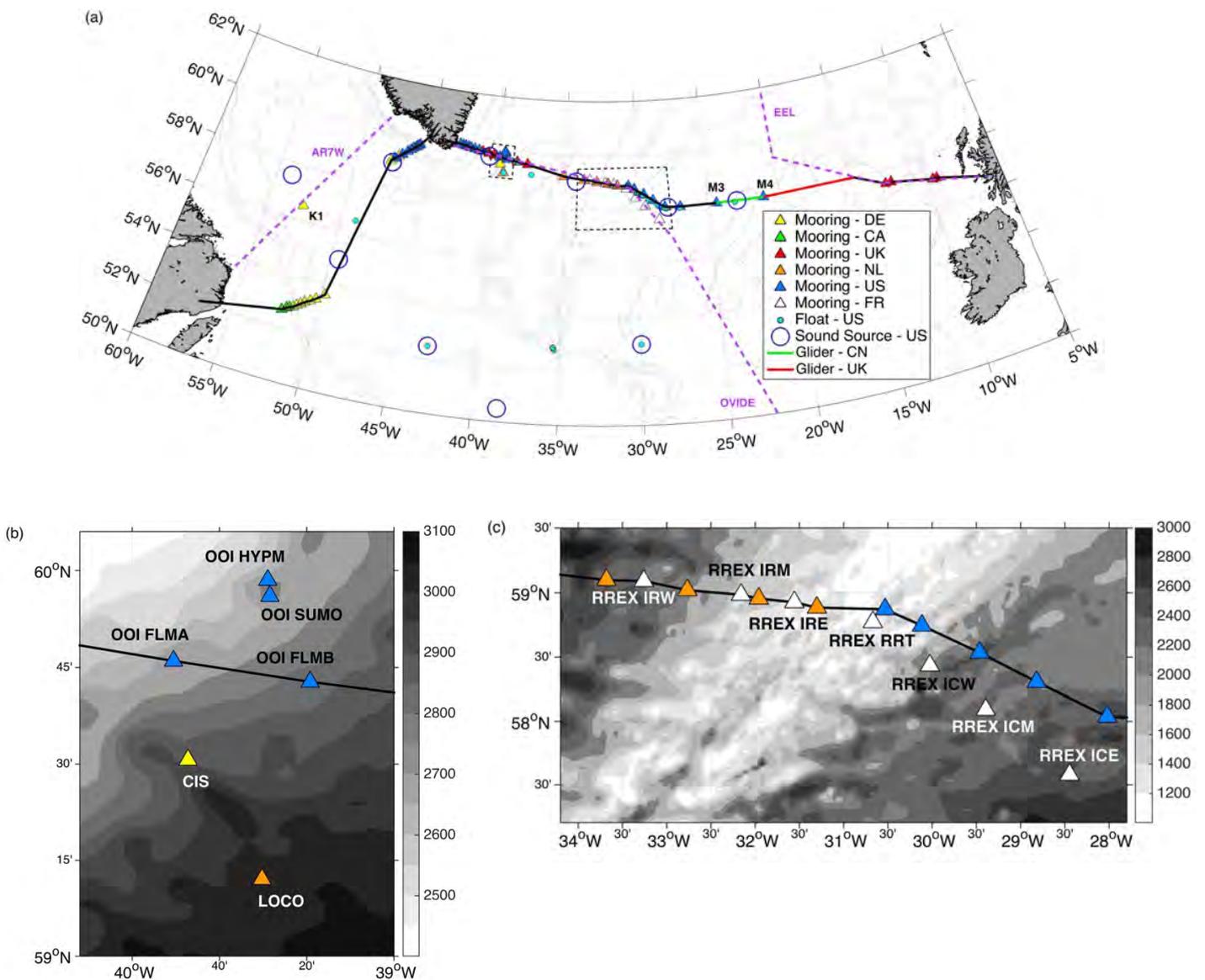


Figure 3. (a) OSNAP observing system: From west to east: Canadian [CA] shelfbreak array and *German [DE] 53°N western boundary array; US West Greenland boundary array; US/UK East Greenland boundary array; Netherlands [NL] western Mid-Atlantic Ridge array; US eastern Mid-Atlantic Ridge array; Chinese [CN] glider survey in the Iceland Basin; UK glider survey over the Hatton-Rockall Bank; UK Scottish Slope current array. Green dots: 2014 US float launch sites. Green line: Chinese glider; red line: UK glider. Blue circles: US sound sources. Purple dashed lines: repeated hydrographic sections. AR7E line is not shown since it mostly overlaps with the OSNAP East line from Greenland to Scotland. The light gray lines represent the 1000m-, 2000m- and 3000m-isobaths. Moorings within the black dashed boxes are specified in Figures 3b and 3c. (b) *OOI Global Irminger Sea Array (blue triangles), *German CIS mooring, and *Dutch LOCO mooring. The OOI FLMA and FLMB moorings are on the OSNAP East line (black line). (c) *RREX mooring array (white triangles) and OSNAP moorings on the flanks of the Reykjanes Ridge. The RREX IRW, IRM and IRE moorings are on the OSNAP East line (black line). In (b) and (c) bathymetry (m) is contoured. An asterisk indicates an observing element that, though used by OSNAP, either existed before the OSNAP program or came online the same time. All other elements were designed specifically for OSNAP.

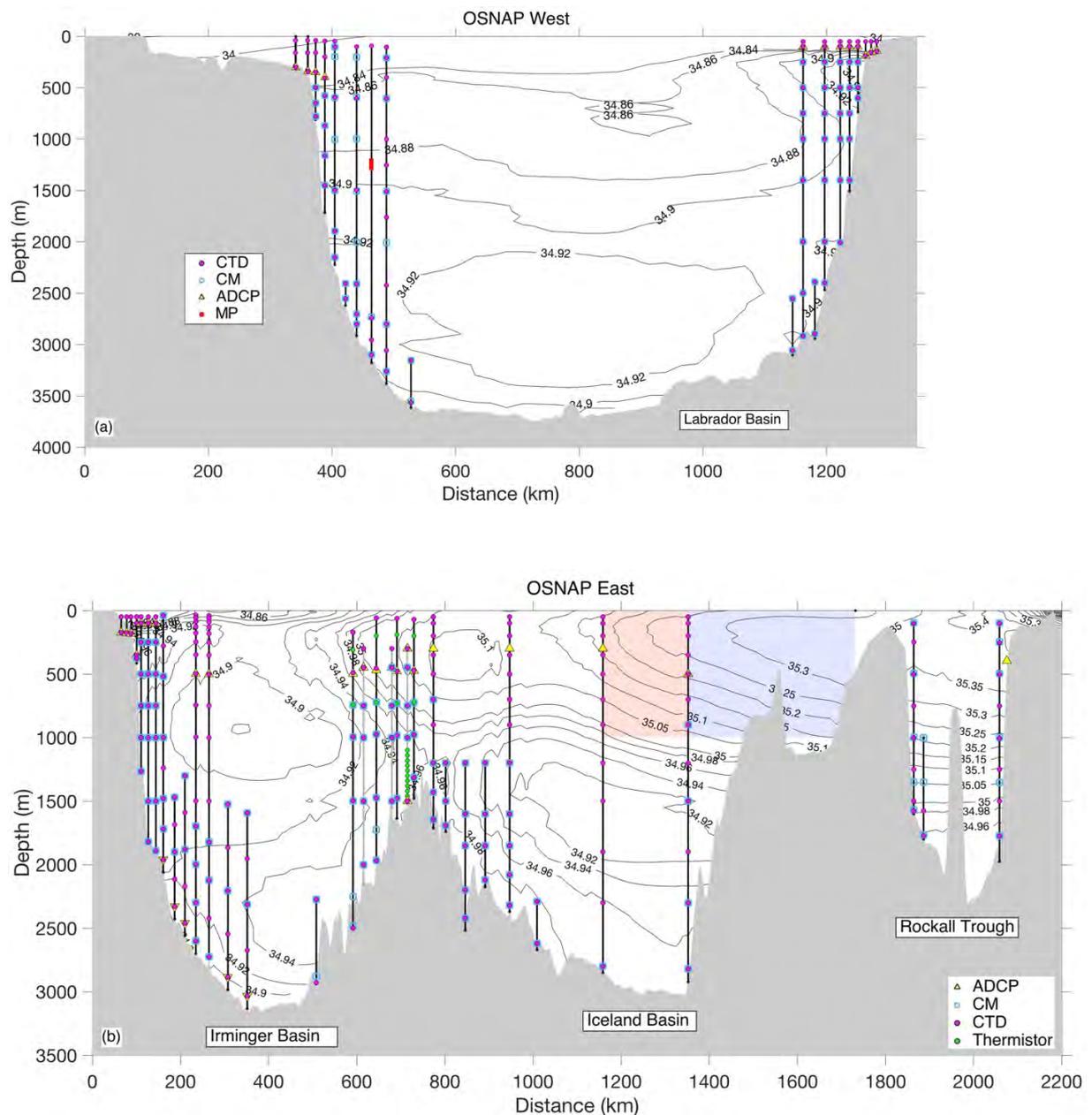


Figure 4. Schematic of moorings along (a) OSNAP West and (b) OSNAP East. The instrument types are as indicated by legend: CTD – Conductivity-Temperature-Depth; CM – Current Meter; ADCP – Acoustic Doppler Current Profiler; MP – Moored profiler. Glider domain is indicated by shaded box: red– Chinese glider, blue – UK glider. Vertical gray lines over the western flank of the Reykjanes Ridge (~600-750 km) along OSNAP East illustrate three French moorings as part of the RREX program. Black contours are 2005-2012 mean salinity from WOA13. Enlarged figures are available on the OSNAP website: <http://www.osnap.org/observations/configuration/>

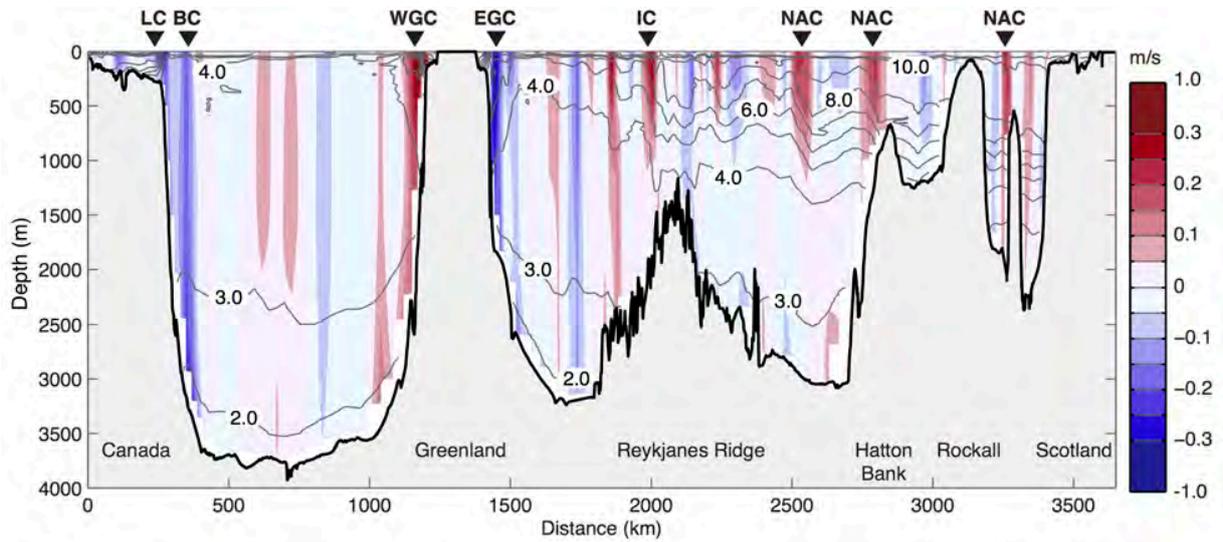


Figure 5. Observations on the OSNAP section in June-July 2014; cross-section velocity in color (positive is poleward, ms^{-1}), and potential temperature ($^{\circ}\text{C}$) (referenced to surface) as contours. Major currents are indicated: Labrador Current (LC), Labrador Sea Boundary Current (BC), West Greenland Current (WGC), East Greenland Current (EGC), Irminger Current (IC), North Atlantic Current (NAC).

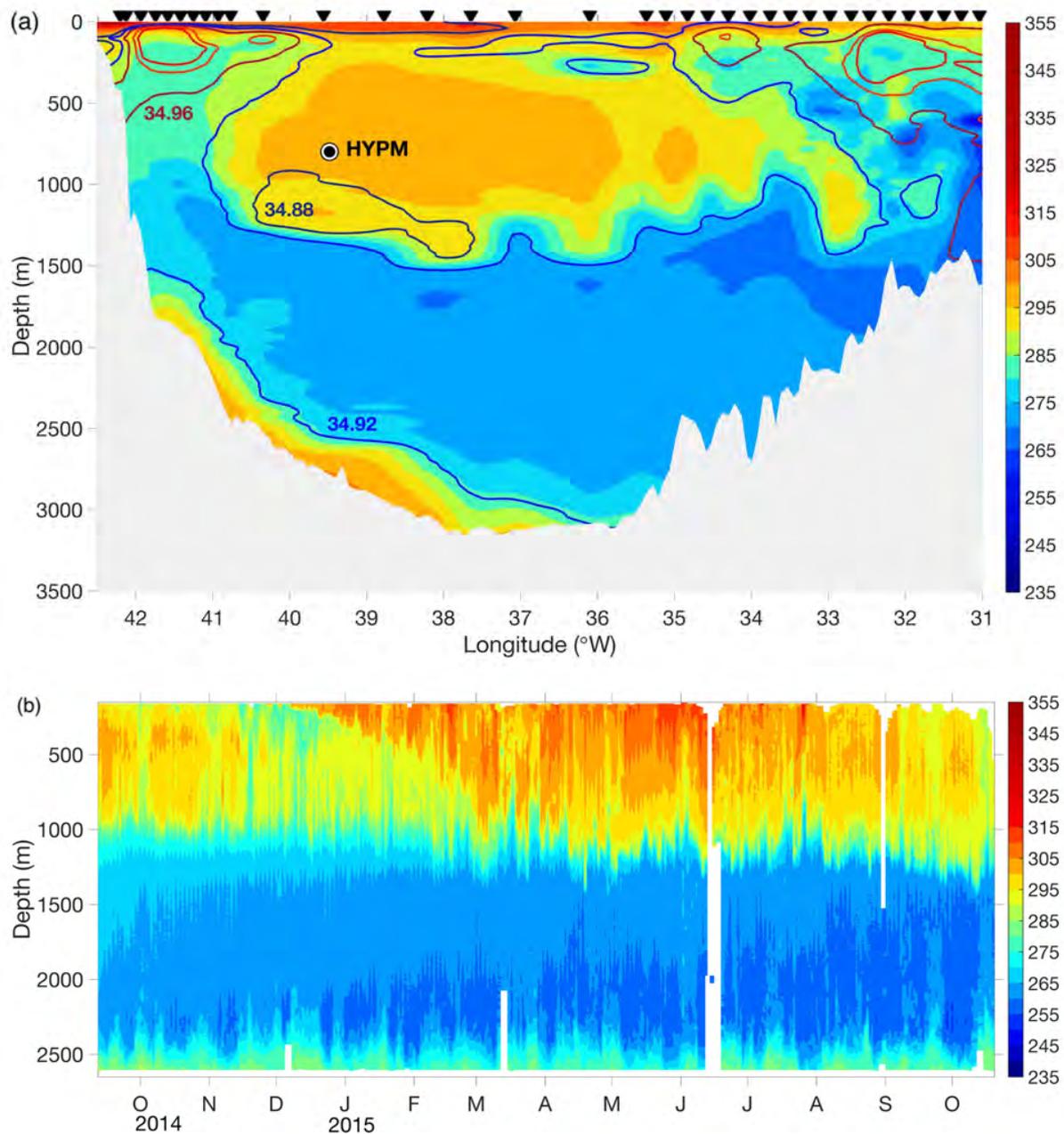


Figure 6. (a) Hydrography in the Irminger Sea observed in July 2015. Dissolved oxygen values are plotted with color shading ($\mu\text{mol kg}^{-1}$). The colored lines are salinity contours plotted at 0.04 intervals. CTD station locations are indicated with triangles at the top. (b) Time-series of dissolved oxygen ($\mu\text{mol kg}^{-1}$) from the OOI HYPM mooring. The location of this mooring is indicated with white circle in (a).

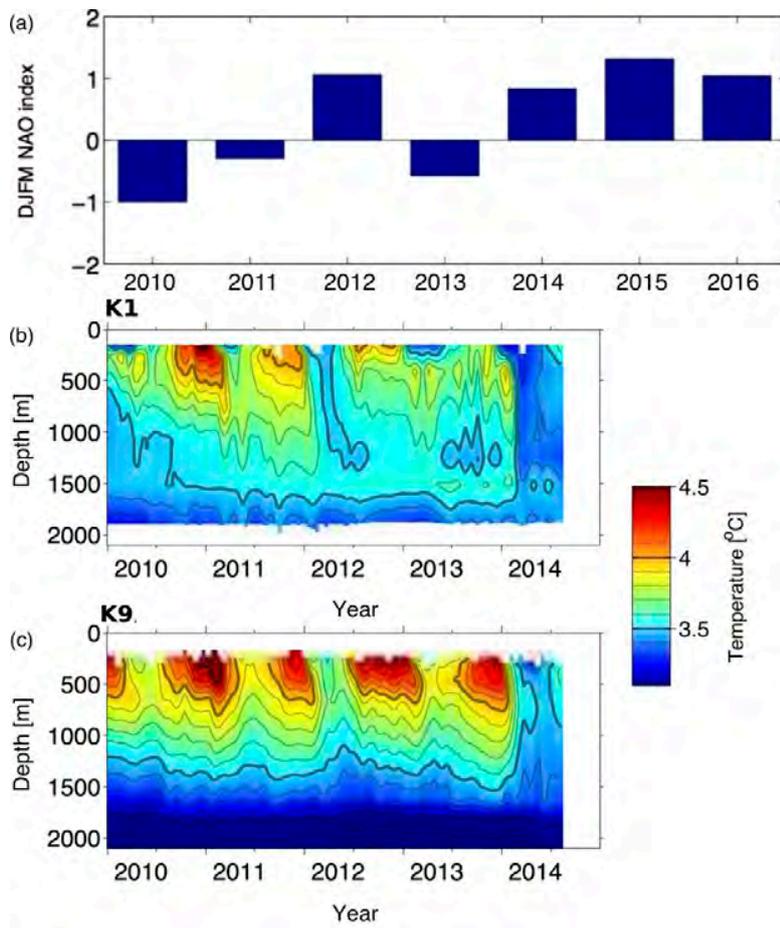


Figure 7. (a) Winter (DJFM) mean NAO index. (b) and (c) show time-series of temperature from the K1 and K9 moorings, respectively. The mooring locations are shown in Figure 3a.

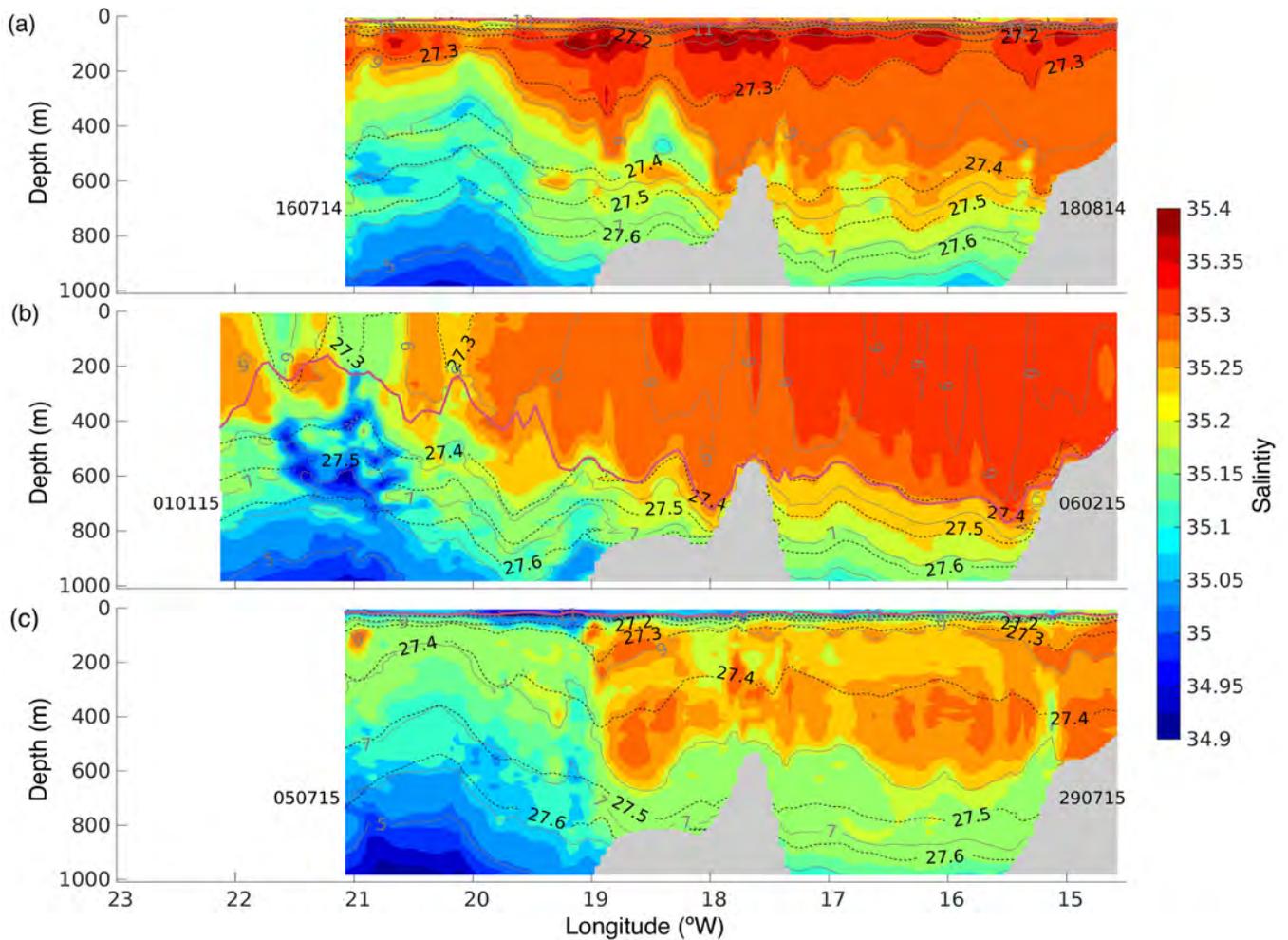


Figure 8. Three glider sections on Rockall Plateau along 58°N in (a) July/August 2014, (b) January 2015 and (c) July 2015. Labels on the left and right side of the sections indicate the date at the beginning and end of the section [ddmmyy]. Contours are of salinity (color), potential temperature (white dashed lines) referenced to surface and potential density (black dashed line) referenced to surface. The mixed layer depth, calculated using a reference level at 10 m depth and a criterion $\Delta\sigma_\theta = 0.03 \text{ kg m}^{-3}$, is shown by the red line. The profile path taken by the glider is V-shaped, with a typical horizontal separation of 2-6 km. Descent and ascent speed is $\sim 10\text{-}20 \text{ cm s}^{-1}$ and forward speed is $\sim 20\text{-}40 \text{ cm s}^{-1}$. Vertical resolution of sampling is $\sim 0.5\text{-}1.5 \text{ m}$ above the main pycnocline and $\sim 1.5\text{-}3 \text{ m}$ below.

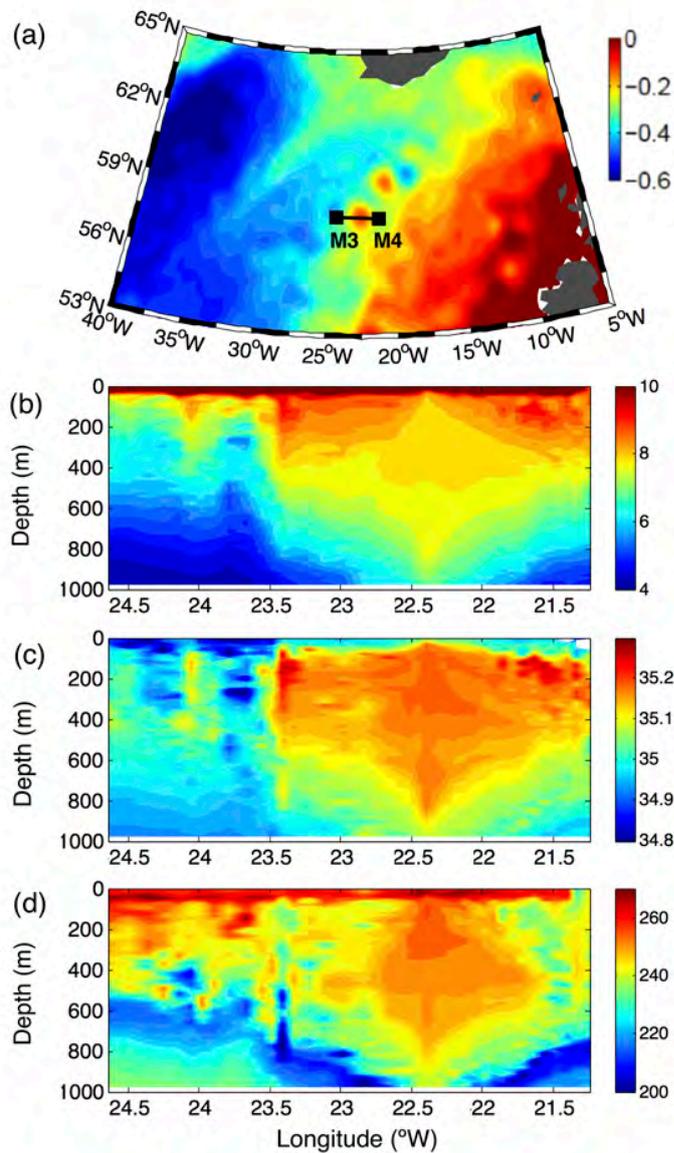


Figure 9. (a) Absolute Dynamic Topography (m) between 23 July and 2 August 2015, showing an anti-cyclonic eddy on the ONSAP line. The two black squares denote moorings M3 and M4 and a black line represents the sampling path. The temperature ($^{\circ}\text{C}$), salinity and dissolved oxygen ($\mu\text{mol kg}^{-1}$) data recorded by the glider during the eddy scenario are shown in (b), (c), (d), respectively.

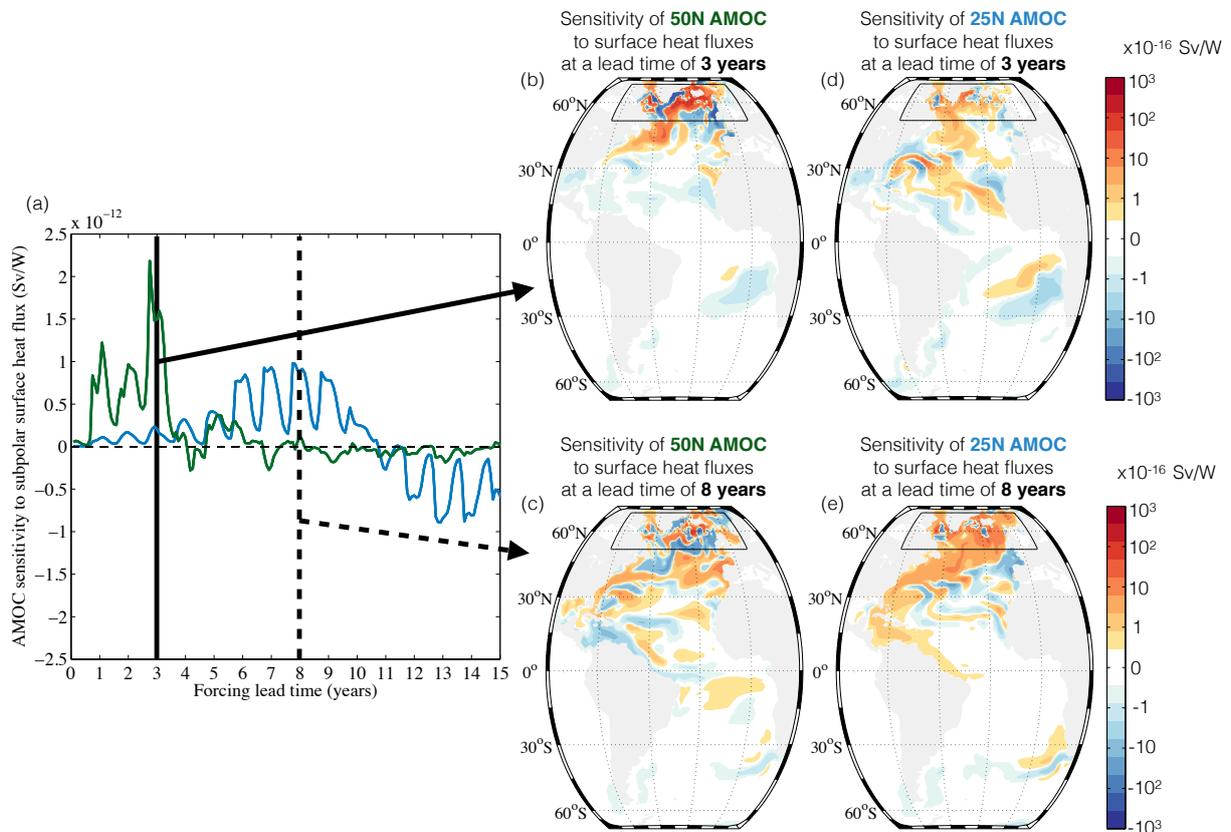


Figure 10. (b-e) Linear sensitivity of the AMOC at (d, e) 25°N and (b, c) 50°N in January to surface heat flux anomalies per unit area. Positive sensitivity indicates that ocean cooling leads to an increased AMOC, e.g., a unit increase in heat flux out of the ocean at a given location will change the AMOC at (d) 25°N or (e) 50°N 3 years later by the amount shown in the colorbar. The contour intervals are logarithmic. (a) The time series show linear sensitivity of the AMOC at 25°N (blue) and 50°N (green) to heat fluxes integrated over the subpolar gyre (black box with surface surface area $\sim 6.7 \times 10^6 \text{ m}^2$) as a function of forcing lead time. The reader is referred to Pillar et al. (2016) for model details and to Heimbach et al. (2011) and Pillar et al. (2016) for a full description of the methodology and discussion relating to dynamical interpretation of the sensitivity distributions.