

The Mid-Depth Circulation of the Northwestern Tropical Atlantic Observed by Floats

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Manuscript ID: DSR1-D-08-00090

Status: May 29, 2009

Submitted to *Deep-Sea Research I*

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1 **Abstract**

2 A comprehensive analysis of velocity data from subsurface floats in the northwestern trop-
3 ical Atlantic at two depth layers is presented: one representing the Antarctic Intermediate
4 Water (AAIW, pressure range 600–1050 dbar), the other the upper North Atlantic Deep
5 Water (uNADW, pressure range 1200–2050 dbar). New data from three independent re-
6 search programs are combined with previously available data to achieve blanket coverage
7 in space for the AAIW layer, while coverage in the uNADW remains more intermittent.
8 Results from the AAIW mainly confirm previous studies on the mean flow, namely the
9 equatorial zonal and the boundary currents, but clarify details on pathways, mostly by
10 virtue of the spatial data coverage that sets float observations apart from e. g. shipborne
11 or mooring observations. Mean transports in each of five zonal equatorial current bands
12 is found to be between 2.7 and 4.5 Sv. Pathways carrying AAIW northward beyond the
13 North Brazil Undercurrent are clearly visible in the mean velocity field, in particular a
14 northward transport of 3.7 Sv across 16° N between the Antilles islands and the Mid-
15 Atlantic Ridge. New maps of Lagrangian eddy kinetic energy and integral time scales
16 are presented to quantify mesoscale activity. For the uNADW, mean flow and mesoscale
17 properties are discussed as data availability allows. Trajectories in the uNADW east of the
18 Lesser Antilles reveal interactions between the Deep Western Boundary Current (DWBC)
19 and the basin interior, which can explain recent hydrographic observations of changes in
20 composition of DWBC water along its southward flow.

21 **Keywords**

22 Floats; Tropical Atlantic; Antarctic Intermediate Water; North Atlantic Deep Water;
23 Equatorial Currents

1 Introduction

This paper considers the area of the open Atlantic Ocean north of 10° S and south of the tropic of cancer (23.5° N), between 65° W and 30° W, which we will refer to as the northwestern tropical Atlantic. The island chain of the eastern Lesser Antilles and the coast of South America limit the domain in the west and southwest, whereas the other boundaries are in the open ocean. Parts of the Mid-Atlantic Ridge cross the domain and, together with the American coastline, define a diagonal sub-basin aligned from the northwest to the southeast that is characteristic of the region. Fig. 1 (top panel) shows a map of the area that includes the geographic features referred to in the text. The middle and bottom panels show the spatial data coverage.

Two depth ranges will be considered: one represents the Antarctic Intermediate Water (AAIW), and the other the upper part of the North Atlantic Deep Water (NADW). The motivation for studying the circulation of the Atlantic at these depths is the involvement of the currents in the Meridional Overturning Circulation (MOC). The Atlantic MOC carries relatively warm water northward near the surface and cold water southward at depth. The resulting northward heat transport is seen as an important part of the climate system (Marshall et al., 2001). AAIW with its northward spreading is associated with the upper limb of the MOC, while NADW is the southward component. This study was initiated as a synergy of three field experiments with subsurface floats that drift with the surrounding water: MOVE¹ originally based at IFM-GEOMAR, NBC² Rings Experiment based at WHOI, and SAMBA³ based at Ifremer. The main objective of MOVE is monitoring the southward transport of NADW east of the lesser Antilles with moored sensors (Send et al., 2002). Floats were deployed to assist the interpretation of the mooring

¹Meridional Overturning and Variability Experiment

²North Brazil Current

³Sub-Antarctic Motions in the Brazil Basin

47 measurements in the early phase of the experiment. The NBC Rings Experiment inves-
48 tigated the NBC off of South America between roughly 5° N and 10° N (Fratantoni and
49 Richardson, 2006). The main constituent of the upper limb of the MOC, the NBC carries
50 waters in the upper 1000 m northward across the equator and sheds anticyclonic current
51 rings in its retroflexion (Johns et al., 2003). SAMBA intends to map out the circulation
52 of the AAIW in the Brazil Basin with a large amount of floats, some of which are within
53 the domain of this study. The areas where data were gathered in these three campaigns
54 complement each other to span almost the entire northwestern tropical Atlantic. Pub-
55 licly available float data from five other field campaigns were added to further enlarge
56 the database (listed in table 2). The total data amount is 305 cumulative years of float
57 data, and the largest individual contributing project is now Argo. None of the individual
58 projects by itself except perhaps Argo in the near future is capable of a basin-wide treat-
59 ment of the circulation at the resolution required to map out the relatively narrow current
60 bands. The combination of multiple datasets makes this possible for the AAIW layer. Pre-
61 vious observations of the circulation patterns (e. g. Stramma and Schott, 1999) are based
62 mostly on mooring or shipborne observations of velocity, which lack spatial resolution,
63 or hydrographic and tracer observations, which are powerful yet only indirect measures
64 of the circulation. Float observations can fill these gaps with area-wide direct velocity
65 observations, and studies of the tropical Atlantic with floats by Boebel et al. (1999a) and
66 Schmid et al. (2003) have shown updated schematics of the circulation. However, these
67 were based on relatively small amounts of data, especially in the northwestern tropical
68 Atlantic, which is addressed here. This paper mostly confirms the previous circulation
69 schematics with estimates of the mean flow that are based on substantially improved data
70 coverage, supported by pathways visible in a multitude of individual trajectories. From
71 eddy-resolving float data, kinetic energy levels and time scales of the mesoscale field are
72 presented. As for the uNADW layer, data coverage remains limited. Older SOFAR float

73 data that have been discussed in the literature (Richardson and Schmitz, 1993; Richardson
74 and Fratantoni, 1999) are included in this study, but the discussion focuses on new data
75 east of the Lesser Antilles, which are brought into context with recent hydrographic ob-
76 servations by Steinfeldt et al. (2007). Where possible, mean flow and mesoscale properties
77 are quantified for the uNADW layer as well.

78 AAIW is formed in subpolar regions around Antarctica, from where it is subducted
79 and spreads throughout the South Atlantic (Talley, 1996; Stramma and England, 1999).
80 Its most conspicuous path is along the shelf break off South America between roughly
81 27° S and 10° N in the aforementioned North Brazil (Under-) Current (NBC, NBUC,
82 Stramma et al., 1995), also called the Intermediate Western Boundary Current (IWBC).
83 Near the equator, the path of AAIW is complicated by bands of alternating zonal flow,
84 which have been described by Ollitrault et al. (2006) in a precursor to this study, and
85 earlier e. g. by Schmid et al. (2003). Stramma et al. (2005) present ship-based measure-
86 ments within the domain that include data in the AAIW, and Boebel et al. (1999b) give
87 a comprehensive account of the intermediate-depth equatorial currents in the earlier liter-
88 ature. The situation within 1° of the equator is complicated by vertically alternating jets
89 (e. g. Gouriou et al., 2001; Send et al., 2002; Schmid et al., 2005), the dynamics of which
90 are not yet well understood. Fig. 1 (middle) schematically shows locations and directions
91 of the NBUC and five equatorial current bands: the Northern and Southern Equatorial
92 Intermediate Currents (NEIC, SEIC) flowing westward near 4° N/S, the Northern and
93 Southern Intermediate Countercurrents (NICC, SICC) flowing eastward near 2° N/S, and
94 the Equatorial Intermediate Current (EIC) flowing westward on average at the equator
95 (seasonal cycles and reversals described e. g. by Ollitrault et al., 2006).

96 The main hydrographic characteristic of AAIW is a minimum in vertical salinity pro-
97 files, shown in fig. 2 with velocities from an LADCP (Lowered Acoustic Doppler Current
98 Profiler) on two sections (data from Rhein et al., 2004, 2005). Current features captured

99 by the LADCP data include the NBC, NEIC, NICC, EIC, SICC, and an eddy that Rhein
100 et al. (2005) identify as an NBC ring. The minimum in salinity can be identified through
101 the entire study domain, although its northern extent does not reach far beyond the trop-
102 ics (e. g. Talley, 1996). Here, floats drifting at pressures between 600 and 1050 dbar will
103 be interpreted as being in the AAIW. This choice agrees with the isopycnals shown in
104 fig. 2, which in turn are used by Stramma and England (1999) and Rhein et al. (1995),
105 although it includes upper Circumpolar Deep Water which is between approximately 900
106 and 1100 dbar.

107 In contrast to AAIW, NADW as a whole stems from convection and mixing processes
108 in the polar and subpolar North Atlantic. Following the North American shelf break
109 southward, it reaches the tropics as a Deep Western Boundary Current (DWBC, cf. figs.
110 1 (bottom) and 2), where it occupies pressure ranges between approximately 1200 and
111 3900 dbar (Rhein et al., 1995). More specifically, we will combine floats in the range
112 1200–2050 dbar as being in the upper NADW (uNADW), a common naming convention
113 used e. g. by Curry et al. (1998, for more details, see Rhein et al. (1995)). In hydrographic
114 measurements, this depth range is characterized by the highest salinity of the NADW (fig.
115 2). NADW too is subject to zonal current bands away from the DWBC in the equatorial
116 region (Richardson and Fratantoni, 1999).

117 A current review of float technology, including all types of instrumentation exploited
118 here, is given by Rossby (2007). Two positioning strategies have evolved for floats: *acous-*
119 *tic* floats are positioned acoustically while submerged, and *profiling* floats return to the
120 surface periodically for satellite position fixes. Currents are derived from the displace-
121 ments between successive fixes. Here, acoustic floats have one or two position fixes per
122 day, which makes them eddy-resolving. Profiling floats, in contrast, are located typically
123 every ten days and therefore do not resolve the mesoscale, but the larger number of them
124 helps to map out the mean flow. Mean currents are derived from combining displacements

125 between individual cycles of profiling floats, and acoustic trajectories sub-sampled at ten-
126 day intervals. The discussion of mesoscale variability is based on acoustic floats only.
127 Typical eddy time scales will be shown to be shorter than ten days, so that successive
128 float displacement cycles can be assumed statistically independent.

129 2 Mean Flow Field

130 2.1 Mean Flow Derived from Float Observations

131 2.1.1 Antarctic Intermediate Water (AAIW)

132 Fig. 3 shows a stream function derived from all available float displacements in the AAIW
133 layer. The individual velocity measurements shown in fig. 1b were interpolated onto a
134 grid of 0.5° resolution, with Gaussian weights of standard deviation 50 km. From these
135 gridpoints, vorticity ζ was derived by central differences, and the stream function Ψ was
136 obtained by numerically solving⁴ the *Poisson* equation $\nabla^2\Psi = -\zeta$ on the domain
137 shown in the figure. The boundary condition along the American shelf is a constant
138 streamline (*Dirichlet* boundary condition), while the boundary conditions in the open
139 ocean are defined through the velocity measurements themselves (*Neumann* boundary
140 conditions). All flow features discussed below are also present in the raw gridded velocity
141 data and therefore not artefacts of the streamline computation.

142 The resulting stream function clearly depicts the NBUC and the following five equa-
143 torial zonal flows as the features with the strongest currents: NEIC, NICC, EIC, SICC,
144 and SEIC. The equatorial zonal flows have been discussed by Ollitrault et al. (cf. 2006).
145 Assuming a layer thickness of 450 m, the mean volume transports of the five equatorial

⁴MatLabTM contains the algorithms in its “PDE toolbox” product.

146 currents in the middle of the basin (longitudes from 40° W for the NEIC to 30° W for
147 the SEIC) are approximately 3.2, 4.5, 3.2, 4.1, and 2.7 Sv, respectively. Until recently,
148 there has been doubt about the mere existence of these intermediate-depth zonal flows
149 (Jochum and Malanotte-Rizzoli, 2003), which has been eliminated by successive observa-
150 tional (Schott et al., 2003; Schmid et al., 2003) and modelling studies (Eden, 2006). The
151 positions of the NEIC and to some extent the NICC shift northward at short distances
152 from the western boundary, in the case of the NEIC from near 4° N in the basin interior to
153 5° N at 45° W. This shifted NEIC location is not reproduced by Schmid et al. (2003, their
154 fig. 17). Stramma and Schott (1999, their fig. 6) generally show the NEIC too far north.
155 The streamlines of the NICC and NEIC in these displacements (west of 40° W) tend to
156 follow the deep isobaths of the Ceara Ridge and the Amazon Cone, suggesting that these
157 topographic features exert some guidance on the AAIW flow although they are at depths
158 exceeding 3000 m. At least it seems likely that the NEIC would continue along 4° N all
159 the way to the western boundary if the ridge were not there. The inflow in the NBUC
160 at 8° S is found to be 5.0 Sv, which is in general agreement with the analysis by Schott
161 et al. (1998). All transport values were obtained by integrating across the streamlines of
162 fig. 3 and are listed in table 3 together with previous estimates.

163 Northwestward from the Guiana Plateau, the streamlines suggest a continuous flow
164 of AAIW parallel to but mostly detached from the shelf break. This mean flow is not easily
165 observed due to masking by the mesoscale eddy field (discussed in section 3), yet it seems
166 to be the major pathway of AAIW west of 53° W. From the Guiana Plateau to Barbados,
167 this path resembles the advection of NBC rings (Fratantoni and Richardson, 2006; Johns
168 et al., 2003; Goni and Johns, 2001). Consistent with these studies on NBC rings, which
169 repeatedly show rings near or even around Barbados, fig. 3 shows northward flow to either
170 side of the island with a larger portion west of it as would be expected of an anticyclone
171 surrounding Barbados as it progresses northward. At 15° N north of Barbados, some

172 northward flow remains close to but not as tightly concentrated at the boundary, while
173 four streamlines fan out northeastward into the ocean interior. The location coincides
174 with one where many NBC rings stall or cease to exist (Fratantoni and Richardson, 2006;
175 Goni and Johns, 2001). Stalling of the rings can explain why hydrographic measurements
176 (Rhein et al., 2005, or fig. 2 here) repeatedly find them there, and why the mean flow
177 decelerates as documented by the fanning out of the streamlines. The separation of the
178 streamlines from the western boundary at 15° N is also consistent with the hydrography,
179 which shows the thickest layer of fresher water (fig. 2) or the highest concentrations
180 of water from the southern hemisphere (Rhein et al., 2005) beginning at least 200 km
181 offshore. In their analysis of water entering the Caribbean between the Lesser Antilles,
182 Rhein et al. (2005) identify higher concentrations of southern waters in passages between
183 the islands south of 15° N, exactly where fig. 3 here finds the mean flow—presumably
184 carrying the highest concentrations of AAIW—closer to the islands than it does further
185 north. Northward transports across 16° N are 1.4 Sv in the interior pathway (east of
186 59° W but west of the Mid-Atlantic Ridge) and 2.3 Sv in the path closer to the boundary.
187 Assuming that transport across 16° N happens by advection of remaining NBC rings,
188 Rhein et al. (2005) derive a transport that agrees with these values (see table 3). We
189 therefore interpret the mean flow in the AAIW layer from the Guiana Plateau onward
190 as the translation of NBC rings, a concept introduced by Richardson et al. (1994) for
191 near-surface data. At the northern limit of the domain (beyond 20° N), the wider spacing
192 of the streamlines and associated low speeds correspond with the northernmost extent of
193 the salinity minimum of AAIW (e. g. Talley, 1996, or WOCE⁵ section A20).

194 The remaining area apart from the equatorial and boundary regimes is characterized
195 by very slow—if any—mean flow. Stramma and Schott (1999) have presented a circulation
196 schematic of the entire tropical Atlantic for the AAIW layer (their fig. 6), based on

⁵Cf. e. g. <http://www.ewoce.org>

197 measurements available then, i. e. before the availability of large float data amounts.
198 Excellent agreement with respect to the equatorial and near-equatorial flow (EIC, NICC,
199 SICC) is found between our fig. 3 and the schematic by Stramma and Schott (1999).
200 However, they display the NEIC further north, and the SEIC is obscured in several
201 branches of the South Equatorial Current and the mostly shallower South Equatorial
202 Undercurrent. Their continued northward flow beyond the NBUC, which they refer to as
203 the IWBC, enters the Caribbean between the southernmost Antilles islands, unlike what
204 floats show here, and they show large inter-basin gyres between 5° and 20° N where float
205 data suggest insignificant mean flow. With the IWBC escaping into the Caribbean, their
206 scheme cannot reproduce the flow towards Barbados and further north. Some of these
207 discrepancies in the equatorial region, approximately 8° S to 5° N, have been clarified in a
208 similar schematic by Schmid et al. (2003, their fig. 17) based on float data included in this
209 study. Schmid et al. (2003) adjust the position of the NEIC and simplify the zonal flow
210 patterns around the SEIC to a degree that matches the findings presented here, although
211 they rely on individual trajectories in some cases. However, they continue to include
212 parts of an inter-basin, anticyclonic gyre north of the NEIC, which is not supported by
213 the present study. We will update the schematics by Stramma and Schott (1999) and
214 Schmid et al. (2003) in the conclusions at the end of the paper.

215 **2.1.2 Upper North Atlantic Deep Water (uNADW)**

216 Data density of the uNADW layer does not allow for a similar map of streamlines, but
217 fig. 4 shows box-averaged mean velocities where data are available. Near the DWBC, the
218 boxes were designed to follow the flow features as seen in individual trajectories (cf. fig. 9).
219 In a broad area east of the Lesser Antilles (between 11° N and 19° N, 58° W and 46° W),
220 there is slow but prevalent westward mean flow of 0.8 cm s^{-1} with a standard error of
221 0.2 cm s^{-1} . For a subset of this data (MOVE), the mean flow is even higher at 1.5 cm s^{-1}

222 with the same standard error. This westward flow comes at least from near the Mid-
223 Atlantic Ridge, possibly from further east, and connects with the southward DWBC near
224 the Lesser Antilles. Steinfeldt et al. (2007) find a strong dilution of the DWBC between
225 16° N and 10° N based on tracer measurements, which can be explained by this inflow
226 from the east. The origin of this westward flow is not obvious from the present dataset,
227 but NADW has been observed to spread southward east of the Mid-Atlantic Ridge at
228 latitudes between 35° N and 50° N (Speer et al., 1999; Bower et al., 2002; Machín et al.,
229 2006). In the same latitudinal range, Paillet et al. (1998) and Getzlaff et al. (2006) discuss
230 a southward path along the ridge. Hence we speculate that the westward flow observed
231 by the floats is fed by a branch of uNADW that does not spread in the DWBC but rather
232 via slower pathways along or east of the Mid-Atlantic Ridge.

233 Centered at about 15° N at the western boundary of the domain, a narrow recircu-
234 lation cell is also present in the mean, which could be yet another reason for the dilution
235 observed by Steinfeldt et al. (2007). Results from the SOFAR floats off South America,
236 which have measured the boundary current and parts of the equatorial current system,
237 have been published by Richardson and Fratantoni (1999) but are not well represented in
238 fig. 4 due to data sparsity.

239 **2.2 Comparison with Other Measurements**

240 Several measurements with moored current meters exist in the study area with instru-
241 ments within the AAIW and the uNADW layers. An overview of the locations of these
242 moorings is included in fig. 1. Figures 5 and 6 show comparisons of mean velocities be-
243 tween float and mooring data across three sections. The sections were designed to be
244 perpendicular to the shelf break. Float data within 167 km (1.5°) to either side of the
245 target sections (within 222 km or 2° for the two southern uNADW sections) are used

246 to compute across-section velocities. Float data are grouped into bins of 100 km width,
247 and the figures show the bin averages, 95% confidence limits, and the scattered cloud
248 of individual float samples. Means and confidence intervals from moored sensors are
249 superimposed. In all sections, the boundary currents are the most prominent features.
250 Here, agreement between mooring and float data is probed to rebut the suspicion that
251 interpretation of float data is flawed by systematic deviations between the two (Stokes
252 Drift).

253 Fig. 5 shows results on the AAIW. Near the endpoints of the northernmost section
254 (a), multi-year mooring records from MOVE and float data concordantly show zero mean
255 flow. Mooring data from Johns et al. (1990, section b) show the northwestward NBUC
256 with mean currents near 13 cm s^{-1} at the boundary, decreasing to almost zero 150 km
257 out, in excellent agreement with the float data. Section (c) contains mooring data from
258 Schott et al. (1993), which show a northwestward NBUC flanked by a southeastward
259 flow. The float averages show the same features, generally with a stronger northwestward
260 component, and disagreements are within the confidence limits. Section (c) in particular
261 highlights how the basin-wide float coverage adds to the interpretation of the existing
262 data, since the floats reveal the southeastward flow seen in the mooring data to be part
263 of the alternating pattern of zonal flows in the equatorial region (the NICC in this case).
264 The streamlines of fig. 3 (included in fig. 5) show how the NBUC flow at section (c) folds
265 back in the NICC, is then re-established at section (b), and successively detrained in a
266 recirculation within the Guiana Basin as well as fanned out away from the coast before
267 reaching section (a).

268 Fig. 6 contains data from the same sections but within the uNADW. Section (a)
269 has abundant multi-year mooring data from MOVE and also GAGE (2000–2002, Guiana
270 Abyssal Gyre Experiment, M. McCartney, pers. comm.). In agreement with the float
271 data, these show virtually no significant mean flow across the section except for the

272 southward DWBC. The westernmost bin of float data, which contains the DWBC, is
273 slightly biased to slower currents than those of the nearby moorings, because the floats
274 only sampled the outer edge of the DWBC with no measurements as far west as the
275 mooring location. The few float data available near the boundary in section (b) resemble
276 the mooring measurements by Johns et al. (1990) and Colin et al. (1994) in that they show
277 the DWBC near 10 cm s^{-1} . In section (c), mooring results by Schott et al. (1993) and
278 float data consistently depict the DWBC mean between 20 and 30 cm s^{-1} . A discrepancy
279 just outside the confidence limits for the outermost mooring coincides with a shortened
280 data record of the moored sensor which was also significantly shallower than most of the
281 floats there.

282 Generally, agreement between the mooring and float observations is surprisingly good
283 given the sparse float data coverage in the uNADW and the fact that the measurements
284 were taken years apart in several instances. Good agreement also exists with mooring
285 results by Johns et al. (1998). Table 3 compares transport estimates from different studies,
286 from which a coherent estimate of the transports in the equatorial zonal flows and the
287 boundary current in the AAIW emerges. High values for the EIC and to a lesser extent
288 the SICC and NICC in early estimates by Schott et al. (1998) are explicable by the
289 timing of the shipborne measurements relative to the annual cycle, which occurred at
290 times confirmed to have maximum transport in the EIC (October and November) and
291 the NICC/SICC (June, Ollitrault et al., 2006, their fig. 4). The subsequent analysis of
292 a larger shipborne dataset (Schott et al., 2003) brings these values much closer to the
293 float-based estimates, with the remaining differences consistent with the (reduced, but
294 still existing) biases in timing of the ship cruises, which have gaps in July, September,
295 and December: high bias in the ship-based values for the NEIC correspond to maximum
296 transport in the well-sampled period February–May, low bias in the SICC and NICC
297 to lack of measurements in July, and high bias in the EIC to oversampling in October

298 and November. Nonetheless, the differences between transports from the ship-based data
 299 (Schott et al., 2003) and the present study are small, and indeed of the same magnitude
 300 as differences between the present study and that by Ollitrault et al. (2006), which use
 301 the same dataset but differ computationally. We therefore conclude that results on the
 302 mean currents obtained from the float measurements are not significantly biased versus
 303 their Eulerian counterparts in the moorings or ship-based measurements.

304 **3 Mesoscale Variability**

305 Section 2 has shown that the observed AAIW mean velocities in the inner basins away
 306 from the equatorial region are very low. However, many individual float trajectories
 307 have relatively high velocities: e. g. for the MOVE floats in the AAIW layer, where the
 308 mean velocity is almost zero, the rms value of the ten-day displacement velocities is still
 309 4.4 cm s^{-1} , and more than 20% of the ten-day velocities exceed 10 cm s^{-1} . This clearly
 310 motivates a closer look at the mesoscale velocity field. Because of their high temporal
 311 resolution (at least one position per day), only the acoustically tracked floats are used
 312 for this. Fig. 7 (top panel) shows the data coverage achieved with acoustic floats in the
 313 AAIW. The lower data density in the uNADW is already indicated in fig. 1.

314 From floats, the mesoscale field is appropriately described by the Lagrangian eddy
 315 kinetic energy (EKE) and the Lagrangian integral time scale (T_{int}). To estimate these,
 316 trajectories were split up in windows of 80 d duration with a 90% overlap (i. e. 72 d).
 317 For each window, the mean and a linear trend were removed from the velocities, and the
 318 variances σ_{\dots}^2 of the velocity data u, v define an EKE measurement per:

$$\text{EKE} = \frac{1}{2}(\sigma_u^2 + \sigma_v^2)$$

319 With the normalized autocorrelation of u at time lag τ written as $R_u(\tau)$, the Lagrangian

320 integral time scale were computed for each window from:

$$T_{\text{int},u} = \int_0^{\infty} R_u(\tau) d\tau$$

321 Here, T_{int} is averaged over u and v , and the integrations are only carried out to the first
322 zero-crossings of $R_{..}(\tau)$. Lagrangian length scales can then be derived as the product of
323 T_{int} and $\sqrt{\text{EKE}}$. Details of the computation are identical to those used by Lankhorst and
324 Zenk (2006, their appendix b).

325 Figure 7 shows the EKE and T_{int} for the AAIW layer in the northwestern tropical
326 Atlantic, spatially filtered and interpolated onto a 1°-by-1° grid. EKE is highest near
327 the boundary (exceeding 100 cm² s⁻²) and decreases to values below 50 cm² s⁻² in the
328 interior. Increased EKE near 12° N and 58° W is caused mainly by the two intense
329 cyclones discussed in section 4.1. A small area between Barbados and the southernmost
330 Windward Islands (Tobago Basin, centered at about 60.5° W and 12.5° N) is separated
331 from the open Atlantic by a submarine ridge and also has high EKE, but the area is
332 sampled by just one float. Another broad maximum of EKE near 100 cm² s⁻² is located
333 between the equator and 5° N, west of about 40° W. This is the region where floats
334 indicate energetic interactions between the equatorial currents (NICC and EIC) and the
335 boundary current.

336 The Lagrangian integral time scale is longest in the interior basin away from the
337 equator and reaches values of typically just below 10 d, which would connect well with
338 findings by Rossby et al. (1986). Closer to shore and within the equatorial region, shorter
339 time scales around 5 d are observed. The float in the Tobago Basin has also experienced
340 short time scales. Computed length scales are 20–30 km for the open ocean areas, ex-
341 ceeding 50 km in the boundary current regime off the Amazon, and near 50 km in the
342 equatorial area offshore. These length scales correspond to about 35% of an eddy di-
343 ameter if one assumes perfectly circular motion. Hence, typical eddy diameters in the

344 off-equatorial northwestern tropical Atlantic are near 70 km, and fluctuations related to
345 the NBUC larger than 140 km.

346 In the uNADW layer, the following mesoscale properties are observed (not shown in
347 figure): along 16° N east of the Lesser Antilles (along section (a) of fig. 6), EKE values
348 decrease from above 30 cm²s⁻² near the western boundary to below 10 cm²s⁻² in the
349 basin interior. T_{int} averages between 7 and 9 d along this section. North of the Amazon
350 delta (approx. along section (b) of fig. 6), SOFAR floats measured significantly higher
351 EKE values of 110 cm²s⁻² near the shelf, which also decrease to below 10 cm²s⁻² further
352 out (Richardson and Schmitz, 1993). T_{int} here seems to systematically increase from 7 d
353 near the boundary to almost 10 d offshore. Corresponding length scales tend to be smaller
354 than in the AAIW layer, mainly because of the lower EKE, but are also in the range of
355 20–70 km with lowest values in the ocean interior and highest values near the boundaries.

356 4 Detailed Studies

357 4.1 Selected Trajectories

358 In the following paragraphs, we highlight a selection of individual trajectories that show
359 peculiar circulation patterns or are representative of features discussed in the previous
360 sections.

361 4.1.1 Antarctic Intermediate Water (AAIW)

362 Fig. 8 shows trajectories from acoustic floats in the AAIW only, from which those with
363 poor tracking geometry or acoustic performance have been removed manually. The seem-
364 ingly chaotic superposition of the trajectories highlights the role of the mesoscale field in

365 the area, as discussed in section 3. Within this complex setting, the following features
366 can be identified at closer look:

367 One float moved southeastward along the shelf break west of the Guiana Plateau
368 (label A in fig. 8), after heading northwestward further offshore. This suggests that the
369 NBUC as a boundary current typically does not reach this far northwest, favoring the idea
370 of a mean flow that detaches from the boundary at Guiana Plateau. The same pattern
371 was visible in fig. 3, and the interpretation is that the mean flow is produced by rings and
372 eddies shed from the NBUC.

373 North of there (label B in fig. 8), two floats independently measured intense small-
374 scale cyclonic eddies, which make the trajectories show looping behavior for long times
375 (exceeding 10 months). The high swirl velocities and the persistence of these two eddies
376 stand out drastically from the data set. One of them has been thoroughly discussed by
377 Fratantoni and Richardson (2006), yet the occurrence of a second one (from the SAMBA
378 data at a different time) suggests that such features might be common in the area. The
379 EKE values in fig. 7 are greatly elevated in this area because of these two eddies.

380 Only two floats penetrated into the Caribbean, through the passage between Mar-
381 tinique and Dominica (approx. 15.1° N, label C in fig. 8), documenting this as a possible
382 but rather unlikely route for AAIW. Once in the Caribbean, the floats lost acoustic track-
383 ing, and the figure shows only their surface positions after their missions were finished.
384 It is surprising that no other floats moved into or back out of the Caribbean, since e. g.
385 Rhein et al. (2005) and Kirchner et al. (2008) document ample flow in either direction
386 through various passages, and the one between Martinique and Dominica does not stand
387 out in any way in their data. They find significant interannual variability in the trans-
388 ports, and with the relatively low number of floats approaching the islands, the most likely
389 explanation is that no float was in the right location at the right time to be advected past

390 the islands. However, perhaps the topography around the Tobago and Barbados Basins—
391 albeit deeper than the AAIW level—shields the passages south of St. Lucia from the open
392 Atlantic, while the northern ones remain more exposed.

393 Within 5° of the equator, floats mainly drift zonally in the five current bands dis-
394 cussed in section 2 (NEIC, NICC, EIC, SICC, SEIC). One exemplary trajectory for each
395 current band is highlighted in fig. 8. Superimposed on the zonal motions, most trajec-
396 tories have wave-like patterns (found also by Boebel et al., 1999b), the dimensions of which
397 are described by the time and length scales in section 3.

398 At the shelf break, only two floats cross the equator (label E), which is again sur-
399 prising given the idea of a boundary current. However, the area immediately upstream of
400 the equator (approx. south of the equator and west of 40° W) is only sparsely populated
401 with floats, because most are removed from there by the SICC. Together, this suggests
402 that AAIW spreads northward preferably via excursions in the zonal flows rather than
403 on a continuous path along the boundary.

404 **4.1.2 Upper North Atlantic Deep Water (uNADW)**

405 Fig. 9 shows sample trajectories from the uNADW layer. The SOFAR floats that comprise
406 most of the data in the southeastern portion of the domain have already been discussed
407 by Richardson and Fratantoni (1999) and initially Richardson and Schmitz (1993), who
408 describe pathways within the southeastward DWBC and zonal excursions into the ocean
409 interior and back.

410 Further north (between roughly 13° N and 21° N), all MOVE and ACCE floats in
411 the uNADW had at least some tendency to drift westward in the open ocean (label F in
412 fig. 9). This broad westward flow is also present in the mean field discussed in section 2.
413 From the trajectories, it seems possible that the westward flow originates east of the Mid-

414 Atlantic Ridge. Five of the MOVE floats were eventually caught in the southward-flowing
415 DWBC. The location where they merge with the DWBC is consistent with the strong
416 dilution of uNADW between 16° N and 10° N as observed by Steinfeldt et al. (2007).

417 When the DWBC reaches a latitude of approx. 12° N southeast of Barbados, the
418 continental slope becomes less steep, and the few floats available show a tendency to
419 diverge at this location (label G in fig. 9). This has also been proposed by Steinfeldt et al.
420 (2007) as a reason for water mass dilution. Because of this detraining from the DWBC,
421 only one MOVE float actually reaches the longitude of 50° W via the DWBC and thereby
422 connects with the area sampled by the SOFAR floats a decade earlier (label H in fig. 9).
423 The other four completed their pre-programmed life spans before traveling this far.

424 In the Tobago and Barbados Basins between Barbados and Trinidad, which are
425 separated from the deep ocean by a system of ridges, one of the profiling floats was
426 subject to erratic flows which trapped it “inshore” of the DWBC for more than half a
427 year (label J in fig. 9). The long stagnation time in this area suggests that the Tobago
428 and Barbados Basins contain older water masses at this depth, although the relatively
429 young uNADW water flows by in immediate vicinity.

430 Two floats recirculated offshore of the DWBC northeast of Barbados in a loop ap-
431 proximately 70 km wide and 400 km long (label K in fig. 9). This forms a narrow recir-
432 culation cell, the velocities of which are significantly larger than those of the basin-wide
433 westward flow at the same latitude, and yet another pathway to dilute water masses of
434 the DWBC.

435 Fig. 10 shows a synoptic one-month snapshot of three MOVE floats that paralleled
436 each other in the DWBC with the inshore ones fastest, highlighting the horizontal velocity
437 shear between them. Extrapolating from this shear, the span of the southward DWBC is
438 estimated as 150 km (zero-crossing), consistent with the width of about 100 km seen in

439 fig. 6 at section (a).

440 **4.2 Interaction between the Boundary Current and the Equa-** 441 **torial Currents**

442 Fig. 3 in section 2 has shown that the strongest features of the mean circulation in the
443 AAIW are the five alternating zonal currents of the equatorial region and the western
444 boundary current. Here, we will take a closer look at exchange between these currents,
445 both in the mean field and individual trajectories, which we will find to be generally
446 consistent but with additional pathways suggested by some trajectories.

447 Bearing in mind that the process of computing the stream function might have
448 introduced uncertainties in the actual pathways of the water masses, fig. 3 suggests the
449 following about interactions between the boundary and the equatorial currents, from
450 south to north: most of the SEIC plus a small fraction of the NBUC recirculate eastward
451 in the SICC. In the eastern half of the basin (east of 35° W), additional input into the
452 SICC comes from the EIC to its North. All streamlines from the EIC that reach the
453 western boundary are brought eastward again in the NICC. The NICC also detrains large
454 portions (all but two streamlines) from the NBUC. The westward NEIC re-establishes the
455 boundary current as it approaches the shelf break.

456 To further investigate sources and sinks of the waters in the equatorial currents
457 near the western boundary, fig. 11 displays trajectory segments of floats that have passed
458 through certain boxes within the equatorial current bands of the AAIW layer. There
459 is one box per current band, and trajectories of up to 80 d prior to entering and after
460 leaving the boxes are shown. Generally, the zonal velocity component of the individual
461 float trajectories meets the expectations from the mean field, which is apparent from the
462 different colors (red vs. green) concentrating east or west of the boxes.

463 Six trajectories leading into the NEIC box do so from the east, two after being
464 ejected from the NICC and the others more directly from the east but with significant
465 meandering motions, likely tropical instability waves (Richardson and Fratantoni, 1999).
466 Two come from the south, one of them directly from the EIC. Two come from the north
467 and none from the west. After leaving the NEIC box, most trajectories lead northwest-
468 ward, consistent with the NBUC: five trajectories exit to the west, three to the north,
469 one to the south, and none to the east. Two of these trajectories, eventually go south-
470 and then eastward in the NICC.

471 The majority of floats entering the NICC box do so through its northern or southern
472 edges with a significant eastward velocity component (six from the north, eight from the
473 south). Two trajectories enter from the west, and none from the east. Six floats entering
474 the NICC box had previous westward motion in the EIC, and then turned northward
475 to join the NICC. At least five tracks from the NBUC into the NICC are documented,
476 along with one trajectory that was along the boundary but in the opposite direction before
477 reaching the box. Three trajectories exit the NICC box through the northern, five through
478 the southern, seven through the eastern and none through the western edge. Most of the
479 trajectories leaving the NICC box stay in the eastward NICC jet, with further wave-like
480 meanders. The concentration of inflowing trajectories in two locations at the northwestern
481 and southwestern corners, and of the outflowing ones at the eastern boundary represents
482 standing or quasi-permanent meanders of the NICC. An anticyclonic circulation centered
483 around 2° N, 44° W is observed in several instances and seems to be a typical motion in
484 this area where the NICC, EIC, and NBUC interact (cf. also fig. 8).

485 All floats entering the EIC box do so in meandering motions from the east: three
486 through the eastern, one through the northern, and three through the southern edge.
487 Four leave the box through the western edge, and one each through the northern and
488 southern edge. Two of these drift northward, then eastward in the NICC, three feed the

489 NBUC, and one follows a southward, and then eastward path resembling either a reversal
490 of the EIC or the northernmost edge of the SICC.

491 Trajectories entering the SICC box count as follows: seven through the northern,
492 three through the southern, nine through the western, and one through the eastern edge.
493 Three of these come from the EIC, two from the SEIC, and four from the boundary regime
494 where they had northwestward motion. Two trajectories had an opposite flow direction
495 when they were near to the boundary. Exit from the SICC box takes places predominantly
496 with an eastward component. Seven trajectories leave through the northern edge, only
497 one of which winds up in the westward EIC. Both trajectories that leave through the
498 southern edge head westward consistent with the SEIC. Ten exit the box through the
499 eastern edge, three of which recurve south-, then westward in the SEIC. Many others
500 again show the characteristic meandering motions mentioned before.

501 The SEIC box receives two trajectories through the northern, three through the
502 southern, and nine through the eastern edge. Two trajectories leave through the northern,
503 three through the southern, seven through the western, and two through the eastern edge.
504 Five trajectories feed the west-northwestward NBUC after leaving the box, two recurve
505 in the SICC, and one leads southward offshore of the boundary current.

506 Many of the above interactions between the NICC, EIC, and SICC have already
507 been identified by Stramma and Schott (1999, their fig. 6) based mainly on water mass
508 analysis and transport estimates, and the float trajectories now confirm them by providing
509 direct velocity measurements. Generally, these findings support the interpretation of fig.
510 8 that all westward current bands (NEIC, EIC, SEIC) have a tendency to add to the
511 northwestward-flowing boundary current, while the eastward current bands (SICC, NICC)
512 strongly drain from an area offshore of the NBUC as well as the NBUC itself. Interior
513 flow from one current band to another is possible but occurs much less frequently than

514 at the boundary. The majority of trajectories are consistent with the mean flow.

515 **4.3 Crossing of the Equator**

516 The immediate vicinity of the equator is dynamically special in oceanography because the
517 Coriolis force, essential for large-scale motions elsewhere, vanishes there. Richardson and
518 Fratantoni (1999) have described how floats in the uNADW cross the equator southward,
519 and here we take a look at the flow of AAIW across the equator northward. Boebel et al.
520 (1999a) have identified how the northward flow from the NBUC is deflected subsequently
521 in the SICC, EIC, and the NICC, but had to base their results on a very small number of
522 floats. Fig. 12 shows a greatly enlarged database of float trajectories near the equator in
523 the AAIW layer: trajectories of floats with position fixes within 0.5° of the equator are
524 shown prior to and after exiting this equatorial strip. The main route detraining the strip
525 appears to be the NBUC north of the Equator, based on the number of trajectories that
526 follow its path. However, there seem to be very few trajectories that continuously follow
527 the NBUC from the southern to the northern hemisphere (cf. fig. 8). Trajectories that
528 leave the equatorial strip in the northwestward NBUC tend to originate in the EIC (i. e.
529 within the box from the east) and thereby come from the ocean interior. Elsewhere along
530 the entire strip, no systematic entrainment or detrainment is obvious either to/from the
531 north or to/from the south, although several trajectories leave and enter the box to/from
532 either side in a seemingly random fashion. This corresponds to the interaction of the
533 zonal equatorial current bands—in this case the EIC—with the surroundings, and the
534 mechanism suggested for such interaction is tropical instability waves (Richardson and
535 Fratantoni, 1999). The main inflow into the equatorial box as it is depicted in the figure
536 stems from the east, outside the domain studied here.

537 To summarize, the major path that carries AAIW northward from the equator is in

538 the NBUC, which in turn appears mostly fed from the ocean interior through the EIC.
539 The direct path along the shelf break is possible but rare. Southward flow along the
540 boundary from the equator as shown by Boebel et al. (1999a) is only observed in one case
541 and thus unlikely. Cross-equatorial exchange in either direction can occur in the ocean
542 interior when water enters or leaves the EIC.

543 **5 Conclusions**

544 Float data coverage in the AAIW (cf. table 1 for all abbreviations) layer in the north-
545 western tropical Atlantic is sufficient to map out the mean flow and the properties of the
546 mesoscale eddy field on a basin-wide domain. The AAIW as a water mass enters the
547 domain from the south in the NBUC (Stramma et al., 1995), as well as from the east
548 through three westward-flowing zonal current bands (NEIC, EIC, SEIC) in the equatorial
549 region at latitudes lower than 5° (e. g. Ollitrault et al., 2006). Between these three, two
550 equatorial currents (NICC, SICC) flow eastward and provide an exit route out of the do-
551 main, thereby forming an exchange mechanism between the western and eastern basins.
552 Direct exchange between these opposite flows along their paths is also observed. Mean
553 transports are given in table 3. Fig. 13 (top) shows a schematic of the mean circulation
554 and relates the new findings to previous results. Float trajectories support the circulation
555 schematic presented by Stramma and Schott (1999) for exchange processes between the
556 NICC, EIC, and SICC near the western boundary. The amendment to this schematic
557 by Schmid et al. (2003), who include the NEIC and SEIC, is corrected in some detail
558 as to the location of the NEIC and how the currents interact with each other and espe-
559 cially the boundary. Another export route for AAIW is to the north along the NBUC,
560 and further downstream in a weak mean northward flow paralleling the coast of South
561 America and the Antilles islands mostly 200–400 km offshore of the shelf break. Stramma

562 and Schott (1999) include such a pathway but take it into the Caribbean through the
563 southernmost passages, and do not report the continued northward flow in the Atlantic.
564 This flow is heavily masked by mesoscale eddy activity, and a possible interpretation is
565 that the measured mean flow downstream of the NBUC represents the advection speed of
566 North Brazil Current Rings, large anticyclonic eddies that originate from the NBC/NBUC
567 system (Richardson et al., 1994). This interpretation is in quantitative agreement with
568 findings by Rhein et al. (2005), which are based on hydrographic measurements. However,
569 there is no evidence of large-scale gyres in the basin interiors as shown by Stramma and
570 Schott (1999) and Schmid et al. (2003), and these are crossed out accordingly in fig. 13. It
571 remains unclear why floats do not show the inflow into the Caribbean through the south-
572 ernmost Antilles islands, which is clearly observed by Rhein et al. (2005). A quantitative
573 description of the mesoscale field shows Lagrangian integral time scales between 4 d and
574 10 d, and eddy kinetic energies between $20 \text{ cm}^2 \text{ s}^{-2}$ and $150 \text{ cm}^2 \text{ s}^{-2}$, with higher energy
575 levels and shorter time scales generally closer to shore. Typical eddy diameters from 70 to
576 greater than 140 km are derived. The repeated occurrence of cyclones with higher energy
577 levels and smaller spatial scales as initially observed by Fratantoni and Richardson (2006)
578 would motivate a further investigation of eddies in the area between Barbados and the
579 Guiana Plateau.

580 In the uNADW layer (fig. 13, bottom), the strongest signal is the southward-flowing
581 DWBC, the speed of which varies along the coast. Interaction with the interior is a
582 likely explanation for varying speeds: the data show a slim recirculation east of the
583 Lesser Antilles and a coherent westward (i. e. onshore) flow throughout the basin near
584 16° N observed at least for several months. The source region of the latter remains to be
585 identified but seems to be at or even east of the Mid-Atlantic Ridge. NADW spreading
586 from the subpolar North Atlantic via interior pathways is a likely possibility. A tendency
587 of the DWBC to diverge at 10° N is directly observed for the first time and, together

588 with the recirculations upstream, is consistent with findings of a dilution of DWBC water
589 as reported by Steinfeldt et al. (2007). South of 10° N, fig. 13 shows an adaptation of
590 previous results by Richardson and Schmitz (1993) and Richardson and Fratantoni (1999),
591 which include the DWBC and various zonal current bands in the equatorial region which
592 closely resemble those of the AAIW layer. Open questions remain as to how the DWBC
593 signal bridges the gap near 57° W, the site of the aforementioned divergence. It is also not
594 quantitatively clear how well the equatorial zonal currents resemble those of the AAIW.
595 Both issues suffer from data sparsity, calling for analysis with numerical models. The
596 mean and mesoscale velocities quantified herein may well serve as ground truth for such
597 numerical simulations.

598 **Acknowledgements**

599 MOVE was funded by the *Bundesministerium für Bildung und Forschung* (grants
600 03F0246A and 03F0377B) as well as by the *Deutsche Forschungsgemeinschaft* (grant
601 SE815/21), NBC by the *National Science Foundation* through grants OCE 97-29765 and
602 OCE 01-36477, and SAMBA was fully supported by Ifremer. The authors are thankful to
603 all float data providers listed in table 2. M. McCartney has generously shared data from
604 the GAGE moorings. CTD and LADCP data for fig. 2 were kindly supplied by M. Rhein
605 and M. Walter. Argo data were collected and made freely available by the International
606 Argo Project and the national programs that contribute to it. Argo is a pilot program of
607 the Global Ocean Observing System.

608 *Dedication:* We dedicate this paper to the memory of the late Friedrich (“Fritz”) Schott,
609 whom we remember as a colleague, friend, and scientist with profound interest in the trop-
610 ical Atlantic. Friedrich Schott’s legacy consists of pioneering observational data of the
611 area and accompanying interpretations, including measurements of the western boundary

612 currents and the equatorial currents discussed in this paper. Several figures and discussion
613 points of this work were motivated by questions he raised as a committee member during
614 ML's doctoral defense. He will remain in our memories as an outstanding, motivated,
615 and quite effervescent scientist.

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- 716 Talley, L. D., 1996. *The South Atlantic: Present and Past Circulation* (Eds.: Gerold
717 Wefer, Wolfgang H. Berger, Gerold Siedler, D. J. Webb). Springer, Ch. Antarctic In-
718 termediate Water in the South Atlantic.

Table 1: List of abbreviations.

AAIW	Antarctic Intermediate Water
ACCE	Atlantic Circulation and Climate Experiment
CTD	Conductivity-Temperature-Depth
EIC	Equatorial Intermediate Current
EKE	Eddy Kinetic Energy
IFM-GEOMAR	Leibniz-Institut für Meereswissenschaften
Ifremer	Institut français de recherche pour l'exploitation de la mer
LADCP	Lowered Acoustic Doppler Current Profiler
MOC	Meridional Overturning Circulation
MOVE	Meridional Overturning Variability Experiment
NADW	North Atlantic Deep Water
NBC, NBUC	North Brazil (Under-) Current
NEIC	Northern Equatorial Intermediate Current
NICC	Northern Intermediate Countercurrent
RAFOS	SOFAR backwards, Ranging and Fixing of Sound
RSMAS	Rosenstiel School of Marine and Atmospheric Science
SAMBA	Subantarctic Motions in the Brazil Basin
SEIC	Southern Equatorial Intermediate Current
SICC	Southern Intermediate Countercurrent
SOFAR	Sound Fixing and Ranging
T_{int}	Lagrangian Integral Time Scale
uNADW	upper North Atlantic Deep Water
WFDAC	WOCE Subsurface Float Data Assembly Center
WHOI	Woods Hole Oceanographic Institution
WOCE	World Ocean Circulation Experiment

Table 2: List of data used in this study. Note that some projects have collected more data than is actually used here. WFDAC refers to the WOCE float data center at wfdac.whoi.edu. Where individual persons are listed, the data was obtained directly from them rather than through WFDAC. From SOFAR floats, only the first year of data is used because of ballasting problems presumably worsening with age (Richardson and Fratantoni, 1999). Argo drift pressures are based on nominal rather than measured values.

Project Name	Float Type	Principal Investigators	Data Source	Data Amount [d]		Press. [dbar] Mean \pm Std.	Sampling Period
				AAIW	uNADW		
MOVE	Acoustic (RAFOS)	U. Send, W. Zenk	IFM-GEOMAR, M. Lankhorst	4370	2410	811 \pm 30 1433 \pm 125	2000–2001 2001–2001
NBC	Acoustic (RAFOS)	D. Fratantoni, P. Richardson	WFDAC, C. Wooding	3030	0	861 \pm 60	1998–2000
SAMBA	Acoustic (Marvor)	M. Ollitrault, A. C. de Verdière	Ifremer, M. Ollitrault	18953	0	813 \pm 26	1994–2003
IFM WOCE-era	Acoustic (RAFOS)	O. Boebel, W. Zenk	WFDAC, M. Lankhorst	930	0	833 \pm 29	1994–1996
Trop. Atl. SOFAR	Acoustic (SOFAR)	P. Richardson, W. Schmitz	WFDAC	4610	3890	839 \pm 72 1863 \pm 39	1989–1990 1989–1990
Argo	Profiling	Multiple	Argo Data Centers	37509	5975	1000 \pm 50 1750 \pm 250	1997–2006 2000–2006
ACCE (WHOI)	Profiling	R. Schmitt	WFDAC, E. Montgomery	16351	99	981 \pm 45 1247 \pm 39	1997–2002 1998–2002
ACCE (RSMAS)	Profiling	K. Leaman	WFDAC, P. Vertes	9659	3459	927 \pm 114 1251 \pm 38	1997–2002 1998–2002

Table 3: Mean transports in Sv for current features in the AAIW layer from different studies in relation to this one. All values are adapted to a common layer thickness of 450 m.

	Method	NBUC at 8° S	SEIC	SICC	EIC	NICC	NEIC	across 16° N
this study	floats	5.0	2.7	4.1	3.2	4.5	3.2	3.7
Ollitrault et al. (2006)	floats (800 dbar)	–	4.7	5.4	3.9	5.8	2.5	–
Rhein et al. (2005)	ring count, hydrography	–	–	–	–	–	–	2.9–4.5
Schott et al. (2003)	ship LADCP	5.7		3.5	5.5	3.9	3.9	–
Boebel et al. (1999a)	floats	4.5	–	–	–	–	–	–
Schott et al. (1998)	misc. shipborne	6.4–7.8	–	5.5	14.2	7.7	–	–

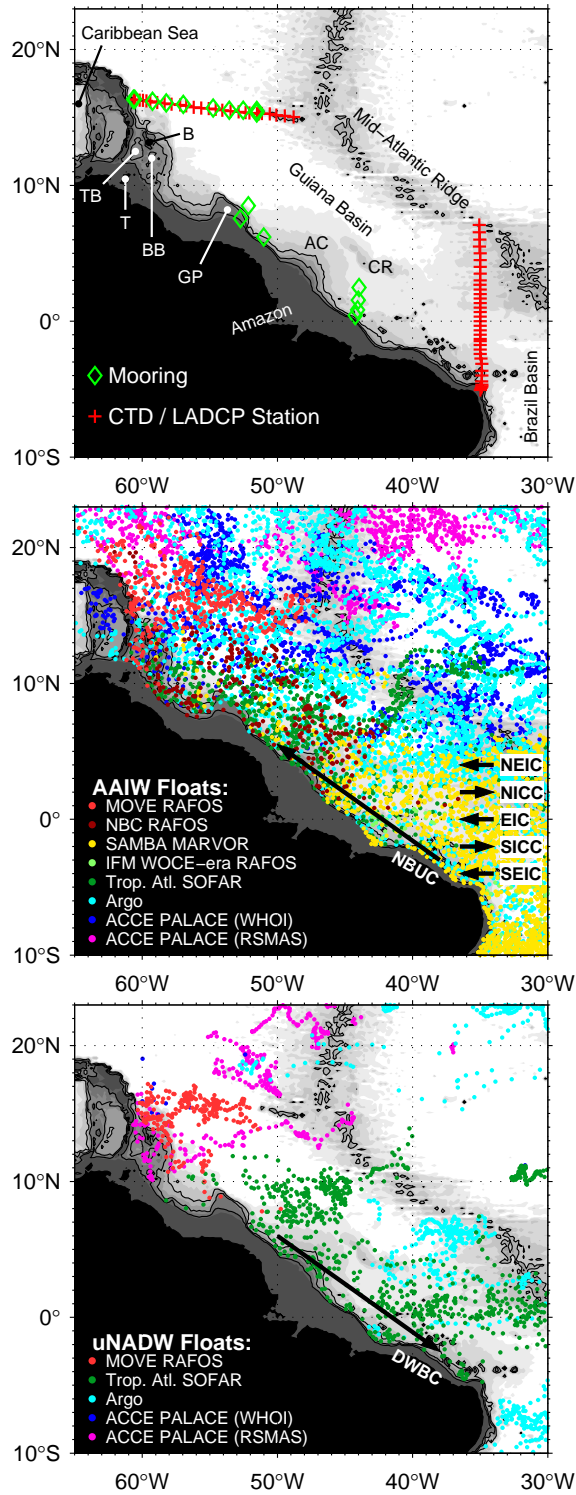


Figure 1: *Top:* Map of the study area indicating locations of two CTD sections (cf. fig. 2) and various mooring locations (cf. figs. 5 and 6). Abbreviations are: AC Amazon Cone, B Barbados, BB Barbados Basin, CR Ceará Ridge, GP Guiana Plateau, T Trinidad, TB Tobago Basin. Bathymetry in grey shades every 500 m down to 4500 m with additional lines at 1000, 2000, and 3000 m.

Middle and bottom: Float data coverage in the AAIW (middle panel) and uNADW (bottom) layers. Colors indicate different research projects. Each dot represents one displacement of typically 10 d duration. Schematics of major currents are included; cf. table 1 for abbreviations.

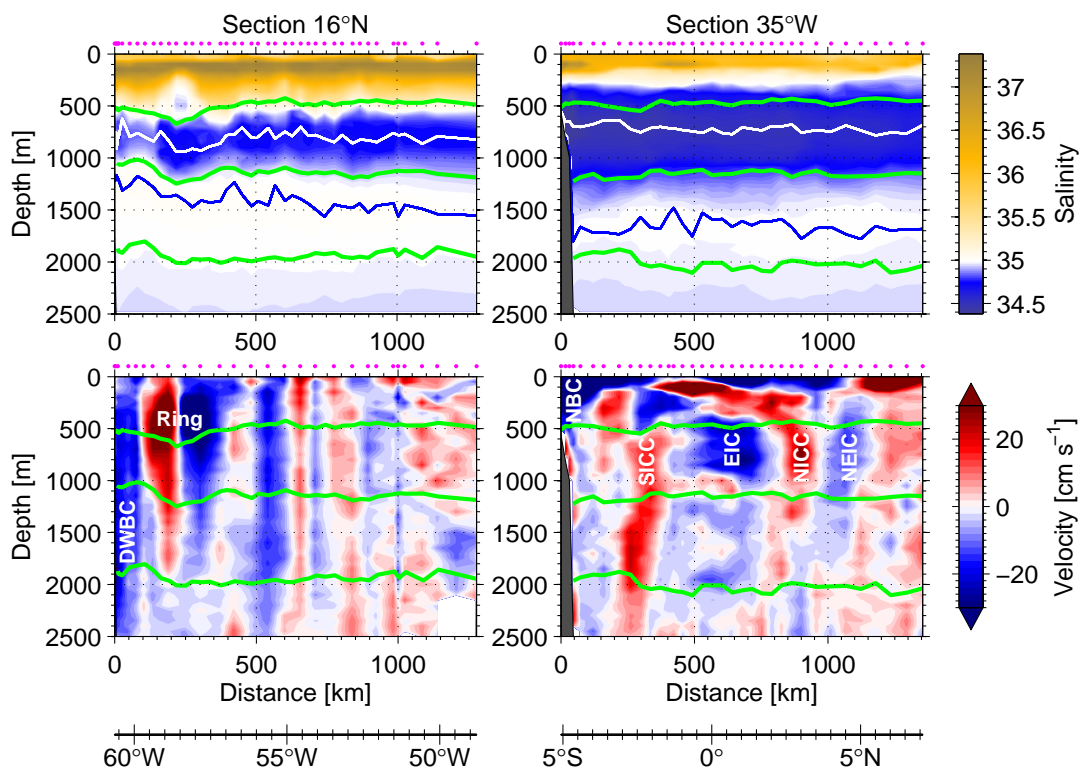


Figure 2: CTD and LADCP sections sampled during RV Sonne cruise 152 in late 2000 (Rhein et al., 2004, 2005). For locations of the two sections, cf. fig. 1: left-hand panels refer to the section near 16° N, and right-hand panels to the one along 35° W. *Top*: Salinity measurements from the CTD. *Bottom*: Across-section velocities from the LADCP (north- and eastward positive), and matching geographic coordinates. Purple dots indicate station locations, and the colored lines denote: depth of minimum salinity in the AAIW (white), depth of local salinity maximum in the uNADW (blue), and isopycnals $\sigma_0 = 27.10$, $\sigma_{1.5} = 34.42$, and $\sigma_{1.5} = 34.70$ (green) representing AAIW and uNADW boundaries. Labeled current features are discussed in the text (cf. table 1 for abbreviations).

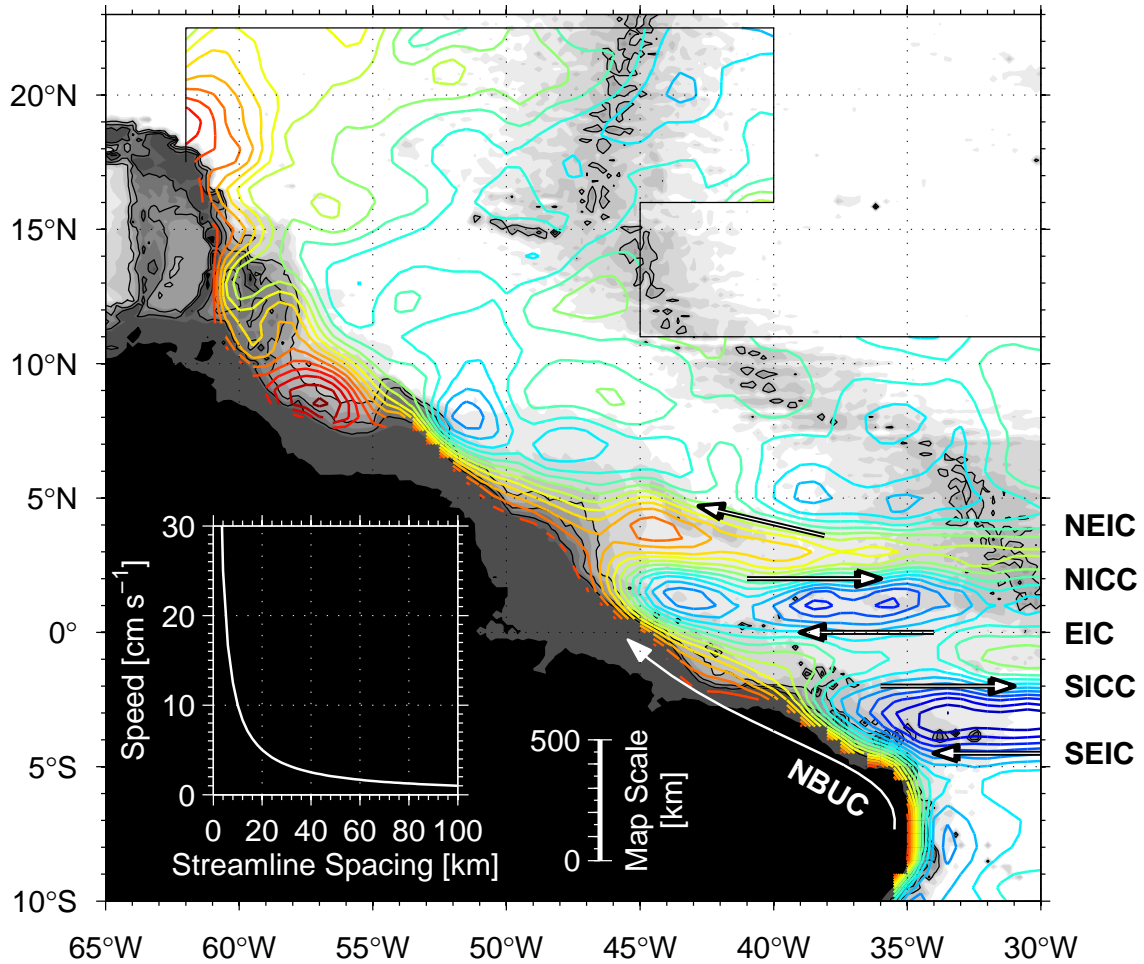


Figure 3: Stream function derived from all float displacements in the AAIW layer. The direction of flow is counterclockwise around reddish features and clockwise around blue ones. Streamline spacing is $1000 \text{ m}^2\text{s}^{-1}$, yielding a volume transport of 0.1 Sv between two streamlines for every 100 m of layer thickness. Cf. table 1 for abbreviations of named currents. Bathymetry as in fig. 1.

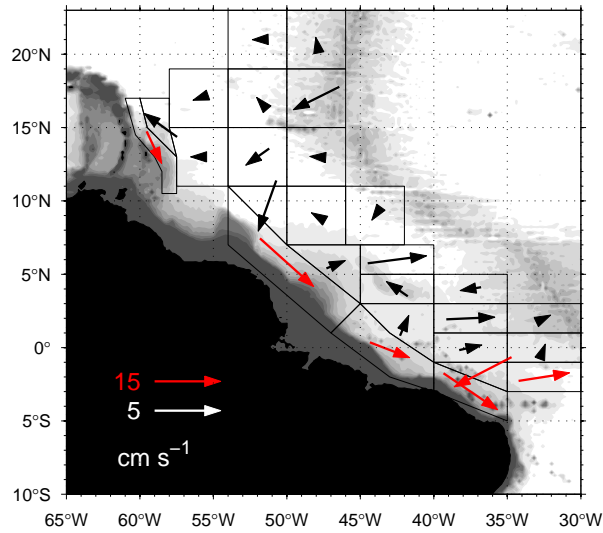


Figure 4: Mean currents in the uNADW layer. Box shapes near the boundary follow the flow features seen in individual trajectories (fig. 9). Arrow colors indicate scale. Bathymetry in shades of grey every 500 m down to 4500 m.

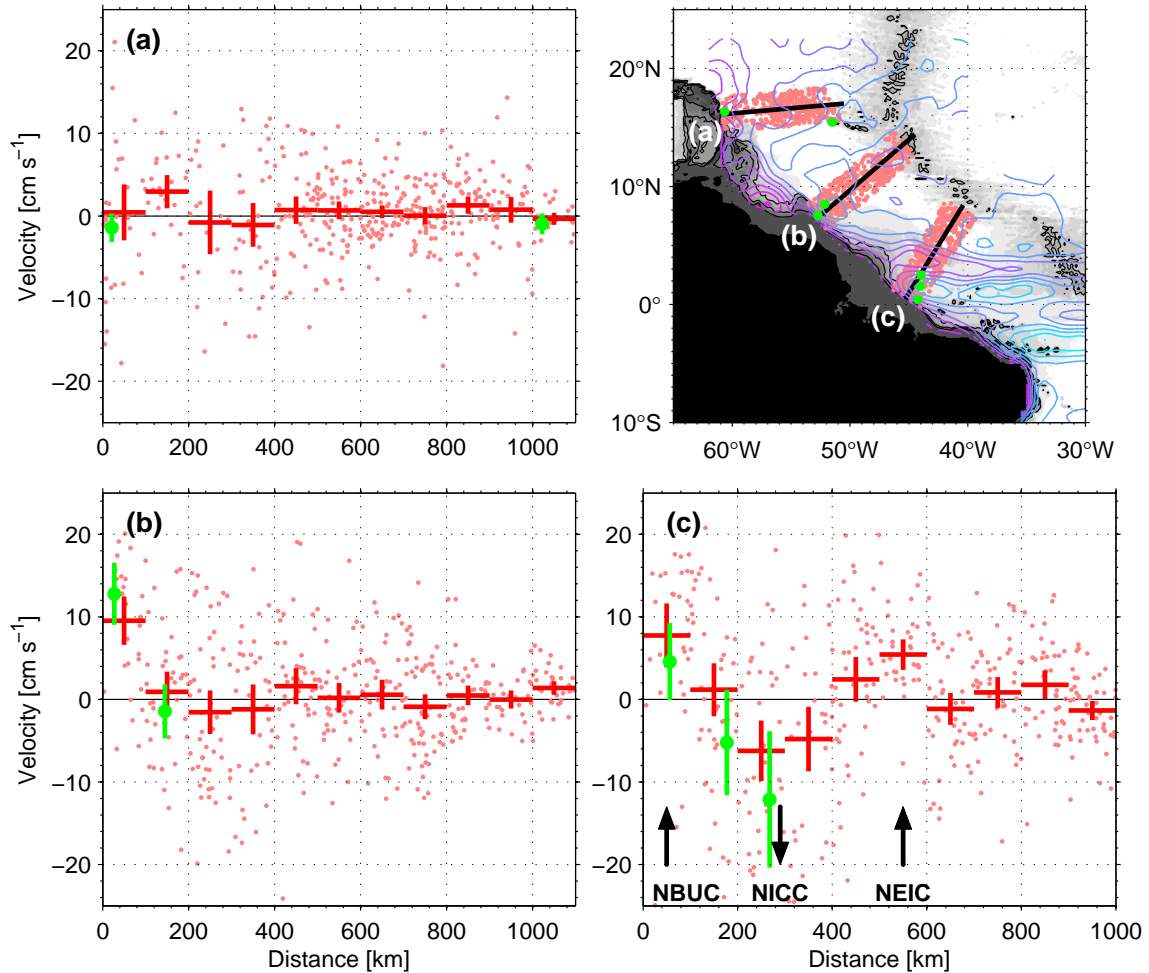


Figure 5: Velocities across three sections in the AAIW layer derived from float displacements (red) and mooring records (green). *Upper right*: Map with the sections (black lines), locations of data collection (red and green), and the stream function of fig. 3 (bluish, spaced every $2000 \text{ m}^2\text{s}^{-1}$) superimposed. *Other panels*: Light red dots refer to individual float displacements of typically ten days duration. Red crosses average these values in bins of 100 km; vertical extents of the crosses indicate 95% confidence intervals. Mooring data are shown as green dots with 95% confidence limits. Mooring data are from (a) the MOVE experiment, (b) Johns et al. (1990), and (c) Schott et al. (1993). Abbreviations in (c) refer to named currents (cf. table 1).

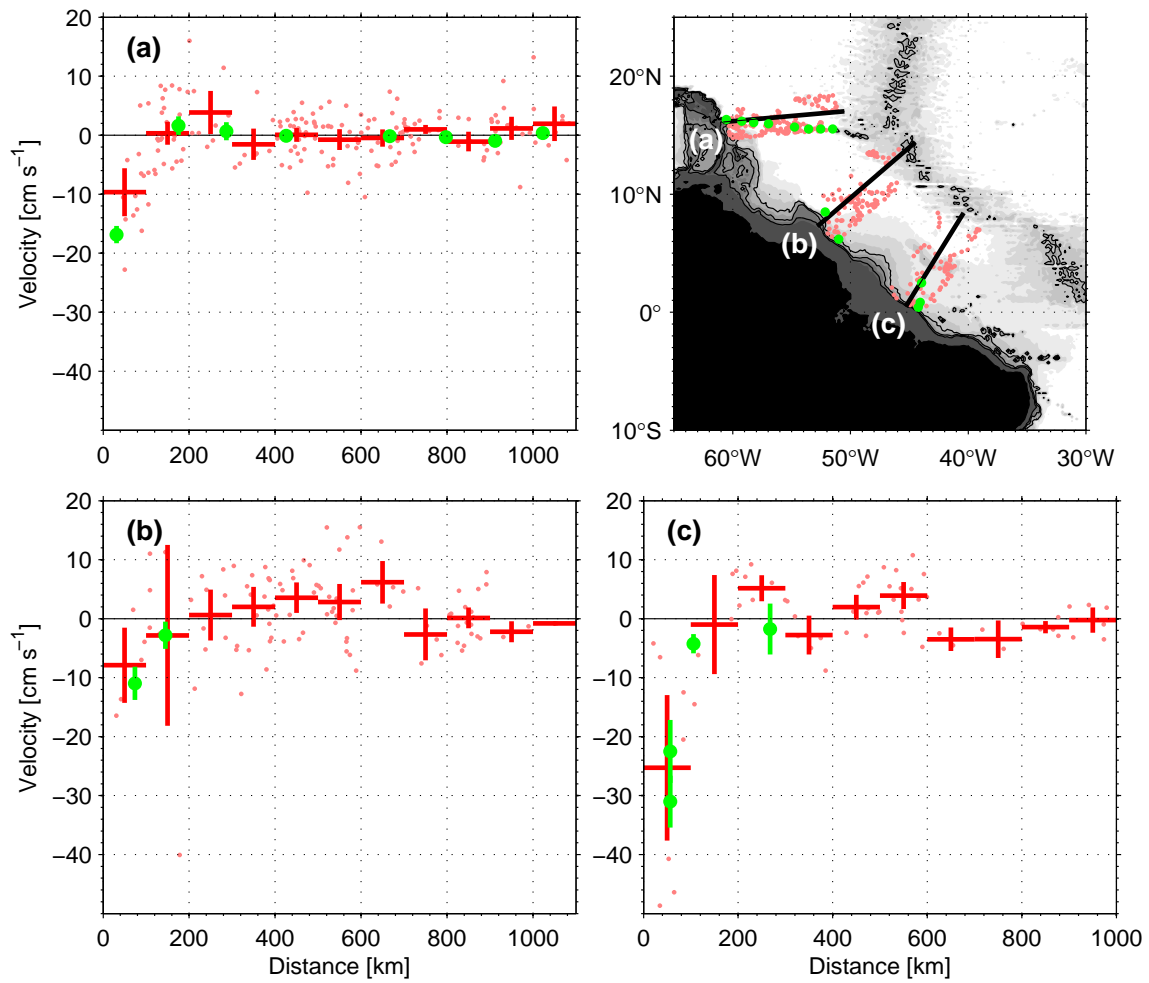


Figure 6: Velocities across three sections in the uNADW layer (otherwise as fig. 5) derived from float displacements (red) and mooring records (green). Mooring data are from (a) the MOVE and GAGE (M. McCartney, pers. comm.) experiments, (b) from Johns et al. (1990) and Colin et al. (1994), and (c) from Schott et al. (1993).

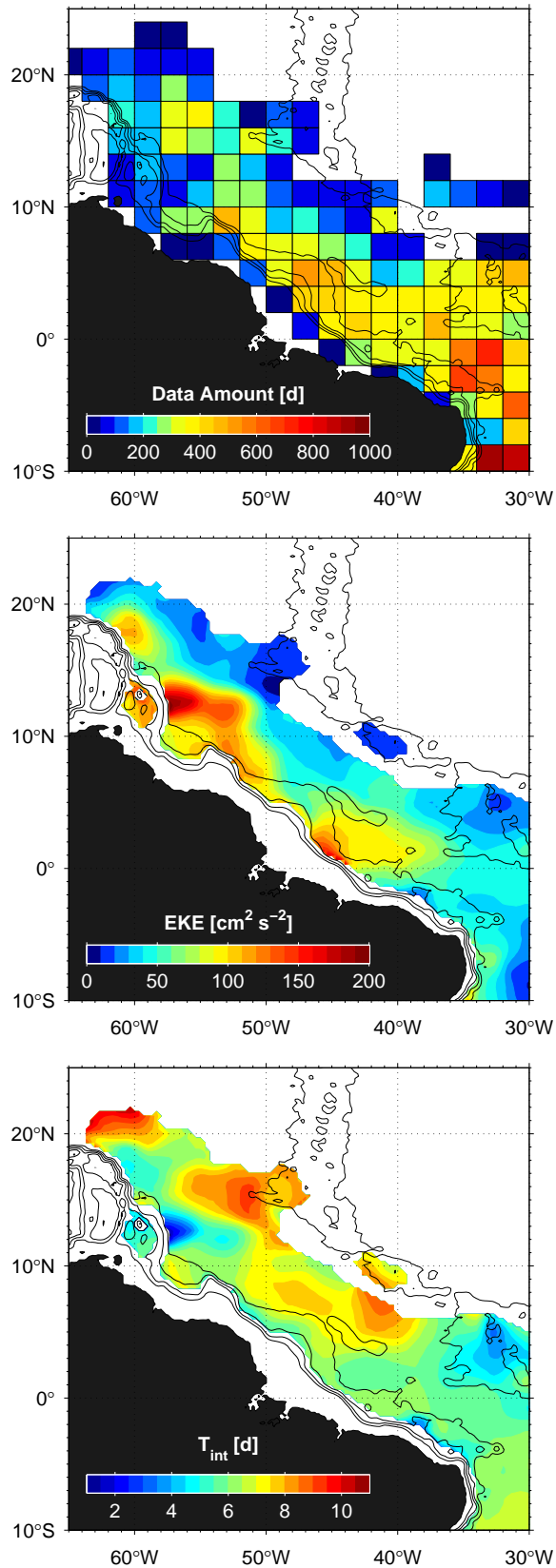


Figure 7: Lagrangian properties of the eddy field in the AAIW layer derived from float data with daily underwater positioning. *Top:* Data coverage in cumulative float days. *Middle:* Lagrangian eddy kinetic energy (EKE). *Bottom:* Lagrangian integral time scale (T_{int}). Bathymetric contours are at every 1000 m down to 4000 m.

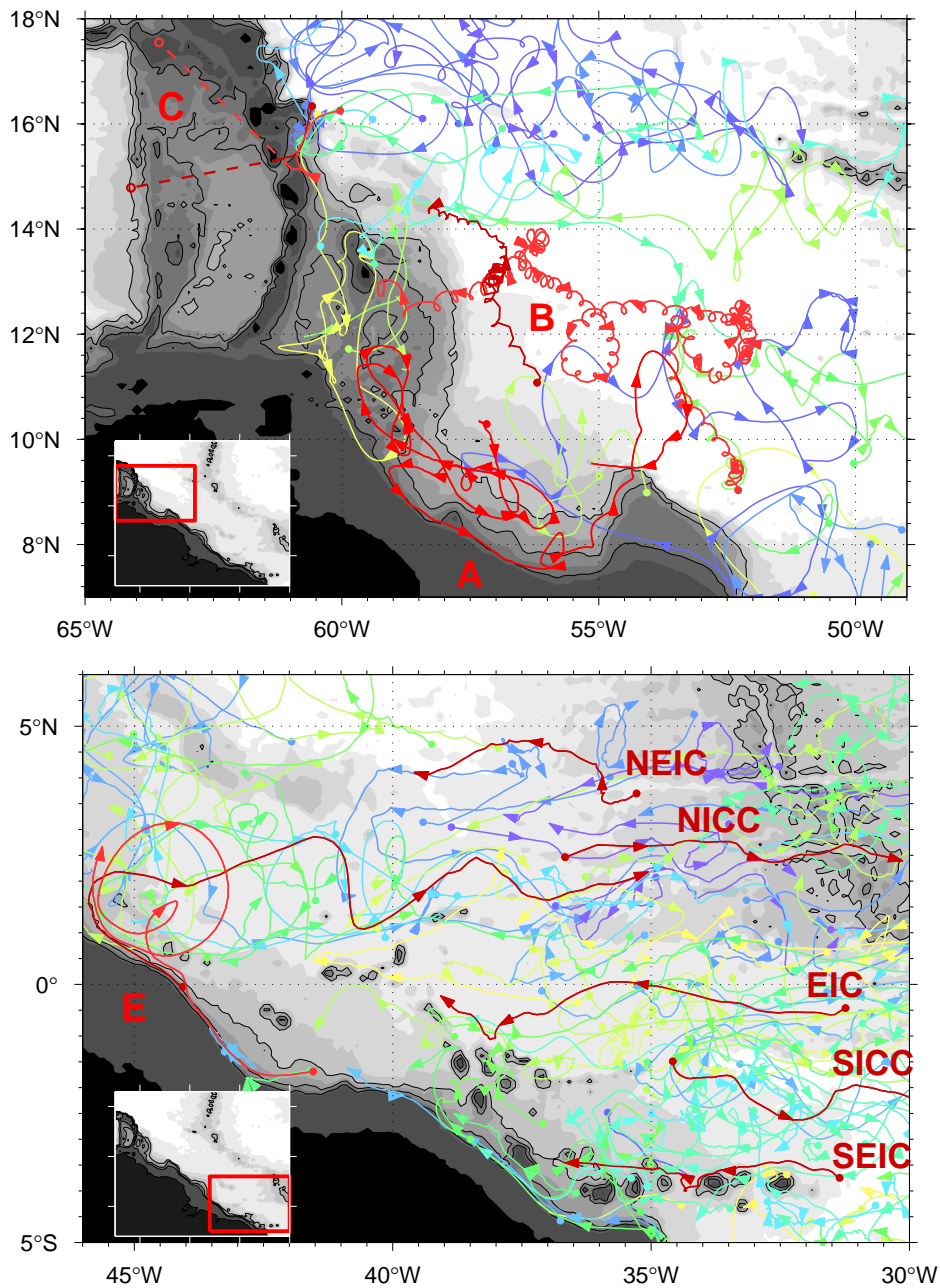


Figure 8: Eddy-resolving float trajectories of the AAIW layer. The selection is limited to acoustic floats from the MOVE, NBC, and SAMBA projects for which tracking was of good quality. Dots are at start points, arrow tips are 30 d apart. Single letters refer to highlighted (red) trajectories discussed in the text (section 4.1), abbreviations to named currents (cf. table 1). Bathymetry as in fig. 1.

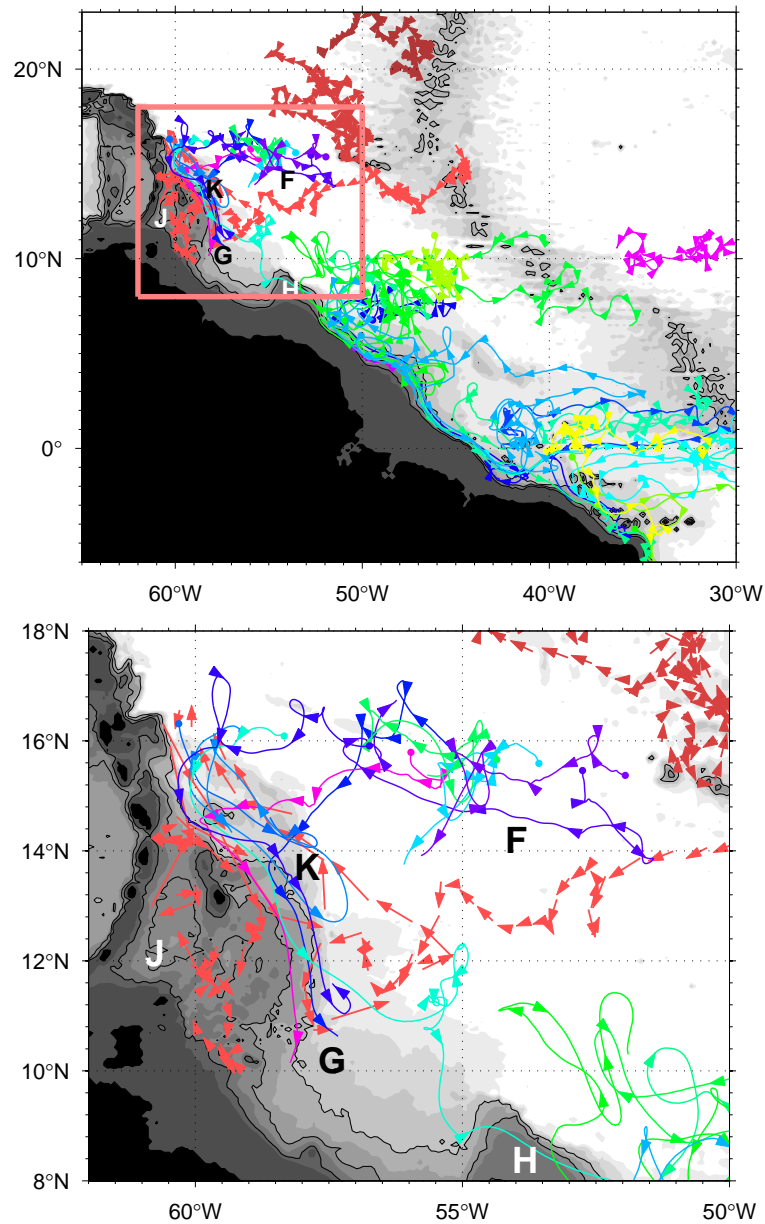


Figure 9: Selected float trajectories of the uNADW layer. Trajectories are from three profiling floats (ACCE RSMAS, shades of red) and the eddy-resolving acoustic MOVE and SOFAR float projects (other colors). Arrows for the profiling floats show their ten-day displacements, and arrow tips in the acoustic trajectories are 30 d apart. Letters refer to trajectories discussed in the text (section 4.1). The bottom panel is a close-up of the box marked in the top panel. Bathymetry as in fig. 1.

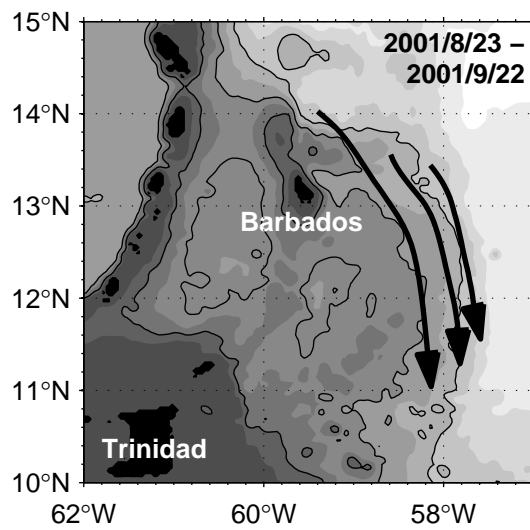


Figure 10: Snapshot of three simultaneous float trajectories drifting at 1400 dbar in the southward-flowing DWBC east of Barbados. The drift time was one month, yielding mean currents of 14.6, 10.7, and 8.6 cm s^{-1} for the three trajectory segments. Bathymetry as in fig. 1.

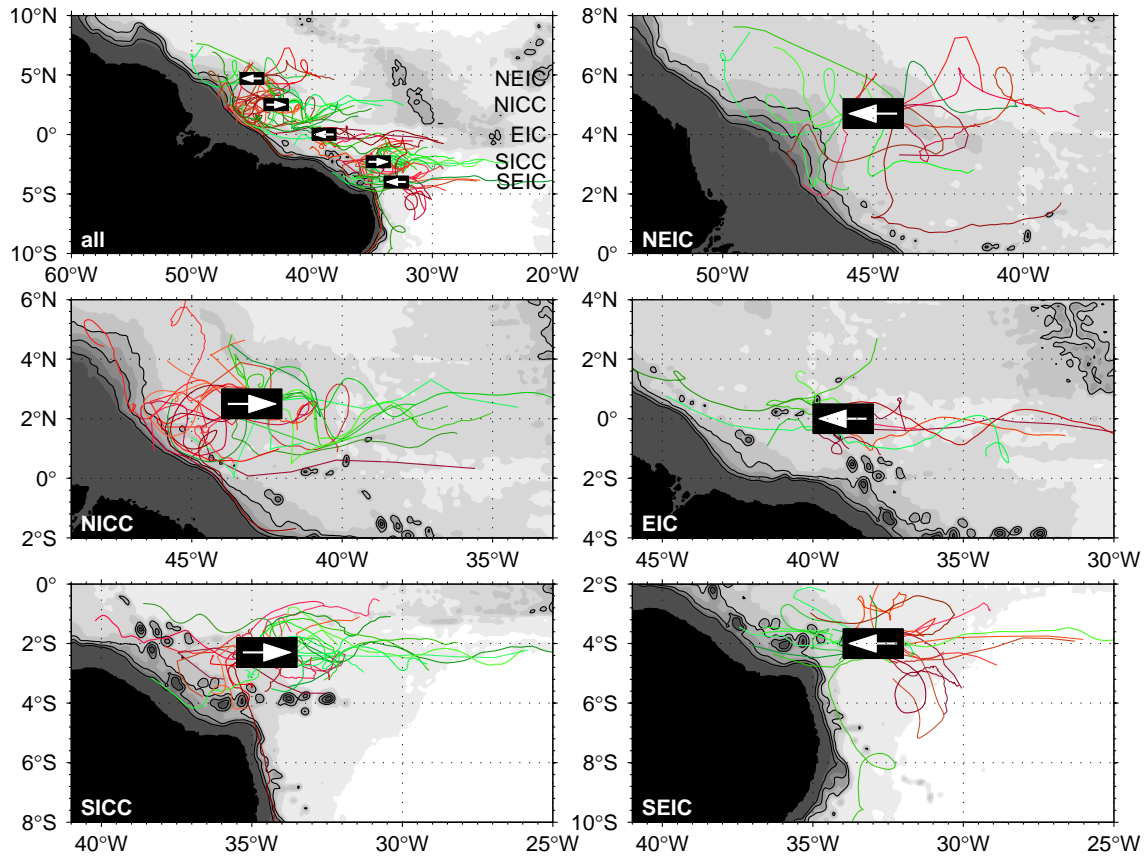


Figure 11: Interaction between the zonal equatorial currents and the boundary. Trajectories that pass through the black boxes are displayed. Red shades represent trajectories up to 80 d before entering the box, and green shades are trajectories up to 80 d after leaving the box. *Top left panel:* All boxes and trajectories superimposed. *Other panels:* Close-ups of individual boxes and corresponding trajectories. Boxes are designed to represent the following currents (cf. fig. 3): NEIC, NICC, EIC, SICC, SEIC. Arrows in the boxes indicate whether mean flow is generally east- or westward in the current band. Bathymetry as in fig. 1, abbreviations as in table 1.

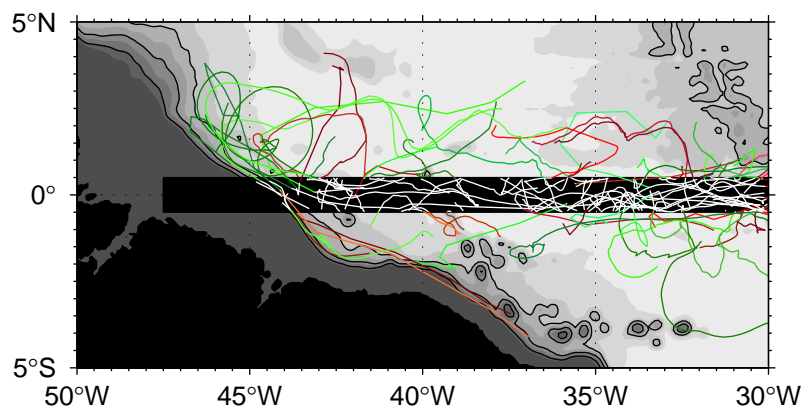


Figure 12: Crossing of the equator in the AAIW layer. Like in fig. 11, float trajectory segments up to 80 d in duration before entering (red) and after leaving (green) the black box are displayed. Trajectory segments in the box are included in white. Bathymetry as in fig. 1.

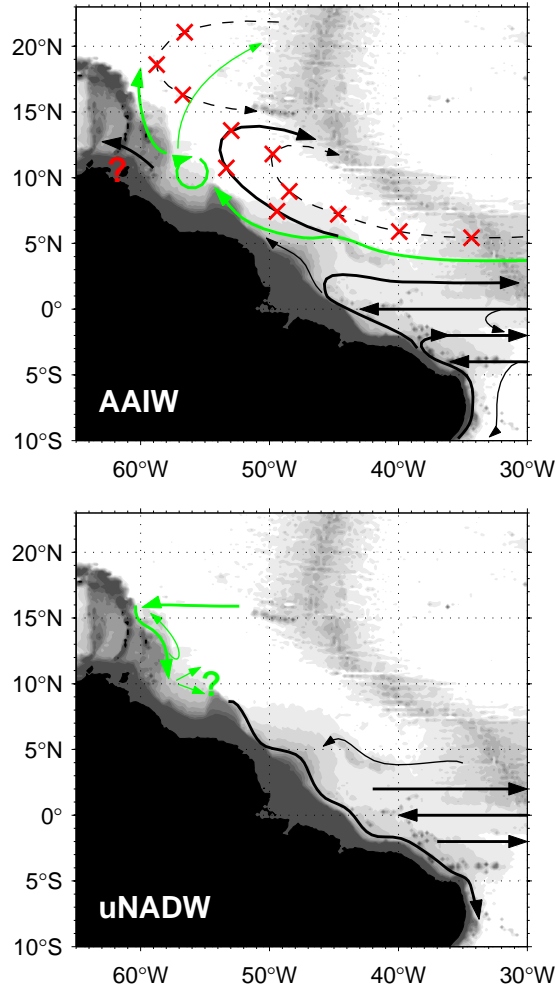


Figure 13: Circulation schematics. *Top*: AAIW layer. Black arrows reproduce results by Stramma and Schott (1999) and Schmid et al. (2003). Green arrows correct and extend these. Red marks show where the previous results were disproven. *Bottom*: uNADW layer. Black arrows interpret results by Richardson and Fratantoni (1999). Green arrows show findings based on the present study.