



HAL
open science

Formation and Evolution of a Freshwater Plume in the Northwestern Tropical Atlantic in February 2020

Gilles Reverdin, Léa Olivier, G. Foltz, Sabrina Speich, J. Karstensen, J. Horstmann, D. Zhang, R. Laxenaire, Xavier Carton, Hubert Branger, et al.

► **To cite this version:**

Gilles Reverdin, Léa Olivier, G. Foltz, Sabrina Speich, J. Karstensen, et al.. Formation and Evolution of a Freshwater Plume in the Northwestern Tropical Atlantic in February 2020. *Journal of Geophysical Research. Oceans*, 2021, 126 (4), 10.1029/2020JC016981 . hal-03263758

HAL Id: hal-03263758

<https://hal.science/hal-03263758v1>

Submitted on 22 Jul 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

A freshwater plume in the northwestern tropical Atlantic in February 2020

Reverdin, G.¹, L. Olivier¹, G. R. Foltz², S. Speich³, J. Karstensen⁴, J. Horstmann⁵, D. Zhang⁶, R. Laxenaire⁷, X. Carton⁸, H. Branger⁹, R. Carrasco⁵, J. Boutin¹

¹LOCEAN-IPSL, Sorbonne Université-CNRS-IRD-MNHN, Paris, France, Paris, France

²NOAA/Atlantic Oceanographic and Meteorological Laboratory, Miami, FL, USA,

³Laboratoire de Météorologie Dynamique, ENS-Ecole Polytechnique-CNRS-Sorbonne Université, Paris, France.

⁴GOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany

⁵Helmholtz-Zentrum Geesthacht, Geesthacht, Germany

⁶CICOES/University of Washington and NOAA/Pacific Marine Environmental Laboratory, Seattle, WA, USA

⁷Center for Ocean-Atmospheric Prediction Studies, Florida State University, Tallahassee, Florida, USA.

⁸Laboratoire d'Océanographie Physique et Spatiale, UBO-CNRS-IFREMER-IRD, Plouzané, France.

⁹IRPHE, CNRS-AMU, Luminy, France.

Corresponding author: Gilles Reverdin (gilles.reverdin@locean.ipsl.fr)

Key Points:

- Very stratified fresh water plume separates from Guiana shelf in early February 2020, carrying northward 0.15 Sv during 10 days.
- After 14 days, the plume reaches an extent of 100000 km², with minimum surface salinity eroding from 30 pss to 33.3 pss.
- Plume probably initiated by wind direction shift closer to the equator, 5-7 days earlier and stirred by a North Brazil Current ring.

1 **Abstract**

2 In February 2020, a 120km-wide freshwater plume was documented by satellite and in situ
3 observations near the Demerara Rise (7°N/54-56°W). It was initially stratified in the upper 10
4 m with a freshwater content of 2 to 3 meters of Amazon water distributed down to 40 m. On
5 February 2nd, ship transects indicate an inhomogeneous shelf structure with a propagating
6 front in its midst, whereas minimum salinity close to 30 pss was observed close to the shelf
7 break on February 5th. The salinity minimum eroded in time but was still observed 13 to 16
8 days later with 33.3 pss minimum value up to 400 km from the shelf break. At this time, the
9 mixed layer depth was close to 20 m. The off-shelf flow lasted 10 days, contributing to a
10 plume area extending over 100000 km² and associated with a $0.15 \cdot 10^6 \text{ m}^3 \text{ s}^{-1}$ freshwater
11 transport. The off-shelf plume was steered northward by a North Brazil Current ring up to
12 12°N and then extended westward toward the Caribbean Sea. Its occurrence follows 3 days of
13 favourable wind direction closer to the Amazon estuary, which contributed to north-westward
14 freshwater transport on the shelf. Other such events of freshwater transport in January-March
15 are documented since 2010 in salinity satellite products in 7 out of 10 years, and in 6 of those
16 years, they are preceded by a change in wind direction between the Amazon estuary and the
17 Guianas that is favorable for north-westward freshwater transport toward the shelf break.

18

19

20 **Plain language summary**

21 This paper documents how freshwater from the Amazon reaches the deep ocean up to 12°N in
22 the northwest tropical Atlantic in January-March. The classical view is that the water is
23 channelled along the shelf to the Caribbean Sea. Here, we document a freshwater plume from
24 in situ and satellite observations during the EUREC4A-OA/ATOMIC program. This plume
25 separated from the shelf near 55°W north of French Guiana on February 2-5. This fresher
26 water was stirred by a North Brazil Current ring up to 12°N before mostly spreading
27 westward. The near-surface water is initially very stratified at least until 10-m from the
28 surface. More than 14 days later and 400 km farther north, salinity as low as 33.3 pss with
29 mixing depths on the order of only 20-m was still encountered. The total area of the
30 freshwater plume reached 100000 km² with a flow of freshwater on the order of 0.15 10⁶ m³ s⁻¹
31 during 10 days. This phenomenon seems to be triggered by changes in the wind direction on
32 the shelf closer to the equator, and has also been observed in 7 out of 10 years since 2010.

33

34

35

36 **1. Introduction**

37 The main topics of this paper are the freshwater transport from the Guiana shelves offshore to
38 the Northwest tropical Atlantic in boreal winter and the processes that control this transport.
39 Fresher surface layers are often relatively thin and induce a strong stratification in the upper
40 ocean layers limiting the turbulent heat and momentum fluxes across the base of the mixed
41 layer. This condition has the potential to enhance near-surface cooling by sensible and latent
42 surface heat fluxes and the trapping of momentum enabling the development of barrier layers
43 and temperature inversions at the base of the halocline (Mignot et al, 2012). Freshwater
44 originating from the shelves can also carry nutrients and organic matter that sustain food
45 webs.

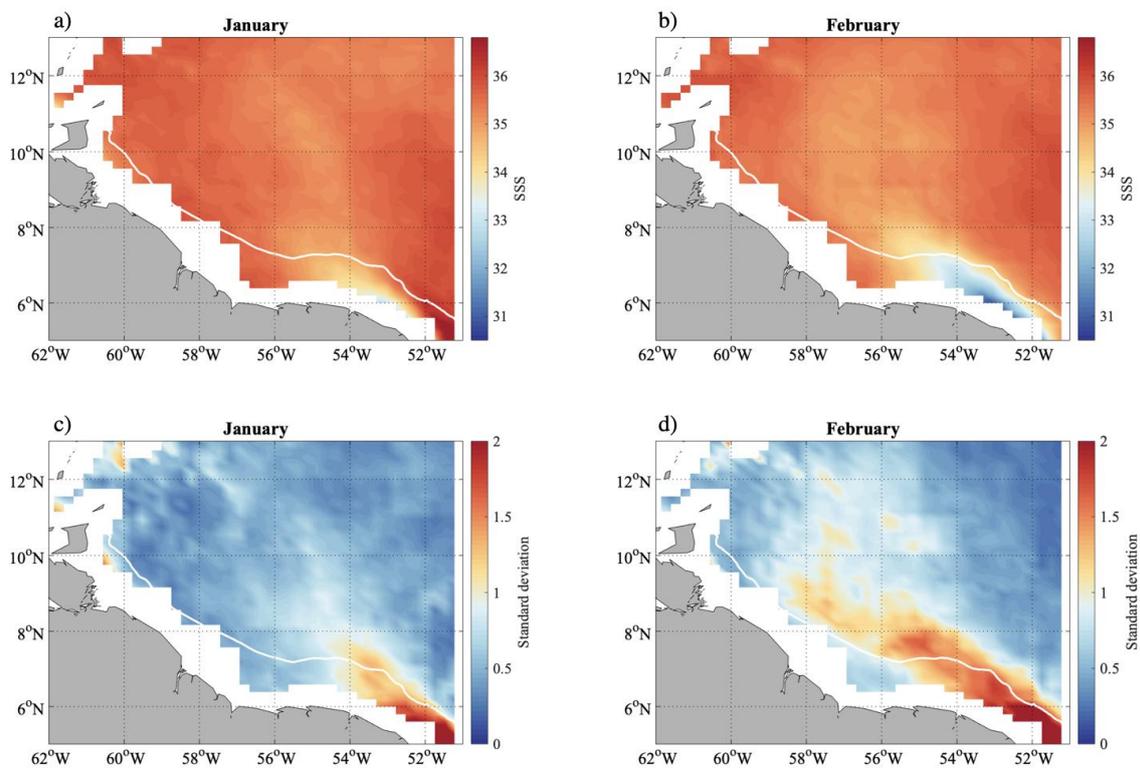
46

47 The freshwater input by the Amazon and other northeastern South American rivers is minimal
48 in December and progressively increases from January to May. During this period, the North
49 Brazil Current (NBC) retroflexion is either non-existent or weak. As a consequence, January
50 through March is the season of maximum salinity in the northwestern tropical Atlantic west of
51 45°W, with no offshore transport of freshwater at the NBC retroflexion, and with salty water
52 flowing over the Guiana shelves and continental slope. In January-March, according to
53 Fournier et al. (2017), the freshwater plume extension (defined by salinity less than 35.5 pss)
54 is minimal north of South America. However, even in this season, occasional freshwater
55 transport from the shelves, either induced by eddies or the winds (via the Ekman transport),
56 might lead to the development of surface freshened layers (Mignot et al, 2012).

57

58 Satellite surface imagery (L-band radiometry) illustrates that this off-shore freshwater
59 transport does not happen frequently in January (Fig 1a, 1b), but it is often present in

60 February (Fig. 1c, d) and later in the year. In February, the weekly sea surface salinity (SSS)
61 product (<http://dx.doi.org/10.5285/4ce685bff631459fb2a30faa699f3fc5>) used here for 2010-
62 2019 shows a band of maximum variability near the shelf break between 54°W and 58°W and
63 peaking near 55°W. Though the maximum is within 100 km of the shelf break, the increase in
64 variability compared to January extends all the way to 12°N in the longitude range 54.5°W-
65 58°W, and it is associated with intermittent fresh plumes. This seems to lower the average
66 surface salinity in this offshore region.



67

68 Figure 1: Average salinity and its standard deviation based on weekly CCI SSS products in
69 2010-2019. Upper panels: averages for January and February, and lower panels the
70 corresponding standard deviations.

71

72 Pathways of surface freshened layers originating from the shelves and ultimately from the
73 Amazon have been followed in the past using satellite ocean colour imagery (Müller-Karger
74 et al, 1988; Hu et al, 2004) and more recently the L-band microwave imagery of surface

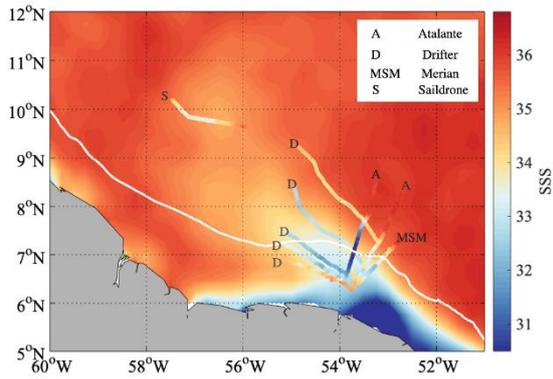
75 salinity (Salisbury et al, 2011; Grodsky et al, 2014; Fournier et al, 2015, 2017). Quantification
76 of advection and transport of surface fresh water in such analyses is hindered in two ways. On
77 one hand, colour imagery is not a direct estimate of salinity (although Salisbury et al, (2011)
78 and Fournier et al. (2015) show how this can be used); on the other hand, the time averaging
79 of the satellite products, in particular from L-Band, is often over one week or more, which is
80 too long to display the detailed processes involved in the freshwater transport.

81

82 Pathways of freshwater transport have also been documented using data from surface drifters
83 (Muller-Karger et al, 1988) and profiling floats (Hu et al, 2004), which illustrate large
84 seasonal variability of the pathways. It is usually expected that in the early part of the year,
85 the freshwater pathway along the Guiana shelves and into the Caribbean Sea is favoured.

86

87 These different studies have highlighted the importance of eddies in shaping where the
88 transport of fresh shelf water to the deep ocean happens, in particular the anticyclonic eddies
89 shed from the North Brazil Current retroflection near 8°N early in the year. These studies
90 have also pointed out the sensitivity of the fresh water transport to wind magnitude and
91 direction. Winds parallel to the coast and the shelf-break were found to be more favourable
92 for offshore transport than wind perpendicular to the shore. Thus, during the early months of
93 the year, when the atmospheric Inter-tropical Convergence Zone (ITCZ) shifts southward, the
94 dominant northeasterly winds are not favourable for this off-shelf transport east of 53°W.



95

96 Figure 2: Average for February 2-19 2020 of the daily salinity fields based on SMOS and
 97 SMAP satellite data, overlaid with the data used in the fresh plume (A for R/V Atalante on
 98 February 2 and 5, MSM for R/V Maria.S.Merian on February 2; D for drifters on February 2
 99 to 7 and S for saildrone on February 16-18). The different tracks/trajectories are colour-coded
 100 with salinity.

101

102 In early February 2020, during the Elucidating the Role of Clouds-Circulation Coupling in
 103 Climate Ocean-Atmosphere (EUREC⁴A-OA) experiment (Stevens et al., 2021), the RV
 104 Atalante and the RV Maria S. Merian (MSM) surveyed an area close to the Guiana shelf just
 105 as a plume of freshwater was ejected from the shelf to the deep ocean (Fig. 2). Five
 106 instrumented drifters were deployed in this fresh water plume, which was also followed daily
 107 using satellite imagery (ocean colour and salinity from L-band radiometry), as well as model
 108 simulations (Mercator PSY2V4) and altimetry. An Uncrewed Surface Vehicle (USV)
 109 saildrone (Zhang et al, 2019) deployed for the EUREC⁴A-ATOMIC (Atlantic Tradewind
 110 Ocean Mesoscale Interaction Campaign) cruises and equipped to measure sea surface
 111 temperature (SST), SSS, and current profiles is also used.

112

113 The period investigated in this paper spans from the 2nd to the 21st of February 2020, after
 114 which the fresh plume was less clear and there were less in situ or remote sensing data
 115 available.

116

117 **2. Data**

118 2.1 In situ data

119 Surface Velocity Program (SVP) drifters were instrumented by the company ‘*Pacific Gyre*’ to
120 measure temperature and salinity every 30 minutes at 20-cm, 5-m and 10-m depths. They also
121 measured surface barometric pressure as well as wind speed and direction 0.5 m above the
122 surface, with regular GPS positioning. Positions were edited for some erroneous data and are
123 less certain for one drifter closer to the coast. Temperature and salinity data retrievals were
124 good at 20-cm depth, with some early loss of data occurring at 5-m and 10-m depth. This was
125 not an issue during the first 10 days of deployment except for one drifter not used here just to
126 the north of the plume. For this investigation, the comparison of the three depth records does
127 not suggest significant salinity biases.

128

129 A fleet of four USV saildrones operated in the eddy-rich area north of the Guianas (9-12°N)
130 and crossed the freshwater plume during 17th-18th February. We use the position, temperature,
131 salinity and wind reported every minute, as well as the ocean velocity profiles (300 kHz RDI
132 Acoustic Doppler current profiler (ADCP)) averaged every 5 minutes from one NOAA
133 saildrone. The velocity profiles from 6 m down to a maximum depth of 104 m are provided
134 with a 2-m resolution.

135

136 Both RV *Atalante* and MSM continuously measured temperature and salinity from
137 thermosalinographs pumping water near 5 m below the surface, and they measured wind from
138 dedicated met-stations. During crossings of the fresh plume on the 2nd and 4th-5th of February,
139 either a moving vessel profiler (MVP) or a fast uCTD were deployed from RV *Atalante*,
140 providing high resolution T-S profile sections across the plume in the upper 50 m. The RV

141 Atalante is also equipped with a 150 kHz RDI ADCP, providing currents 29 m below the sea
142 surface. The MSM 75 kHz ADCP provides calibrated currents starting at 18 m below the sea
143 surface (8-m bins).

144

145 In addition, on board MSM, the coherent on receive marine radar (MR) developed at the
146 Helmholtz-Zentrum Geesthacht was operated for monitoring the surface roughness as well as
147 the ocean surface currents in vicinity of the vessel. The MR operates at X-band (9.4 GHz)
148 with a pulse repetition of 2 kHz with vertical polarization. The pulse length of 50 ns results in
149 a range resolution of 7.5 m and the 7.5' antenna array allows an azimuthal resolution of 0.9°.
150 The radar was operated with an antenna rotation frequency of ~0.45 Hz covering a range
151 distance of 3.2 km around the vessel, thus a 6.4 km width along the track of the vessel. The
152 normalized backscatter intensity results from the temporal mean radar backscatter intensity at
153 every point, which is normalized and corrected for range and wind direction dependencies
154 (Dankert and Horstmann, 2007). As the normalized backscatter intensity is strongly
155 dependent on the ocean surface roughness it depicts all structures that affect the surface
156 roughness. In addition, the MR image sequences are utilized to retrieve the near-surface
157 current (approximately the upper 5 m currents) maps by analyzing the wave signal (Senet et
158 al., 2001; Huang et al., 2016; Lund et al., 2018). Therefore, MR image sequence are
159 converted from the spatio-temporal domain to the wavenumber-frequency domain via a 3D
160 FFT. Within the wavenumber-frequency domain, the wave signal is located on the so-called
161 dispersion shell. In the presence of a current, the Doppler effect leads to a translation and
162 dilation of the dispersion shell. The current is determined using a fit that minimizes the wave
163 signal's distance from the dispersion shell.

164

165 Between the two crossings of the plume, the two vessels surveyed a salinity-stratified area on
166 the shelf. During this survey, the free-drifting platform Ocarina (Bourras et al, 2019) was
167 deployed for a little more than 12 hours. This platform was equipped with a 1200 kHz ADCP
168 to measure current profiles at 0.5 m resolution between 0.29 m and 17.29 m from the sea
169 surface. These data are combined with temperature and salinity profiles collected from the RV
170 Atalante MVP to estimate the gradient Richardson number (Ri) in this stratified near-surface
171 layer at different times of the day.

172

173 2.2 Satellite data

174 The satellite data used are daily products of chlorophyll, mapped surface current from near-
175 real time (NRT) DUACS-NRT altimetry products, and daily analyses of surface salinity based
176 on a blend of data from different L-band radiometry satellite missions.

177

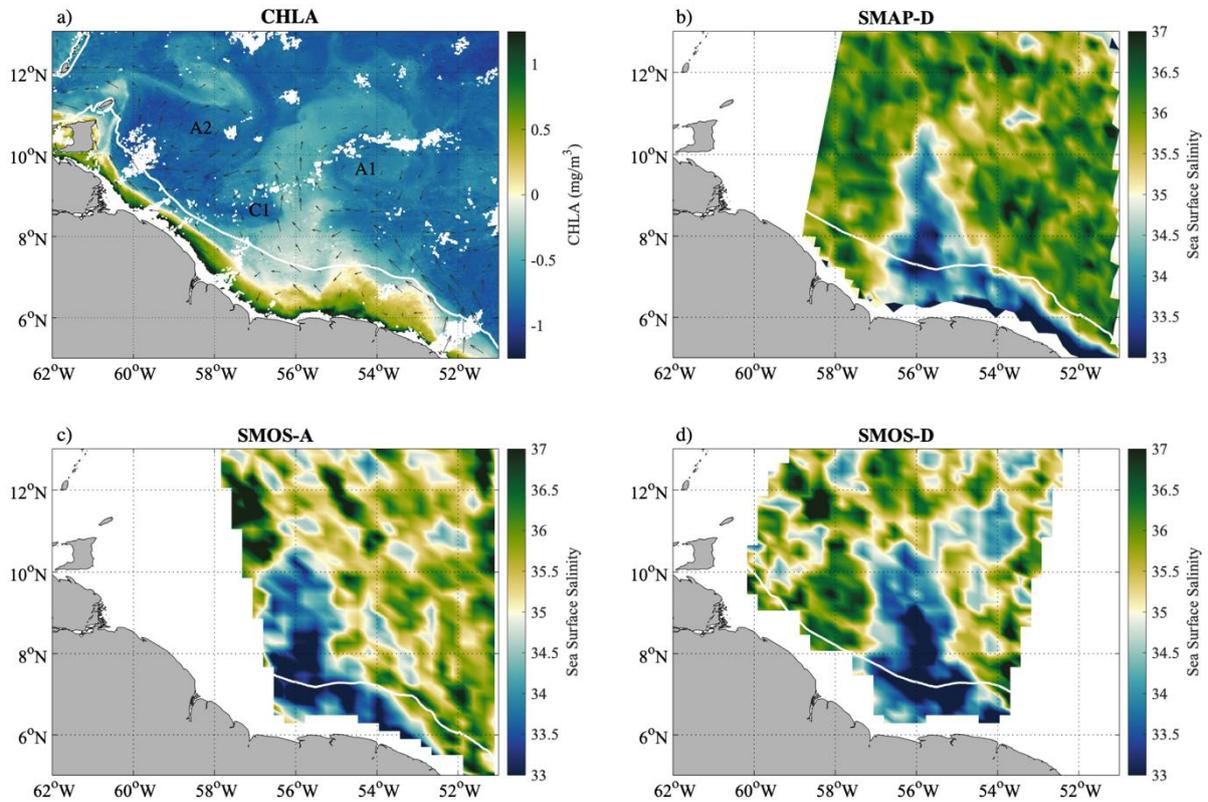
178 Daily chlorophyll-a (Chla) concentration maps on a spatial grid of 0.02° are provided by CLS
179 (<https://datastore.cls.fr/catalogues/chlorophyll-high-resolution-daily>). The maps are
180 composites built from four satellite sensors, VIIRS (on Suomi-NPP and NOAA-20 US
181 platforms) and OLCI (on Sentinel 3A and 3B Copernicus European platforms). The VIIRS
182 L1A products are downloaded from the NASA Ocean Color Web, whereas the OLCI L1
183 products are downloaded from the EUMETSAT Copernicus On-line Data Access in NRT. As
184 described in Stum et al. (2015), the Polymer software (Steinmetz et al, 2011) is used since
185 2014 to compute Chla from the top of atmosphere reflectances. During our period of interest,
186 they are usually without many gaps, except on the 13th to 17th of February. We use them
187 qualitatively, so contamination by coloured dissolved matter or particles is not an issue for the
188 objectives of this study. Geostrophic current maps are produced by Ssalto/Duacs and
189 distributed by Copernicus-Marine Environment Services (CMEMS). The currents are

190 computed from absolute dynamical topography (ADT) mapped using an optimal interpolation
191 method (Taburet et al, 2019). The maps (product
192 SEALEVEL_GLO_PHY_L4_NRT_OBSERVATIONS_008_046) are produced daily on a 0.25°x 0.25°
193 grid, based on combined altimetric data of all the satellite missions within the time window
194 from at least 15 days before to 6 days after the date of interest. Mean currents are added to the
195 anomaly as described in Rio et al. (2011). The spatial scales resolved in the currents are
196 usually on the order of 100 km or more, with significant damping at smaller scales (see also
197 Dibarboure et al, 2011, for an earlier product).

198

199 The salinity products used are level 2 (L2) fields of the Soil Moisture Ocean Salinity (SMOS,
200 Jan. 2010-present), and Soil Moisture Active Passive (SMAP, Apr. 2015-present) missions.
201 The European-led SMOS and the NASA-led SMAP missions observe the surface by L-band
202 radiometry from sun-synchronous polar-orbiting satellites (Font et al, 2009; Kerr et al, 2010;
203 Entekhabi et al, 2010; Piepmeier et al, 2017). Both SMOS and SMAP orbits cover the entire
204 globe within 3 days with data provided close to 6 am and 6 pm local time. The retrieved SSS
205 has a spatial resolution of ~45 km for SMOS and between ~40 and ~50 km for SMAP. Here,
206 we use the SMOS L2Q fields (doi: 10.12770/12dba510-cd71-4d4f-9fc1-9cc027d128b0),
207 corrected for systematic errors depending on the geometry of acquisition of the satellite
208 (Boutin et al. 2018), delivered by Centre Aval de Traitement des Données (CATDS) and the
209 SMAP L2 fields delivered by Remote Sensing System (RSS v4 40 km). The SMAP product is
210 a little smoother than SMOS, and it generally has smaller errors also suggesting slightly larger
211 scales resolved. Two SMOS images with evidence of Radio-frequency interference
212 contamination have been removed during the period investigated, and the contamination
213 became worse later in February. We also use SMOS and SMAP combined weekly SSS
214 generated by the Climate Change Initiative Sea Surface Salinity (CCI+SSS) project

215 (doi:10.5285/4ce685bff631459fb2a30faa699f3fc5). It provides weekly SSS data from 2010 to
 216 2019 at a spatial resolution of 50 km, a sampling of 25km and one day, by combining data
 217 from the SMOS, Aquarius and SMAP missions.



218
 219 Figure 3: Satellite maps on February 12th. Chla and geostrophic currents (grey arrows, a),
 220 SMAP SSS along its descending track (b), SMOS SSS along its ascending (c) and descending
 221 track (d) for the 12th of February. The shelf break is represented by the 100-m bathymetry
 222 contour (white line). Two anticyclonic (A1, A2) and one cyclonic (C1) eddy are labelled in
 223 (a).

224
 225 We illustrate the different products on the 12th of February, when the fresh plume was fully
 226 developed along 56°W (Fig. 3). Both SMAP and SMOS SSS show a mostly south-to-north
 227 structure along 56°W extending from the shelf over to the deep ocean (shelf break in white),
 228 although with a slightly different pattern (note that they are taken 12 hours apart). The Chla
 229 map also shows filaments and regions of higher load, which could be either chlorophyll,
 230 remnants of Colour Dissolved Organic Matter (CDOM) or remnants of sediment and detrital

231 matter not fully filtered out of the products. These structures align to some extent with the
232 currents that connect the outer area of the shelf to the deep ocean. They are located on the
233 western side of a large anticyclonic eddy shed by the North Brazil Current retroflexion (A1).
234 A smaller cyclonic structure (C1) is also visible close to the shelf break, southwest of the
235 northward currents. The *Chla* map presents finer scales, as expected from the better resolution
236 of the satellite imagery in the visible part of the spectrum compared to L-band radiometry.

237

238 SMAP and SMOS L2 maps present systematic differences with respect to in situ data that
239 also depend on whether they correspond to descending or ascending tracks. The issue is
240 particularly large for the SMOS product where the systematic differences are also found to
241 vary across the tracks, in particular on the eastern edge of the descending tracks due to a sun-
242 tail contamination not filtered out in the L2Q fields. Part of this contamination is however
243 detectable on the estimated error provided in the SMOS L2Q products and we eliminated
244 SMOS data for which the estimated error was larger than 1 pss. We attempted to correct the
245 remaining systematic differences on a track by track basis, although this is often uncertain at
246 the 0.1 to 0.2 pss level, in particular for SMOS. We did not correct island effects on the
247 SMAP maps that are particularly noticeable to the east/north-east of islands (Grotsky et al,
248 2018) because they are mostly outside of the main area of our study.

249

250 In order to provide full salinity fields and reduce errors by averaging enough data, we
251 combined SMOS and SMAP L2 gridded fields. As the fresh plume evolves on a roughly daily
252 time scale, as observed for example from *Chla* maps, it is best to keep a rather short time
253 averaging. For half the days, combining the tracks at 6 am and 6 pm (local time) was
254 sufficient to provide a full coverage of the fresh water plume. For other days, it was necessary
255 to add data from 6 pm of the previous day (thus a total time span exceeding 24 hours). This

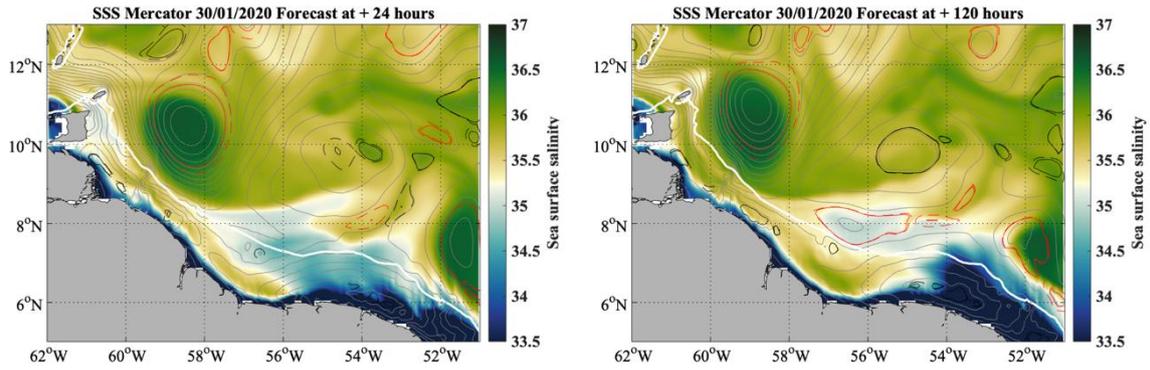
256 leaves only two days with no salinity product, out of the 20 days investigated.

257

258 At each grid point, the field value is estimated by a simple weighting of data inversely
259 proportional to the L2Q estimated error, and with a spatial weight decaying as a Gaussian
260 with a radius of 30 km as a function of the distance of the data to the grid point. No data
261 farther than 50 km is incorporated. We also assumed that errors on data closer than 25 km are
262 fully correlated to account for the real footprint of the satellite data which is on the order of 50
263 km. The resolution of the final daily field is probably close to 70 km. Estimated uncertainties
264 on the daily fields are typically on the order of 0.5 pss, consistent with the comparison to in
265 situ data. These comparisons also suggest that the lowest salinities in the fresh plume often
266 have been overestimated in these fields, with compensating underestimates on the sides of the
267 plume. These are possible effects of the data smoothing, although we could not fully verify it
268 as data coverage was not evenly distributed. These fields nevertheless give precious
269 information on the fresh salinity distribution as illustrated on Fig. 2 for the average over 18
270 days.

271

272 The IFREMER CERSAT Global Blended Mean Wind Fields product, distributed by
273 CMEMS, is used in this paper. It provides 6-hourly surface winds in the region of interest on
274 a spatial grid of 0.25° in latitude and longitude. From 2010 to 2018 the reprocessed product is
275 used (WIND_GLO_WIND_L4_REP_OBSERVATIONS_012_006), while for 2019 and 2020
276 we used the near real time one
277 (WIND_GLO_WIND_L4_NRT_OBSERVATIONS_012_004).



278

279 Fig. 4: Mercator SSS (colour) and sea level (grey contours) forecast and eddy detection made
 280 on the 30 Jan 2020 for 31 Jan 2020 (left) and 04 Feb 2020 (right). The eddy detection is
 281 shown by dashed contours (red for anticyclones and black for cyclones; Laxenaire et al,
 282 2018). The shelf break is represented by the 100-m bathymetry contour (white line).

283

284 Finally, we used ocean velocity and salinity outputs from the Mercator model PSY2V4, both
 285 in analysis and forecast modes. These were made accessible, together with all satellite data to
 286 guide the ships during the field campaign in order to survey the fresh water plumes (Fig. 4).
 287 Since January 30th it consistently suggested a westward (and possibly offshore) extension of
 288 the eastern Guiana shelf fresh pool, although it sometimes missed the full extent of the
 289 plume's offshore extension.

290

291 3. Results

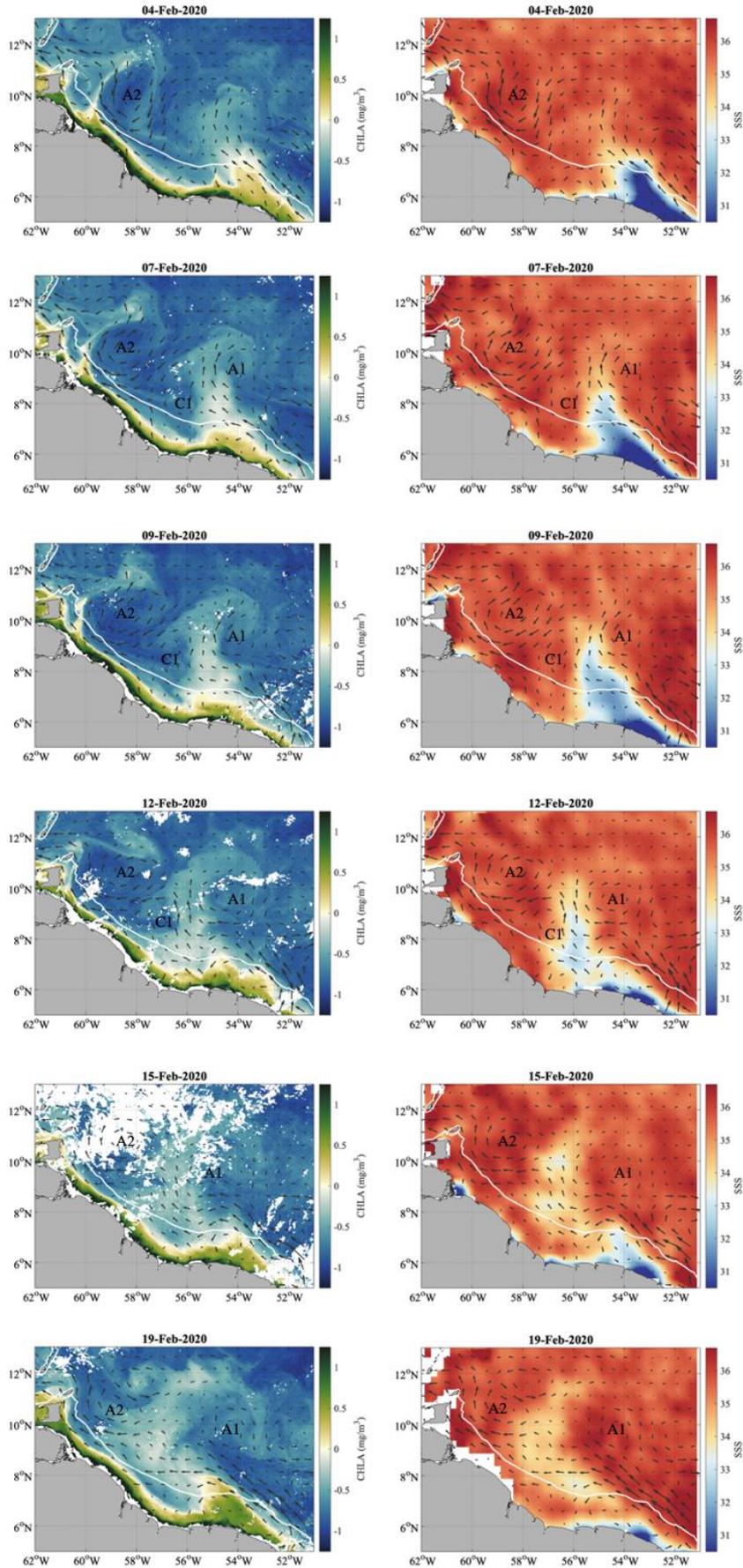
292 3.1 Life of the plume

293 In late January, the region located between 7°N north of the continental shelves of the
 294 Guianas and up to 12°N is mostly covered by surface water with a salinity between 35 and
 295 36.5 pss, which is typical in this season of low precipitations and low input of freshwater from
 296 the Amazon and Orinoco rivers (Fig. 1). Freshwater is witnessed edging north-westward on
 297 the shelf east of French Guiana in late January, both in satellite products and in the Mercator
 298 simulations. Near 53°W, the shelf break bathymetry changes. Overall, the shallow isobaths
 299 tend to be zonally oriented west of 53°W, with a large cone (Demerara Rise) associated with

300 past sediment transport extending farther offshore and presenting less steep off-shelf
301 topography. Changes in geostrophic currents, often associated with the retroflexion of the
302 NBC and formation of anticyclonic eddies to the northeast of the cone, would favour near-
303 surface northward transport. In addition, the wind direction being less orthogonal to
304 bathymetry would also favour off-shelf Ekman transport. Off-shelf transport events are thus
305 expected near that longitude.

306

307 Indeed, this is what was forecasted from the Mercator PSY2V4 operational model on January
308 30th with a clear off-shelf extension of the fresh pool indicated on February 4th, even though it
309 did not extend as a full-fledged plume (Fig. 4). Three SVP drifters were released into this
310 fresh plume on February 2nd, and two additional drifters were deployed during a return section
311 of RV Atalante on the 4th-5th of February a little further north, as the plume extended in that
312 direction (with salinity dropping across this section to close to 30 pss) (Fig. 2).



314 Fig. 5: Snapshots of daily salinity and Chl*a* maps with overlaid geostrophic currents (grey
315 arrows) for the 4th, 7th, 9th, 12th, 15th and 19th of February 2020. The shelf break is represented
316 by the 100-m bathymetry contour (white line).

317

318 To illustrate the plume evolution, we present (Fig. 5) daily snapshots of Chl*a* and surface
319 salinity. The freshwater off-shore event started on February 4th, when the plume began to
320 detach from the shelf, overflowing the shelf break near 53-54°W. An anticyclonic NBC ring
321 (A1) northeast of the plume had already entrained relatively fresh water (SSS on the order of
322 35 pss) since late January all the way up to 10°N. This feature is also seen on the Chl*a*
323 distribution across the shelf break. The northward offshore transport of fresh and productive
324 water continued on the 7th of February, following fairly well the surface geostrophic currents.
325 The anticyclonic eddy (A1) centred around 54.5°W-9.5°N likely participated in advecting
326 water from the plume northward (on its western side) and limited its westward propagation. A
327 small cyclonic eddy (56.5°W-8°N, C1) channelled the northward geostrophic flow and also
328 contributed in steering the plume northward. The situation was quite similar on the 9th and on
329 the 12th with the northernmost part of the plume, rich in chlorophyll, steered by the northern
330 part of the anticyclonic eddy A1. In the meantime, the plume started to be influenced to its
331 west by the eastern side of a second anticyclonic eddy (A2, centred around 58.5°W-11°N).
332 Around the 12th, we observe the first indication (in particular in SSS) suggesting a future
333 separation of the plume from the shelf. This separation started on the 14th of February and was
334 clearly visible on the 15th. The dynamic situation changed quickly as the cyclonic eddy C1
335 disappeared, with a strong north-westward current near the shelf almost topographically
336 steered, and the two anticyclones north of 9°N. The fresh pool formed by the plume spread
337 horizontally (and probably vertically), with surface salinity on the order of 33.5-34 pss.

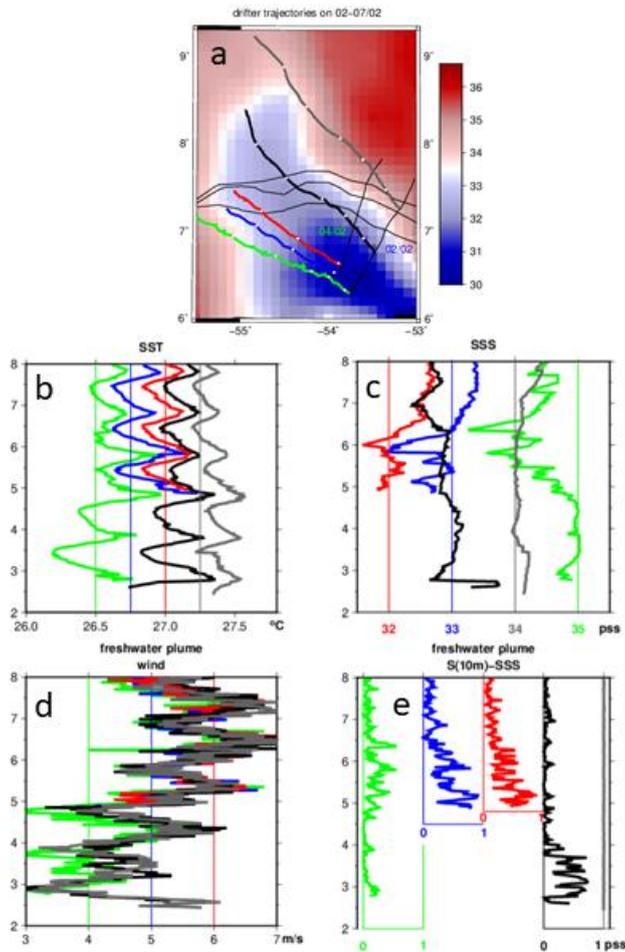
338

339 Intrusion of salty water from farther west near 9°N might have contributed to the erosion of

340 the salinity minimum. This is particularly pronounced on the February 15th map. At that date,
341 two drifters close together experienced very large salinity differences (up to 0.5 pss at 3-km
342 distance near 9°N/56.6°W), illustrating how sharp the gradients were near this wedge of salty
343 and low *Chla* water. Horizontal mixing with the plume water can be expected from this date,
344 except if the saltier/*Chla*-free water is entrained under the fresher water. This penetrating
345 saltier water seems to partially separate fresher water to the north from the freshwater closer
346 to the shelves.

347

348 On the 17th and 18th of February, the saildrone crossing the fresh pool still encountered SSS as
349 low as 33.3 pss near 9.8°N/56.5°W, similar to what is suggested by the salinity maps (Fig. 2
350 and Fig. 5). Then, by February 19th, the low salinity pool became less pronounced (minimum
351 values increase to 34 pss), but extended further westward. At places from 7°N to almost 12°N
352 its width reached up to 2° of longitude. Afterwards, it was difficult to follow because of the
353 uncertainties in the salinity maps that are on the order of 0.5 pss.



354

355 Figure 6: The drifter time series from February 2nd to 7th. Top panel, the trajectories (with dots
 356 each day at 0 GMT), as well as the SSS map for February 7. Below, four panels as a function
 357 of time (vertical axis in February days) for temperature (b, top left), salinity (c, top right),
 358 measured winds (d, bottom left in m/s), and salinity stratification $S(10m)-S(0.2m)$ (e, lower
 359 right). The curves are colour-coded for the different drifters based on panel 6a (on 6e, the
 360 colored vertical straight lines correspond to no-stratification for that drifter).

361

362 Another way to investigate the plume evolution is to consider a Lagrangian perspective, based
 363 on the time series of the five drifters deployed in the plume (SSS lower than 35 pss) on
 364 February 2nd and 4th either on the shelf or near the shelf break. For the first four-five days
 365 after deployment they drifted north to north-westward and remained coherently separated
 366 cross-stream (Fig. 6a). The drifters are drogued at 15-m depth, which might be within the
 367 stratified layer under the freshest surface water, in particular at deployment (see section 3.2).

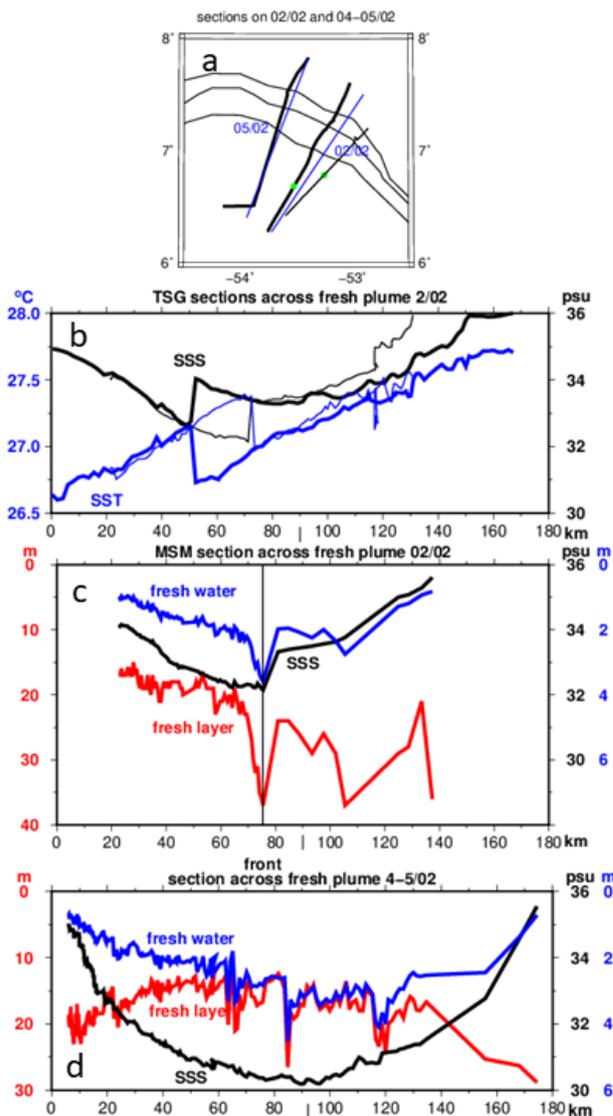
368 The drifters were deployed in a horizontal gradient of SST (1°C change across the plume),
369 with coldest water closest to the continent. Interestingly, this gradient as observed by the
370 drifters remained fairly consistent over time, although its amplitude gradually diminished
371 (Fig. 6b). Moreover, large temperature daily cycles are observed, with initial amplitude
372 exceeding 0.5°C . The wind (Fig. 6d) also illustrates a daily cycle with strongest wind in the
373 early morning and weakest wind in the late afternoon. It was relatively weaker at the
374 beginning of the deployment near the shelf break, in line with the corresponding larger
375 temperature daily cycle. For all drifters the wind increased over time during this initial five-
376 day period and as the drifters moved away from the shelf.

377

378 Salinity (Fig. 6c) variability between the different trajectories is not as regular as temperature
379 variability. The trajectories present some rather fast changes of SSS (by up to 1 pss), which
380 indicate the presence of small-scale gradients/blobs advected relative to the drifters. The red
381 salinity curve, corresponding to one of the middle deployments, remained the lowest.
382 Nevertheless, 7 days after its deployment, it has values very close to the black curve
383 (corresponding to a drifter located to its northeast, in slightly warmer water). It is the drifter
384 farthest east (grey line, always off shelf) which presents the least variability. All together
385 during this period and for all drifters, salinity is very similar at 0.20-m and 5-m depths
386 whereas there are gradients of up to 1 pss between the surface and 10 m for most drifters (Fig.
387 6e). This is not found for the drifter that is farthest from the shelf (grey curve). It indicates a
388 deeper fresh layer in this region, even though at times this drifter presents lower salinity than
389 the drifter closest to shore (green curve). The periods of large salinity stratification between
390 the surface and 10 m depth are not found at the same times for the different drifters (Fig. 6e).
391 They tend to be less common on February 6th and 7th, after a few days of drift away from the
392 shelf and with the stronger winds.

393

394 3.2 Sections across the plume (extension, gradients, thickness)



395

396 Figure 7: Sections across the shelf break near 53-54°W. (a) (top panel) Map with the different
397 sections (thick black line for RV Atalante on February 2nd, and 4th-5th and thin black line for
398 MSM on February 2nd). The blue lines indicate the axis along which the data are projected for
399 the plots (the 100-m, 300-m and 500-m isobaths are plotted), and the green dots the positions
400 of a T/S front. (b) SST (blue) and SSS (black) sections on 2nd of February from RV Atalante
401 (thick) and MSM (thin) transects. The horizontal axis is distance from the end point on the
402 shelf (53.72°W/6.27°N) and the data of the two ships are projected on the same line median to
403 the two ship tracks. (c) and (d) lower panels: the MVP section on 2/02 (MSM) and 4-5/02
404 (Atalante) plotted for SSS (black), fresh layer thickness (red) and freshwater thickness (blue),
405 with respect to distance from its origin on the shelf (starting at 75 km/134 km on the

406 first/second section, the MVP was replaced by a uCTD). The vertical bar on bottom axis on
407 both panels indicates the location of the 100-m isobath. For (c), the position of the sharp front
408 in SSS/SST is noted by a vertical line.

409

410 On the 2nd of February both RV Atalante and MSM crossed the nascent plume (Fig. 7a). The
411 overall currents were directed to the northwest, so in general the MSM section is upstream
412 from the Atalante sections. Both vessels were coming from the deep ocean over the outer
413 shelf, with salinity decreasing and reaching a plateau, until a sharp front was encountered by
414 the two ships. This front is located on the shelf near 53.51°W-6.68°N (Atalante) and
415 53.25°W-6.78°N (MSM), with much fresher (by more than 1.2 pss) and warmer water on the
416 inner-shelf side of the front (Fig. 7b; in the plots, the inner-shelf is to the left with values on
417 the x-axis increasing offshore). Interestingly, the front was farther away from the coast and
418 with warmer and fresher water on its southwest side for the MSM section compared to the
419 Atalante section (Fig. 7b). The surface front width is crossed in less than 100 m based on the
420 RV Atalante intake temperature sensor measurements, and is possibly as narrow as 50 m. The
421 respective positions of the front crossings by the two vessels suggest that the front was
422 oriented northeast to southwest. The lower SSS seen by MSM suggests that the front might
423 have been propagating from east to west, as fresher water was found farther upstream along
424 the shelf break and shelf (i.e., farther southeast) according to the salinity satellite maps and
425 Mercator model forecasts. Indeed, it is probably the same sharp front that was crossed by one
426 drifter (black line in Fig. 6c with more than 1 pss drop and 0.4°C warming in an hour) less
427 than 4 hours after its deployment from RV Atalante. As it is located a little to the north of the
428 position of the front crossed by RV Atalante, it suggests that the drifter was also encountering
429 freshwater coming from its east or southeast.

430

431 The MVP-uCTD section collected by MSM on February 2nd (note that the MVP started just

432 after crossing the surface front) will be summarized by presenting the thickness of the
433 freshwater plume and total fresh water content (cf. salinity section in Supp. Inf. S4). The
434 thickness of the freshwater plume (red curve in Fig. 7c) is defined here by the depth of the
435 isohaline $0.5*(36.4 + SSS)$ corresponding to the depth where the fractions of surface and
436 subsurface waters are equally mixed assuming homogeneous salinity profiles above and just
437 below this depth and where 36.4 pss is a typical subsurface salinity near 50 m in this survey.
438 The total fresh water content is estimated by vertically integrating the salinity profiles
439 assuming mixing of fresh water with salty water at 36.4 pss. The thickness of the fresh layer
440 and the total fresh water content (referred to 36.4 pss) present strong variability across the
441 section (Fig. 7c). In particular, there is a large bulge in the freshwater layer thickness just
442 inshore (left on Fig. 7c) from the front. Indeed, in this bulge, the very fresh surface water
443 presents stratified salinity down from the near-surface to 40-m depth, with water properties at
444 22 m corresponding to those in the surface water that was crossed northeast of the front (cf.
445 Supp. Inf. S4). This suggests that the freshest surface water had recently overlaid the
446 saltier/warmer water, which had downwelled under the front. Farther to the northeast along
447 that section, there is only a slight decrease of the fresh water content (blue curve on Fig. 7d)
448 despite higher surface salinity (black curve on Fig. 7c, d), due to deeper surface mixed layer,
449 especially east of the shelf break (but the number of profiles collected is insufficient to fully
450 apprehend this structure).

451

452 On the 4th and 5th of February, RV Atalante crossed the fresh plume on its way from the shelf
453 to the western side of the anticyclonic eddy A1 of Fig.3, a little bit to the west of the earlier
454 crossings (Fig. 7a). Salinity dropped to nearly 30 pss close to the outer edge of the shelf (Fig.
455 7d) and presents very regular and symmetric along-track variability relative to the shelf edge,
456 with no trace of the earlier fronts witnessed on February 2nd. This suggests that at that time the

457 plume was rather broad and at least 120 km across, assuming that the section was at a right
458 angle to it. This assumption about the angle (maybe closer to 70°) is supported by the salinity
459 maps, the drifter trajectories and the ship's vessel mounted ADCP (VM-ADCP), which
460 suggest that the upper ocean currents were nearly at right angles to the cruise track.

461

462 The MVP (and uCTD) profiles provide information on the plume structure on February 5
463 (Fig. 7d). They indicate thicker fresh layers on the sides of the plume than in its middle, but
464 shifted towards the shelf (red curve). The isohaline defining this layer thickness was typically
465 found near 12 to 20-m depth, but the section presents also some very fast variability between
466 successive profiles of the fresh layer thickness, for example at 65, 83, and near 120 km, which
467 could be indicative of internal waves or solitons. There is no associated signature of the
468 localised deep layers in surface salinity or temperature. The fresh water thickness is on the
469 order of 2 to 4 m in the central part and outer part of the plume, whereas it decreases a little
470 more towards the shelf edge of the plume.

471

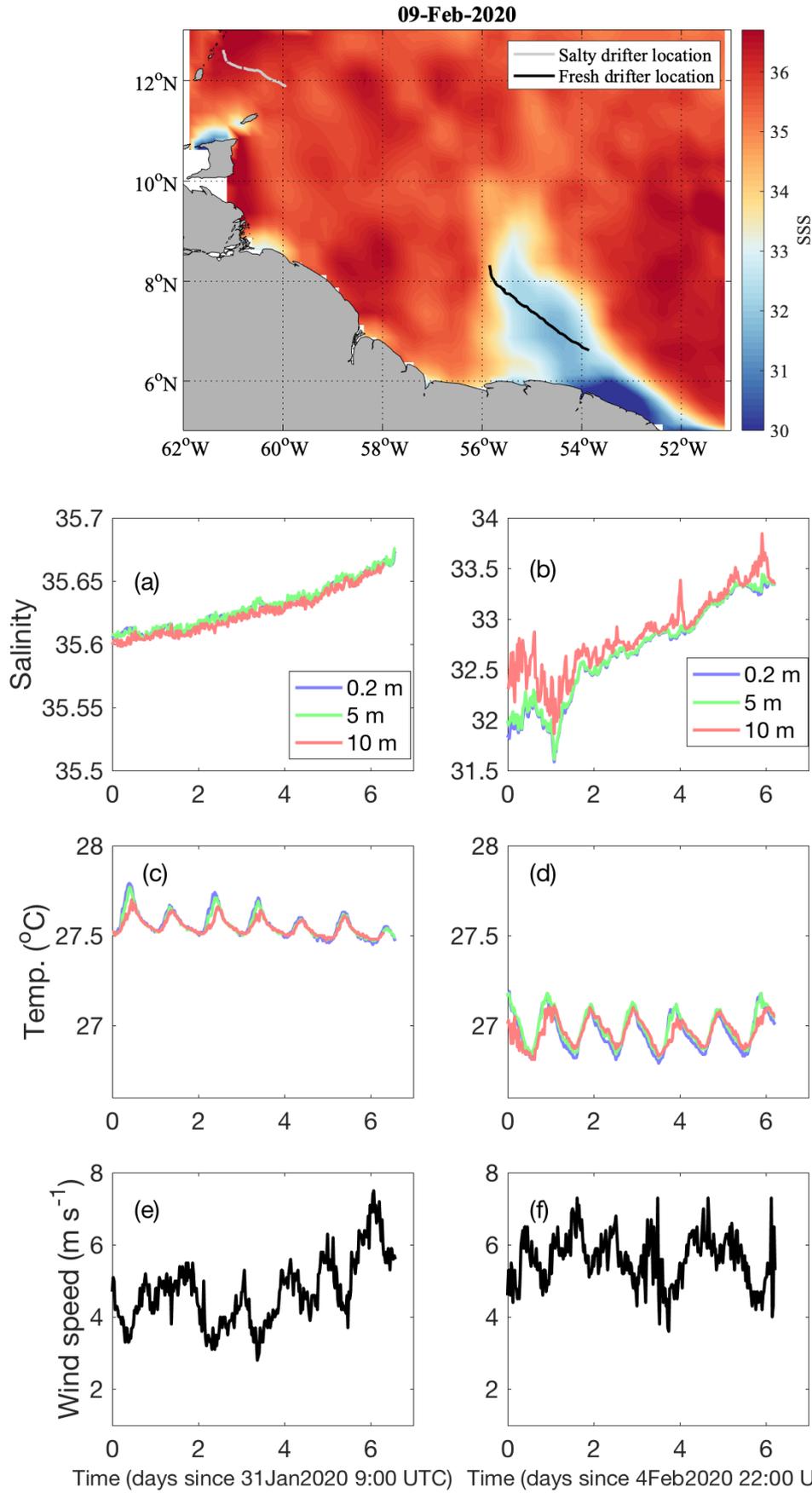
472 3.3 Stratification and shear in the surface layer

473 The MVP sections performed close to the time when the plume separated from the shelf
474 indicate that the fresh layer was rather shallow. We will present evidence of how this
475 stratification constrains vertical mixing and the extent to which off-shore changes in the
476 salinity plume are related to vertical mixing with the deeper saltier water.

477

478

479



481 Figure 8: Salty (light grey) and fresh (dark) drifter trajectories are overlaid on the salinity map

482 for February 9 (g, top map). Under it, comparative time series for (left column) a drifter
483 deployed in salty water (on Jan 31 at 09 GMT) and (right column) one in fresh water (on Feb
484 2 at 22 GMT). Top panels for temperature measurements at 0.2, 5 and 10m; middle panel for
485 the salinity at these three levels, and bottom panel wind measurements.

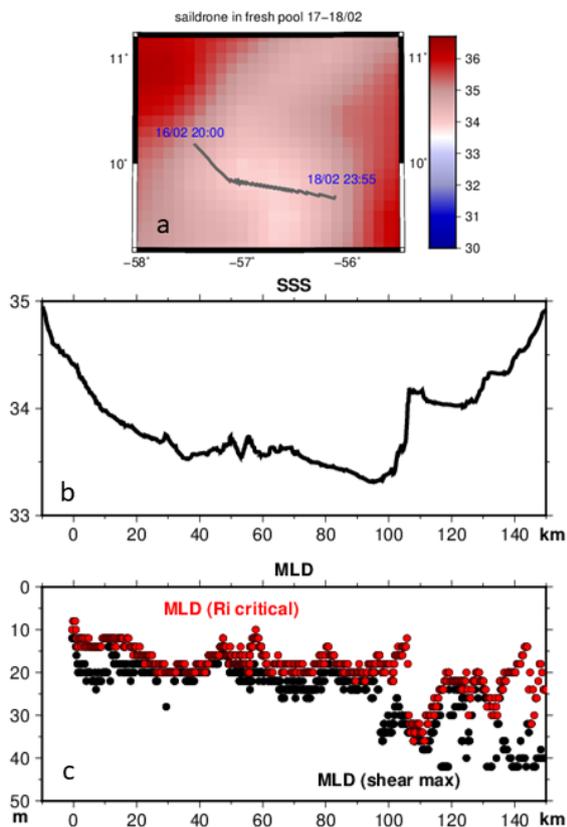
486

487 The drifters show variable salinity stratification between the surface and 10-m depth in the
488 first five days (Fig. 6e). Such stratification is less common afterwards, but some of the drifters
489 also left the core of the fresh plume. Drifters launched in January, stayed out of the fresh
490 water region and can be compared with those launched in the plume in order to identify the
491 characteristics of this surface layer. Such an example is presented in Fig. 8, and although
492 some differences might be related to weather conditions, such as different cloudiness, there
493 are major differences between the drifter data in the plume and outside of the plume that we
494 will comment. First, the temperature diurnal cycle is present in both the salty and fresh
495 regions at the three depth levels but with strikingly different amplitudes (Fig. 8). The larger
496 diurnal cycle is observed for the buoy located in the freshwater plume despite experiencing
497 winds which were often larger than for the out-of-the-plume drifter. At night in the freshwater
498 plume, temperature remains a little warmer at 10-m depth than at the surface. 10-m
499 temperature however usually decreases during night-time, which suggests active night-time
500 vertical mixing near the surface entraining the 10-m subsurface water. Furthermore, surface
501 salinity increases similarly during day and night-time in the salty region, whereas the increase
502 is observed with more diurnal variations in the fresh plume. Except for an event on the second
503 day (Fig. 8), this seems to confirm the night entrainment of subsurface (salty) water into the
504 near surface layer resulting in a late-night relative surface salinity maximum.

505

506 The records of the drifter data in the fresh plume therefore suggest night-time active mixing in
507 the stratified layer near 10-m depth, just below the well-mixed surface layer. We do not have

508 direct information at that time of turbulence activity with the resolution needed. However,
509 there is some indirect evidence provided by the Ocarina platform deployment over the shelf
510 on February 3rd (Supp. Inf. S1). As the local depth was larger than 50 m, interaction of the
511 surface mixed layer with the deep boundary layer should have been small. Nearby MVP
512 profiles collected by RV Atalante are combined with the simultaneous Ocarina current data to
513 estimate a Richardson number (Ri) profile (Supp. Inf. S1). This indicates values between 0.2
514 and 0.8 in the 6 to 16-m layer. As the profiles were not exactly simultaneous in space and
515 time, we cannot estimate individual Ri profiles and derive precise statistics on the Ri
516 distribution, although the average is on the order of 0.4. These averaged values suggest that
517 the whole layer might have witnessed active turbulent conditions, with values close to the
518 critical Ri for shear-induced instability (Galperin et al, 2007). This happened despite the
519 stratification induced by daily heating, found at least between 6 and 14 m (15 m coincides
520 with the lowest temperature in the profiles).



521

522 Figure 9: Saildrone section (16/02 evening to 18/02) across the fresh plume. (a) Track
523 overlaid on the SSS map for February 17; (b) SSS; (c) different estimates of MLD (maximum
524 shear depth in black and from critical Ri number in red). (b) and (c) are plotted along the
525 section from west to east, as a function of distance from an entrance point in the fresh pool.

526

527 The saildrone crossed the fresh pool two weeks later than the ship on the 17th and 18th of
528 February (Fig. 9a). They did not measure stratification directly, but the ADCP data at 2-m
529 resolution can be used to estimate a mixing depth. It is done by assuming $Ri=0.4$ in this layer,
530 where $Ri = -g/\rho * (d\rho/dz)/\text{shear}^2$. Thus, a density profile in the actively mixed layer is obtained
531 by vertically integrating $Ri * \text{shear}^2 * \rho/g$ down from the surface. The bottom depth of this layer
532 is reached when the density has increased relatively to the surface by 0.12 kg/m^3 (Foltz et al.
533 2018). Alternatively, we use the current profiles to identify the depth of maximum shear. This
534 depth is known to be deeper than the mixing depth, either because of internal waves under the
535 base of the mixed layer or the wind momentum input into the surface layer (Foltz et al. 2020).
536 The two estimates of the mixing depth are quite similar, with the one based on maximum
537 shear being deeper by about 9 m on average. They are weakly correlated (0.42) over the
538 crossing of waters with salinity less than 34 pss (Fig. 9b, c). That low correlation results from
539 a small area near 100 km where the maximum shear is found deeper than the MLD based on
540 critical Ri. Both estimates usually illustrate rather shallow mixing layers, often on the order of
541 20 m thick (averaging 17 m for the density criterion). The estimate is deeper in the eastern
542 part after the sharp salinity frontal increase to 34.05 pss, where the two depths are closer to
543 30-40 m, which is more typical of what was found during the EUREC4A-OA surveys, at least
544 at night time.

545

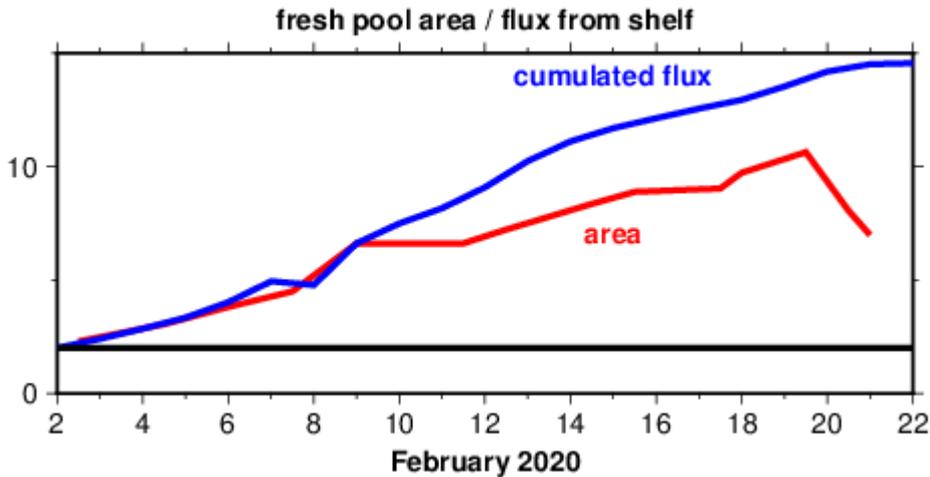
546 So, overall, the mixing layer depths (and presumably the freshwater layer thickness) in the
547 plume are larger, possibly by close to 10 m, than what is observed on the sections two weeks

548 earlier and closer to the shelf. There is also no clear diurnal cycle of the mixed layer depth
549 (MLD) within the plume, based on this indirect estimation (the freshest part of the plume was
550 crossed in more than one day). This fits with the expectation that density stratification under
551 sustained winds is constrained by the salinity stratification in these shallow and fresh surface
552 layers. Interestingly, the width of the plume did not change much between February 2 (Fig. 6)
553 and February 18. On the other hand, it expanded northward significantly based on the satellite
554 maps (Fig. 4), extending to close to 12°N and becoming less linear. Minimum salinities
555 reached in the plume are however larger by February 18.

556

557 3.4 Advective budget for the surface area.

558 To determine the causes of the freshwater plume's expansion, first we estimate the fresh water
559 pool area from mapped satellite SSS daily products. We define it as the area bounded by the
560 35 psu isohaline and offshore of the 100 m isobath. We also estimate an advective area flux
561 based on the currents across the shelf in sectors with salinity less than 35 psu. Currents are
562 estimated by combining AVISO geostrophic currents and Ekman currents estimated with a
563 mixing depth of 20 m and using wind stress estimates from the drifter closest to the shelf
564 break. Note that 20 m is typical of the fresh layer thickness from the sections on the 2nd, 4th
565 and 5th of February (Fig. 7c, d), but that is larger than the near 10-m MLD found on the
566 southern part of those sections. It is also typical of the MLD observed by the saildrone section
567 of February 17 (Fig. 9). The rate of change of the area should equal the area transport,
568 assuming 2-D dynamics, no effect of mixing on this area, and conservation of SSS (no air-sea
569 exchange of water).



570

571 Figure 10: The area of the deep ocean sector with $S < 35$ pss and with depth larger than 100-
 572 m (in red; area expressed in 10^4 km^2); the cumulated flux is the horizontal area with $S < 35$ pss
 573 fed by advection from the shelf, estimated assuming horizontal dynamics, no mixing and
 574 conservation of surface salinity (in blue).

575

576 The two terms are comparable, although there is often a smaller area increase compared to the
 577 flux. The area of the freshwater plume increases rapidly from the 2nd to the 9th of February
 578 (Fig. 10) before increasing more slowly until the 19th and reaching a maximum of close to 100
 579 000 km^2 . Regarding fluxes, the increase is fast until the 14th of February and a bit slower until
 580 the 20th. As commented earlier on the plume history (section 3.1), starting on 13th-14th of
 581 February (Fig. 3), there are some signs of partial separation of the fresh water from the shelf
 582 (and thus, some plume discontinuity). Interestingly the total area transport was driven almost
 583 equally by Ekman and geostrophic advection until the 11th, and more by Ekman advection
 584 afterwards.

585

586 We have estimated the total freshwater transport based on ocean currents and the surface
 587 salinity maps, though this might be less precise compared to the area transport. We use a
 588 constant freshwater layer thickness of 20 m based on the initial sections (Fig. 7), and mixing
 589 with a 36.5 pss deep source. It indicates that the transport of fresh water in this off-shelf

590 plume averaged 0.15 Sv ($10^6 \text{ m}^3 \text{ s}^{-1}$) in the 11 days from February 2nd to 11th, and 0.6 Sv from
591 the 11th to the 20th. During the first period, the transport is comparable to the expected outflow
592 of the Amazon River in late January (based on climatology).

593

594 Until now, we have not commented on the uncertainties of these estimates. In Supp. Inf. S2,
595 we estimate that uncertainties on the cumulative fluxes (blue curve on Fig. 10) are between
596 15% and 50% (depending on whether or not the error is random in the daily flux estimates),
597 whereas the error on the total area is likely to be on the order of 10%.

598

599 Interpreting the difference between the two curves on Fig. 10 is therefore probably within the
600 error bars. Some of the assumptions done for this budget might also break down. Vertical
601 mixing might result in diminishing the area by bringing more salty water and thus the MLD
602 salinity rising in some areas above the threshold (we found evidence of MLD deepening in
603 the saildrone section on February 17th and 18th). There are also clearly some lateral
604 intrusions/mixing with saltier water; how this affects the overall area is not straightforward.
605 These issues will be more easily addressed in high resolution numerical simulations and a full
606 three-dimensional budget, as the salinity fields clearly don't have the required resolution for
607 these mesoscale or sub-meso scale features).

608

609 It is even more uncertain to provide an estimate of the total freshwater transport, as the
610 freshwater thickness is not closely correlated to surface salinity, as illustrated in Fig. 7.

611

612 **4. Discussion**

613 4.1 Frequency of such freshwater plumes

614 How often do these freshwater events occur in the winter season during the January to mid-

615 March period, and what drives them? Using the 10 years of weekly CCI SSS products, in each
616 year we find events of freshwater leaving the shelf and reaching the open ocean. Some events
617 happened farther west, west of 56°W and in some cases the fresh water did not extend north
618 of 10°N . These events (two thirds of the total) were unlikely to have a lasting influence in this
619 sector of the Atlantic, with the freshwater being quickly washed across the Antilles into the
620 Caribbean Sea. Events closer to the one observed in early February 2020 happened in 7 out of
621 10 years during the winter season (Supp. Inf. S3).

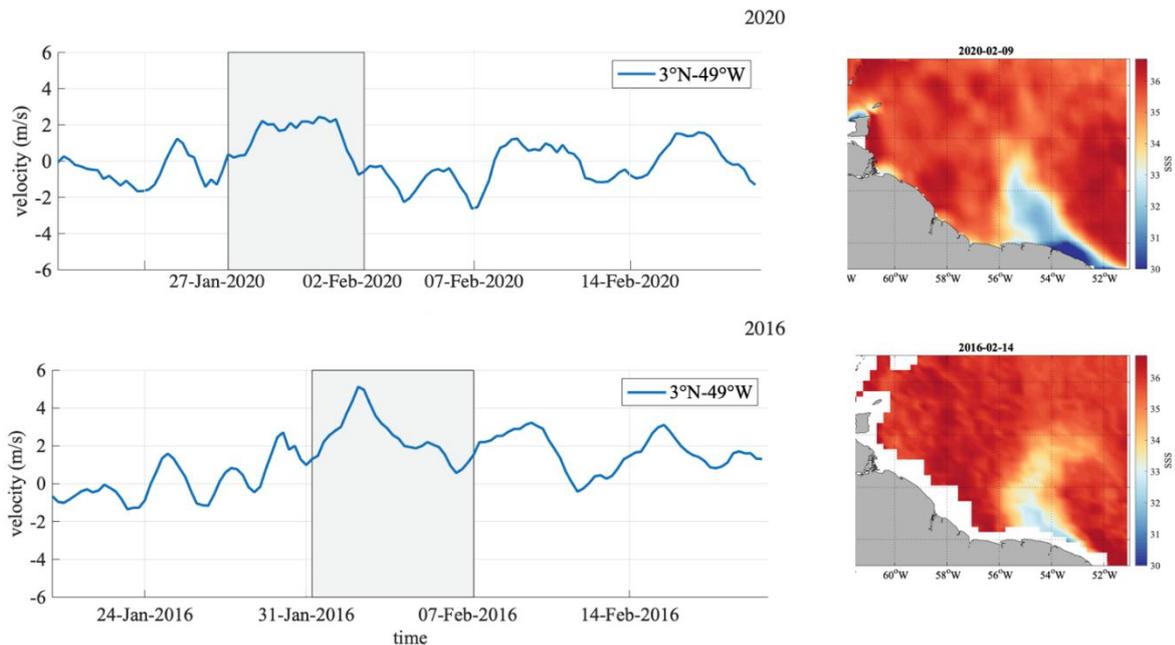
622

623 An important question is what determines the presence or absence of off-shelf transport. For
624 that, a main requirement is a north-westward shelf transport of freshwater from near the
625 equator to $7^{\circ}\text{N}/54^{\circ}\text{W}$. At this place, the shelf-break direction changes and winds become less
626 perpendicular to bathymetry and thus more prone to induce off-shelf transport. Southeast of
627 that, the winds tend to be perpendicular to the shelf break, and even oriented a little farther
628 anti-clockwise during that season. Therefore, close to the equator in this season, they often
629 hinder the north-westward transport of freshwater on the shelf.

630

631 Thus, we considered the wind direction in 2020 and in the earlier years and defined an index
632 based on the wind component parallel to the shelf-break at 3°N , which is a transition latitude
633 with respect to the Coriolis force. It is halfway along the shelf between the Amazon estuary
634 and French Guiana and is almost always bathed in freshwater. The index is the deviation of
635 the wind component parallel to the shelf break from its average during the months of January
636 and February of that year (positive to the northwest). In 2020, between mid-January to late
637 February, we find only one four-day period (January 28-February 1) when the index is
638 positive (Fig. 11). This change in wind direction would be favourable to a north-westward
639 transport of freshwater which, if it propagates at 50 cm/s , would reach the shelf-break near

640 53-54°W in early February. The timing is thus fairly close to what is observed.



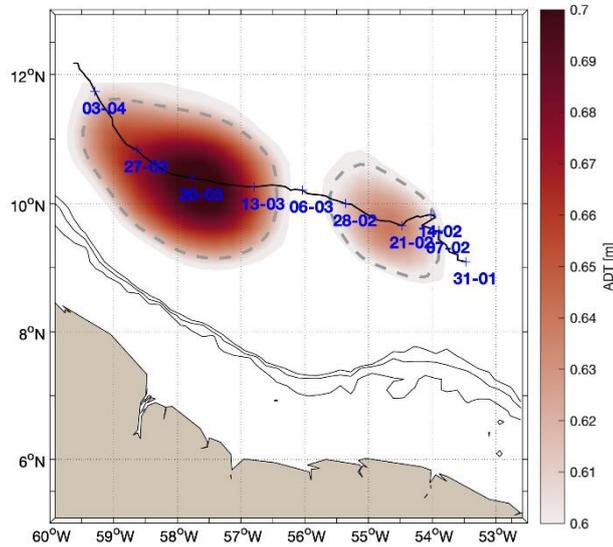
641

642 Figure 11: Winds at 3°N/49°W in relation to development of fresh plume events. Only the
643 component of the wind parallel to 100-m isobath is shown on left side for two years (2020,
644 the event we study here; and 2016, a typical other year), with the corresponding developed
645 fresh plumes presented on the right side (for 2016, from CCI 7-day products). The grey time
646 domain on the wind time series corresponds to the period between the start of the wind event
647 and the start of the fresh plume separation from the shelf near 54-56°W.

648

649 We cannot carry out such a detailed calculation in other years, as we don't know the precise
650 date of appearance of the plume. However, we find in 6 out of the 7 years when a fresh plume
651 developed (the exception being 2018), a preceding period with significant positive wind index
652 lasting for a few days. An example of that is presented in the lower panels of Fig. 11. The
653 average length of these positive index events is 5.3 days (varying between 2 and 8.5 days),
654 and the duration between the initial date of the wind event and the development of the fresh
655 plume is 6.3 days (varying between 4 and 9 days). These estimates are in the range of what
656 we expect for wind-induced currents. The time scales are long enough that geostrophy and
657 Ekman divergence at the coast might be operating, which would reinforce the north-westward

658 geostrophic current. Of course, other dynamics such as those associated with the shelf-break
 659 currents, or the build-up of a pressure head and its evolution at the mouth of the Amazon
 660 estuary might also take place.



661

662 Figure 12: Trajectory of anticyclone A1 derived from ADT maps by the TOEddies algorithm
 663 (Laxenaire et al, 2018). Composite ADT signature of A1 are indicated for the Fe 23 and Mar
 664 21. The shelf break is represented by the 100-m, 300-m and 500-m bathymetry contours
 665 (black lines).

666

667 Another key feature favouring the transport of the plume off the shelf is an anticyclonic eddy
 668 (A1) with a core lying slightly east of 54°W. This is actually a common area crossed by NBC
 669 rings. In 2020, the analysis of eddy A1 shows that it did not move very swiftly north-
 670 westward before February 21 (Fig. 12). In particular, between February 7 and 14, the core
 671 stalled and only marginally moved to the north, while separating from the shelf-break. This
 672 slow motion and the earlier presence of cyclonic feature C1 favours the channelling of the
 673 fresh plume by the geostrophic flow from the shelf-break farther north. At the same time, C1
 674 weakens, and A2, another anticyclonic feature farther west slowly moves westward until mid-
 675 February, leaving a large area for the plume spreading. Then A1 rapidly moves farther west
 676 and intensifies, which would channel a large part of the fresh water closer to the shelf break

677 near Trinidad towards the Antilles (Fig. 12), as is suggested by the drifters and later weekly
678 salinity maps.

679

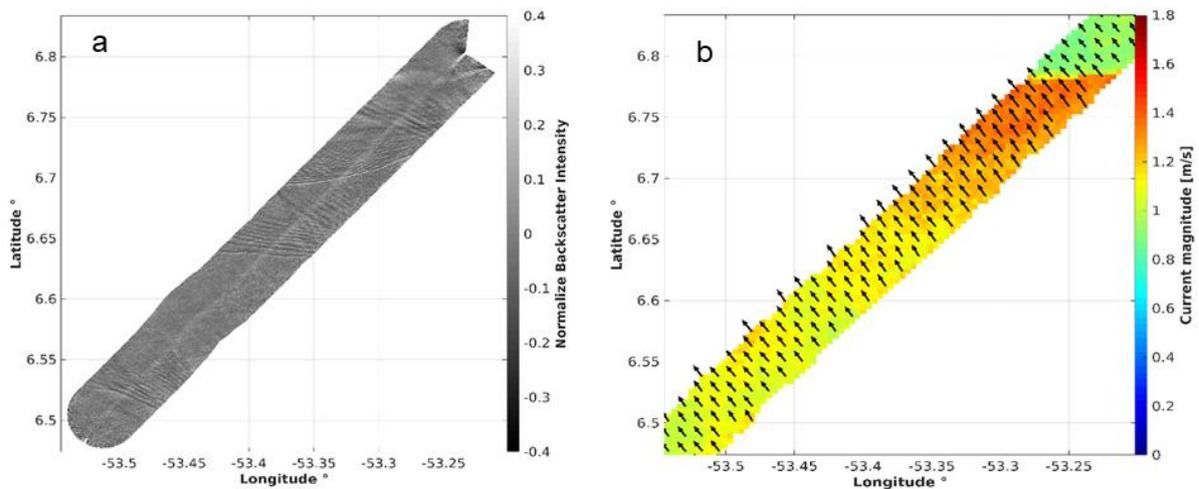
680 4.2 Sharp fronts

681 The daily salinity composite fields have a resolution on the order of 70 km, whereas the daily
682 composites for *Chla* have a resolution slightly blurred by the compositing (for example a
683 feature moving at 30 cm/s will be displaced by 26 km in one day), and the geostrophic current
684 maps do not resolve structures with diameters smaller than 150 km, implying a large time
685 averaging. Much finer fronts are features common in the surveys (for example on Fig. 7 and
686 9). Some of these fronts have very large amplitudes, comparable to the mesoscales and are
687 associated with strong surface density changes, and thus are dynamically active. The best
688 resolved structure is the one crossed by two research vessels and one drifter on February 2nd
689 (Fig. 7). The intake temperature record of RV *Atalante* suggests a horizontal scale of the SST
690 and SSS front of less than 100 m and possibly as short as 50 m. According to the VM-ADCP
691 data of the two vessels, this surface front was embedded in a wider and deeper current
692 pointing north-westward. However, data also suggest a rather narrow surface velocity
693 structure just south of the front, with a sharp change of velocity at the sea surface front.

694

695 For instance, the RV *Atalante* absolute velocity presents a westward velocity peak of close to
696 30 cm/s at the front relative to the velocity before and after the front, despite the ship
697 navigating at a constant speed relative to the sea surface. This peak velocity lasts less than 3
698 minutes, thus over a rather small distance of less than 1 km. There is also some indication of a
699 change in the meridional velocity across the front, with the surface velocity is directed more
700 northward south of the front than north of the front. On MSM VM-ADCP shallowest bin at
701 18-m depth, the velocity vectors also suggest that the structure is converging at least in the

702 direction of the ship's track. There is also a westward narrow velocity peak of 25 cm/s over
703 less than 7 km relative to velocities further away. However, because of the large salinity bulge
704 southwest of the front (Fig. 7c) under the lowest surface salinity, these velocity structures at
705 18 m are difficult to interpret, as the bin is within the fresher layer close and southwest of the
706 front, whereas it is in the saltier water under it in other areas. Fortunately, there is also the
707 evidence from the MR radar surface data (Fig. 13)



708

709

710 Figure 13: marine radar data between 14:03 and 17:42 on Feb 2 2020. Left panel show
711 backscatter intensity, whereas right panel shows retrieved surface currents, both as arrows and
712 colour-coded. The surface front was observed in T-S close to the north-east corner of the plots
713 near $-53.25^{\circ}\text{W}/6.78^{\circ}\text{N}$.

714

715 As the normalized backscatter intensity is strongly dependent on the ocean surface roughness
716 it depicts all structures that affect the surface roughness, including several internal wave
717 packets are depicted along the track, as well as the strong current front close to the northeast
718 corner of the plot. During the 3:39 h track plotted, the surface currents (top 5m) are pointing
719 to the northwest with an increase of velocity along the track towards the northeast, until the
720 velocity front is encountered at the same location as the SST/SSS front. The velocity front at

721 6.78°N is almost zonal with a slight southward tilt towards the west, and is associated with a
722 current gradient of approximately 0.5 m/s.

723

724 The drifter that crossed the front also shows a 50 cm/s westward velocity surge near the front.
725 This surge lasted over 2.5 hours, longer than the change in surface temperature and salinity
726 that lasted less than 1 hour. It is difficult to translate that into a horizontal scale of the current
727 feature, as it would involve knowing the velocity of the front relative to the drifter. Also,
728 notice that, according to the MSM section, the freshwater layer in the fresher part of the front
729 likely extended past the drogue depth centred at 15-m, so the drifter current represents a mix
730 of the velocity in the fresh surface layer and below it.

731

732 These different velocity estimates are in the same bulk range, and although the width of the
733 associated velocity structure is not the same between MSM and Atalante surface data, these
734 larger velocities in the 25-50 cm/s range close or just south of the front (near the freshwater
735 bulge) are close to the expected velocity of an internal gravity current assuming a Froude
736 number of 1 (with the change in stratification of a little over 1 pss and layer thickness of
737 ~20m). The velocity data suggest a front/gravity current propagating to the northwest or west
738 with respect to the underlying water at the time it was crossed. Such a propagating front
739 would quickly spread (by 20-40 km/day) the freshest shelf surface waters on top of the less
740 fresh waters found on the other side of the front, contributing to increased stratification of
741 salinity and density. Further investigation is required to better understand what sets this front
742 and its characteristics, and how it sheds internal waves, as is known to happen in other fresh
743 plumes (Nash and Moum, 2007).

744

745 4.3 Thickness of the fresh layer

746 The fresh layers appeared to have a shallow MLD even at night on February 5th, with a
747 stratified layer reaching to within 10 m of the surface. This stratification is also observed on
748 the earlier sections on February 2nd, and in the drifter data during the first five days after
749 deployment and as the fresh water starts separating from the shelf. However, the fresh layer is
750 thicker by 10-15 m or more in the MVP surveys just southwest of the surface front. These
751 different sections were positioned rather close to the north-westward edge of the fresh water
752 penetrating from the shelf, based on the daily SSS maps. This is also the case for the drifters,
753 with the salinity map in Fig. 6 for the last day of the trajectories on February 7th suggesting
754 close proximity of the drifters to the front. The mixing depth is somewhat deeper by February
755 17th-18th from the indirect estimate of the saildrone (at least 17 m), but with a large
756 uncertainty as density profiles were not measured. The difference between the two estimates
757 suggests that there has been some vertical mixing and entrainment of deeper saltier water into
758 the shallow surface fresh water during these 14 days. This is coherent with the velocity
759 profiles suggesting active turbulence in the fresh plume stratified salinity layer.

760

761 Such shallow layers also imply that the drogue of the SVP drifters, which is between 12 and
762 20-m depth, is only partially within the surface mixing layer, at least at their deployment in
763 the initial fresh plume. Their drift might thus differ from the speed of the freshest surface
764 water, possibly explaining why most drifters deployed in the fresh plume ultimately crossed
765 the salinity fronts to the west of the fresh plume (with Ekman veering, we expect the mixing
766 layer current to be to the right of the currents near its base). The observations from Ocarina on
767 the shelf in a salinity stratified layer (although much less stratified than in areas of lowest
768 surface salinity), also indicated a strong shear of the current within the top 17 m (close to 40
769 cm/s shear between depths of 1 m and 17 m). Such shear and shallow layer imply a strong
770 slippage of the surface layer relative to the layer just below, which could explain the fast

771 spreading to the north and north-west of the fresh water.

772

773 **5. Conclusions**

774 In early February 2020, in the core of the saltiest and driest period, a freshwater plume was
775 observed by satellite and in situ data entering the deep north-western tropical Atlantic near
776 54°W. This changes the perception that during this period, freshwater transport takes place
777 mainly on the shelf and close to the shelf break. This plume was initially very surface trapped
778 with stratification up to 10-m depth and with a width on the order of 120 km. Its freshwater
779 content corresponded of 2 to 3 meters of Amazon water and was distributed down to 40 m,
780 although most of its water is found in the top 20 m. The off-shelf transport lasted for at least
781 10 days with freshwater transport comparable to the Amazon outflow in January. The plume
782 was still quite well defined 16 days after it started spreading off the shelf break to reach a
783 maximum area of 100000 km², and up to 400 km further north. At this time, the mixed layer
784 had not deepened to more than 20 m as indicated by current profiler data during a saildrone
785 transect. Of course, this is hard to put into context from the limited *in situ* data, but the mixed
786 layer was shallower than night-time mixed layers found nearby in saltier waters. A slight
787 change in wind direction along the shelf between the Amazon estuary and 6°N for more than
788 3 days in late January seems to have triggered the north-westward flow of Amazon freshwater
789 along the shelf and towards the shelf break. The off-shelf plume was steered by eddies, and in
790 particular by a nearly-stationary anti-cyclonic North Brazil Current ring up to 12°N. It also
791 spread towards the Caribbean, due to the evolution of the different mesoscale eddies and to
792 the Ekman transport.

793

794 The presence of such events of freshwater transport in February is documented since 2010 in
795 7 out of 10 years, where changes in wind direction closer to the equator concomitant to the

796 presence of anticyclonic eddies to the east of the plume separation from the shelf seems to
797 have contributed to their development and evolution. Such events should contribute largely to
798 freshening the surface salinity in February or March north of the Guiana shelves and south of
799 12°N. It seems that the mechanism at work here is rather different than what was commented
800 for anomalies later in the year leading to boreal summer, where both current anomalies, wind
801 anomalies, interannual anomalies of Amazon outflow, or conditions upstream south of the
802 equator seem to play important roles.

803

804 The position of the 2020 plume's first offshore extension near 54°W is east compared to the
805 other plumes detected in CCI products for the other years. We found that such plumes in
806 February are not rare, and are also commonly associated with NBC rings such as A1 that was
807 nearly stationary during the plume development. This near stationarity could be linked with
808 the presence of the Demerara Rise to its west that might act to trap the eddy and prevent its
809 fast westward propagation. Clearly more research on the frequency of this phenomenon and
810 how it is modulated seasonally and interannually will be interesting. Also, from the CCI
811 weekly salinity maps, this also seems to happen in March, and maybe early April, though this
812 will require further investigation. Afterwards in the spring season, with the seasonal wind
813 changes and large Amazon outflow, it is however likely that other processes involved in the
814 development of interannual salinity anomalies in this region east of the lesser Antilles and
815 north of the Guiana shelves might dominate.

816

817 **Acknowledgments**

818 This work is a contribution to the LEFE/IMAGO-GMMC project EUREC⁴A-OA, to the JPI-
819 Ocean project EUREC⁴A-OA, and to the TOSCA SMOS-Ocean project supported by CNES
820 (Centre National d'Etudes Spatiales). LO was supported by a scholarship from ENS and

821 Sorbonne Université. Support for the salinity drifters was provided by the Climate Variability
822 and Predictability Program of NOAA's Climate Program Office. GRF was supported by base
823 funds to NOAA/AOML's Physical Oceanography Division. DZ was supported by NOAA's
824 Climate Program Office, Climate Variability and Predictability Program. We benefited from
825 numerous data sets made freely available and listed here : the SLA and currents produced by
826 Ssalto/Duacs distributed by the CMEMS (<https://resources.marine.copernicus.eu>), the Chla
827 maps produced by CLS, the SMOS L2Q maps produced by CATDS (CATDS, 2019) and the
828 SMAP maps produced by Remote Sensing System and CCI+SSS maps produced in the frame
829 of ESA CCI+SSS project.

830

831 **References**

832 Boutin, J., Vergely, J.-L., Marchand, S., d'Amico, F., Hasson, A., Kolodziejczyk, N., et al.
833 (2018), New SMOS Sea Surface Salinity with reduced systematic errors and improved
834 variability. *Remote Sensing of Environment*, 214, 115–134.

835 Bourras D., Cambra R., Marié L., Bouin M.N., Baggio L., Branger H., Beghoura G., Reverdin
836 G., Dewitte Boris, Paulmier Aurélien, Maes Christophe, Arduin F., Pairaud I., Fraunié P.,
837 Luneau C., Hauser D. (2019), Air-sea turbulent fluxes from a wave-following platform during
838 six experiments at sea. *J. Geophys. Res. Oceans*, 124 (6), 4290-4321. ISSN 2169-9275.

839 CATDS (2019). CATDS-PDC L3OS 2Q - Debaised daily valid ocean salinity values product
840 from SMOS satellite. CATDS (CNES, IFREMER, LOCEAN, ACRI).

841 <https://doi.org/10.12770/12dba510-cd71-4d4f-9fc1-9cc027d128b0>

842 Dankert, H., & Horstmann, J. (2007), A marine radar wind sensor. *J. Atmosph. Ocean.
843 Technol.*, 24 (9), 1629-1642.

844 Dibarboure G., Pujol M.-I., Briol F., Le Traon P.-Y., Larnicol G., Picot N., Mertz F., & Ablain
845 M. (2011), Jason-2 in DUACS: first tandem results and impact on processing and products.
846 *Marine Geodesy Jason-2 Special Issue*, 2 (34), 214-241.

847 Entekhabi, D., Njoku, E. G., O'Neill, P. E., Kellogg, K. H., Crow, W. T., Edelstein, W. N., et
848 al. (2010), The soil moisture active passive (SMAP) mission. *Proceedings of the IEEE*, 98(5),
849 704–716.

850 Foltz, G. R., Hummels, R., Dengler, M., Perez, R. C., & Araujo, M. (2020), Vertical
851 turbulent cooling of the mixed layer in the Atlantic ITCZ and trade wind regions. *J. Geophys.*
852 *Res.*, 125, e2019JC015529, doi:10.1029/2019JC015529.

853 Foltz, G. R., Schmid, C., & Lumpkin, R. (2018), An enhanced PIRATA data set for tropical
854 Atlantic ocean-atmosphere research. *J. Climate*, 31, 1499-1524, doi:10.1175/JCLI-D-16-
855 0816.1.

856 Foltz, G. R., Schmid, C., & Lumpkin, R. (2015), Transport of surface freshwater from the
857 equatorial to the subtropical North Atlantic Ocean. *J. Phys. Oceanogr.*, 45, 1086-1102,
858 doi:10.1175/JPO-D-14-0189.1.

859 Font, J., Camps, A., Borges, A., Martín-Neira, M., Boutin, J., Reul, N., et al. (2009), SMOS:
860 The challenging sea surface salinity measurement from space. *Proceedings of the IEEE*,
861 98(5), 649–665.

862 Fournier, S., Chapron, B., Salisbury, J., Vandermark, D., & Reul, N. (2015), Comparison of
863 spaceborne measurements of sea surface salinity and colored detrital matter in the Amazon
864 plume. *J. Geophys. Res.*, 120, 3177-3192.

865 Fournier, S., Vandermark, D., Gaultier, L., Lee, T., Jonsson, B., & Gierach, M.M. (2017),
866 Interannual variation in offshore advection of Amazon-Orinoco plume water: observations,
867 forcing mechanisms, and impacts. *J. Geophys. Res.*, 122, 8966-8982.

868 Galperin, B., Sukoriansky, S., Anderson, P.S. (2007), On the critical Richardson number in
869 stably stratified turbulence. *Atmos. Sci. Lett.*, 8, 65-69, <https://doi.org/10.1002/asl.153>

870 Grodsky, S. A., Reverdin, G., Carton, J. A., & Coles, V. J. (2014), Year-to- year salinity
871 changes in the Amazon plume: Contrasting 2011 and 2012 Aquarius/SACD and SMOS
872 satellite data. *Remote Sens. Environ.*, *140*, 14–22, doi:10.1016/j.rse.2013.08.033.

873 Grodsky, S. A., Vandermark, D. & Feng, H. (2018), Assessing coastal SMAP surface salinity
874 accuracy and its application to monitoring Gulf of Maine circulation dynamics.
875 *Remote Sens.*, *10*(8), <https://doi.org/10.3390/rs10081232>

876 Hu, C., Montgomery, E. T., Schmitt, R. W., & Muller-Karger, F.E. (2004), The dispersal of
877 the Amazon and Orinoco River water in the tropical Atlantic and Caribbean Sea: Observation
878 from space and S. PALACE floats. *Deep-Sea Res. II*, *51*, 1151-1171,
879 <https://doi.org/10.1016/j.dsr2.2004.04.001>.

880 Huang, W., Carrasco, R., Shen, C., Gill, E.W., & Horstmann, J. (2016), Surface current
881 measurements using X-band marine radar with vertical polarization. *IEEE Trans. Geosci.*
882 *Rem. Sens.*, *54* (5), 2988-2997.

883 Kerr, Y. H., Waldteufel, P., Wigneron, J.-P., Delwart, S., Cabot, F., Boutin, J., et al. (2010),
884 The SMOS mission: New tool for monitoring key elements of the global water cycle.
885 *Proceedings of the IEEE*, *98*(5), 666–687.

886 Laxenaire, R., Speich, S., Blanke, B., Chaigneau, A., & Pegliasco, C. (2018), Anticyclonic
887 eddies connecting the western boundaries of Indian and Atlantic oceans. *J. Geophys. Res.*
888 *Oceans*, *123* (11), 7651-7677, doi:10.1029/2018JC014270.

889 Lund, B., Haus, B. K., Horstmann, J., Graber, H. C., Carrasco, R., Laxague, J. M., Novelli,
890 G., Guigand, C. M., Özgökmen, T. M. (2018), Near-surface current mapping by shipboard
891 marine X-band radar: A validation. *J. Atmos. Oceanic Technol.*, *35* (5), 1077-1090,
892 doi:10.1175/jtech-d-17-0154.1

893 Mignot, J., Lazar, A., & Lacarra, M. (2012), On the formation of barrier layers and
894 associated vertical temperature inversions: a focus on the northwestern tropical Atlantic. *J.*
895 *Geophys. Res.*, *117*, C02010, doi:10.1029/2011JC007435.

896 Muller-Karger, F.E., Mc Lain, C.R., & Richardson, P.L. (1988), The dispersal of the
897 Amazon's water. *Nature*, *333*, 56-58.

898 Nash, J. D., & Moum, J.M. (2005), River plumes as a source of large- amplitude internal
899 waves in the coastal ocean, *Nature*, *437*, 400– 403.

900 Piepmeier, J. R., Focardi, P., Horgan, K. A., Knuble, J., Ehsan, N., Lucey, J., et al. (2017),
901 SMAP L-band microwave radiometer: Instrument design and first year on orbit. *IEEE Trans.*
902 *Geosci. Rem. Sens.*, *55*(4), 1954–1966.

903 Reul, N, Grodsky, S. A., Arias, M., Boutin, J., Catany, R., Chapron, B., et al. (2020), Sea
904 surface salinity estimates from spaceborne L-band radiometers: An overview of the first
905 decade of observation (2010–2019). *Remote Sensing of Environment*, *242*, 111769.

906 Rio M. H., Guinehut, S., and Larnicol, G. (2011), New CNES CLS09 global mean dynamic
907 topography computed from the combination of GRACE data, altimetry, and in-situ
908 measurements, *J. Geophys. Res.*, *116*, C07018, <https://doi.org/10.1029/2010JC006505>.

909 Salisbury J., Vandemark, D., Campbell, J., Hunt, C., Wisser, D., & Reul, N. (2011), Spatial
910 and temporal coherence between Amazon River discharge, salinity, and light absorption by
911 colored organic carbon in western tropical Atlantic surface waters. *J. Geophys. Res. Oceans* ,
912 *116*(C00H02), 14 p. Publisher's official version : <https://doi.org/10.1029/2011JC006989> ,
913 Open Access version : <https://archimer.ifremer.fr/doc/00041/15218/>

914 Senet, C.M., Seemann, J., & Ziemer, F. (2001), The near-surface current velocity determined
915 from image sequences of the sea surface. *IEEE Trans. Geosci. Rem. Sens.*, *39* (3), 492-505.

916 Steinmetz, F., Deschamps, P.Y, & Ramon, D. (2011), Atmospheric correction in presence of
917 sun glint: application to MERIS. *Optics Express*, *19*(10), 9783-9800.

918 Stevens, B., et al. (2021), EUREC⁴A. Submitted to Advances in meteorology.

919 Stum, J., Tebri, H., Lehodey, P., Senina, I., Greiner, E., Lucas, M., & Steinmetz, F. (2015),
920 NRT operational chlorophyll maps for marine applications. Poster presented at the 2nd IOCS
921 meeting, San Francisco, June 15-18, 2015. Available at [http://www.eposters.net/pdfs/nrt-](http://www.eposters.net/pdfs/nrt-operational-chlorophyll-maps-calculation-for-marine-applications.pdf)
922 [operational-chlorophyll-maps-calculation-for-marine-applications.pdf](http://www.eposters.net/pdfs/nrt-operational-chlorophyll-maps-calculation-for-marine-applications.pdf)

923 Taburet, G., Sanchez-Roman, A., Ballarotta, M., Pujol, M. I., Legeais, J.-F. Fournier, F.,
924 Faugere, Y., & Dibarboure, G. (2019). DUACS DT2018: 25 years of reprocessed sea level
925 altimetry products. *Ocean Sci.*, 15, 1207–1224, <https://doi.org/10.5194/os-15-1207-2019>.

926 Zhang D, Cronin, M.F., Meinig, C., Farrar, J.T., Jenkins, R., Peacock, D., Keene, J., Sutton,
927 A., & Yang, Q. (2019), Comparing Air-sea flux measurements from a new unmanned surface
928 vehicle and proven platforms during the SPURS-2 Field Campaign. *Oceanography*,
929 32(2):122-133.