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► To cite this version:

Jacqueline Boutin, Jean-Luc Vergely, Stéphane Marchand, Francesco d'Amico, Audrey Hasson, et al.. New SMOS Sea Surface Salinity with reduced systematic errors and improved variability. Remote Sensing of Environment, 2018, 214, pp.115-134. 10.1016/j.rse.2018.05.022 . hal-01844300

HAL Id: hal-01844300

<https://hal.sorbonne-universite.fr/hal-01844300>

Submitted on 19 Jul 2018

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New SMOS Sea Surface Salinity with reduced systematic errors and improved variability

J. Boutin⁽¹⁾, J.L. Vergely⁽²⁾, S. Marchand⁽¹⁾, F. D'Amico⁽¹⁾, A. Hasson⁽¹⁾, N. Kolodziejczyk⁽³⁾,
N. Reul⁽³⁾, G. Reverdin⁽¹⁾, J. Vialard⁽¹⁾

⁽¹⁾ Sorbonne Université, CNRS, IRD, MNHN, Laboratoire d'océanographie et du climat :
expérimentations et approches numériques (LOCEAN), 75005 Paris, France

⁽²⁾ ACRI-st, Guyancourt, France

⁽³⁾ LOPS, CNRS/UBO/Ifremer/IRD, Plouzané/Toulon, France

Highlights:

1. Improved SMOS salinity systematic error correction from Kolodziejczyk et al. (2016).
2. Refined variability of surface salinity near e.g. major river mouths.
3. Consistent mesoscale patterns observed by SMOS and SMAP satellite missions.

Corresponding author: Dr. Jacqueline Boutin, E-mail: jb@locean-ipsl.upmc.fr

19 **Abstract**

20 Salinity observing satellites have the potential to monitor river fresh-water plumes mesoscale
21 spatio-temporal variations better than any other observing system. In the case of the Soil
22 Moisture and Ocean Salinity (SMOS) satellite mission, this capacity was hampered due to the
23 contamination of SMOS data processing by strong land-sea emissivity contrasts.

24 Kolodziejczyk et al. (2016) (hereafter K2016) developed a methodology to mitigate SMOS
25 systematic errors in the vicinity of continents, that greatly improved the quality of the SMOS
26 Sea Surface Salinity (SSS). Here, we find that SSS variability, however, often remained
27 underestimated, such as near major river mouths. We revise the K2016 methodology with: a)
28 a less stringent filtering of measurements in regions with high SSS natural variability
29 (inferred from SMOS measurements) and b) a correction for seasonally-varying latitudinal
30 systematic errors. With this new mitigation, SMOS SSS becomes more consistent with the
31 independent SMAP SSS close to land, for instance capturing consistent spatio-temporal
32 variations of low salinity waters in the Bay of Bengal and Gulf of Mexico. The standard
33 deviation of the differences between SMOS and SMAP weekly SSS is less than 0.3 pss in
34 most of the open ocean. The standard deviation of the differences between 18-day SMOS
35 SSS and 100-km averaged ship SSS is 0.20 pss (0.24 pss before correction) in the open
36 ocean. Even if this standard deviation of the differences increases closer to land, the larger
37 SSS variability yields a more favorable signal-to-noise ratio, with r^2 between SMOS and
38 SMAP SSS larger than 0.8. The correction also reduces systematic biases associated with
39 man-made Radio Frequency Interferences (RFI), although SMOS remains more impacted by
40 RFI than SMAP. This newly-processed dataset will allow the analysis of SSS variability over
41 a larger than 8 years period in regions previously heavily influenced by land-sea
42 contamination, such as the Bay of Bengal or the Gulf of Mexico.

43

44 **1. Introduction**

45 With 8 years and counting, the Soil Moisture and Ocean Salinity (SMOS) European mission
46 (Kerr et al., 2010; Font et al., 2010) provides the longest record for Sea Surface Salinity
47 (SSS^a) monitored from space over the global ocean (2010-present). The pioneered SMOS
48 (2010-) and Aquarius (2011-2015) (Lagerloef, 2008) satellite missions have demonstrated the
49 capability of L-band radiometry for monitoring SSS from space (e.g. Reul et al., 2014a;
50 Lagerloef, 2012).

51 Salinity is a key ocean variable that plays a fundamental role in the density-driven global
52 ocean circulation, the water cycle, and climate (Siedler et al., 2001). Salinity controls the
53 density of sea water, together with temperature. At the ocean surface, in cold waters ($T = 2$
54 $^{\circ}\text{C}$), a SSS change of $\sim 0.1 \text{ pss}^{\text{b}}$ is equivalent, in terms of density, to a sea surface temperature
55 (SST) change of 1°C . SSS variations therefore greatly constrain the global thermohaline
56 circulation as salinity drives the high latitude convective overturning. In warmer regions
57 ($T=28^{\circ}\text{C}$), a 0.44 pss change is equivalent to a 1°C change in terms of density. Salinity
58 stratification within a near isothermal layer (known as the barrier layer, e.g. Lukas and
59 Lindstrom, 1991) can furthermore inhibit the vertical mixing of heat and momentum, and
60 play a role in major phenomena such as the El Niño Southern Oscillation (e.g. Vialard and
61 Delecluse, 1998), the southwest monsoon rain distribution (e.g. Shenoi et al. 2002) or the
62 oceanic productivity (e.g. Picaut et al. 2001). Finally, SSS is considered as a passive tracer of

^a SSS will hereafter refer to the salinity measured between 1 cm -as monitored by satellite measurements- and at a few meters depth -as monitored by most *in situ* measurements.

^b pss is used here as an equivalent to gram of salt per kilogram of standard sea water, see UNESCO (1985) for more details

63 the hydrological cycle, recording for instance its intensification in response to anthropogenic
64 climate change (e.g. Durack et al. 2012). For all these reasons, SSS has been designated as an
65 ECV (Essential Climate Variable) by the Global Climate Observing System (GCOS).

66 SMOS data has enabled the study of salinity changes associated with two El Niño events
67 (Hasson et al. submitted) and a La Niña event (Hasson et al. 2014), climate variability in the
68 equatorial Indian Ocean (Durand et al. 2013), decadal salinity changes in the subtropical
69 Pacific Ocean (Hasson et al. 2013) or North Atlantic Ocean (Grotsky et al. 2017). The spatial
70 resolution and spatio-temporal coverage of the SMOS mission (50 km resolution; global
71 coverage every 3 to 5 days) also allow the unprecedented detection of SSS mesoscale features
72 associated with the transport across frontal regions (e.g. Reul et al., 2014b; Kolodziejczyk et
73 al., 2015), very hardly accessible from Aquarius measurement (100-150 km resolution; global
74 coverage every 8 days).

75 SMOS demonstrated performance in monitoring open-ocean salinity variations has been
76 impressive so far. SMOS results have, however, been disappointing close to land, for instance
77 in the Bay of Bengal, where Aquarius and more recently the Soil Moisture Active Passive
78 (SMAP; 2015-) mission perform better (Akhil et al. 2016 and Fournier et al. 2017).

79 SMOS is an Earth Explorer mission. It carries an L-band Microwave Interferometric
80 Radiometer with Aperture Synthesis (MIRAS), which is the first interferometer and the first
81 L-band radiometer observing Earth from space. L-band (1.4 GHz) is a passive protected
82 frequency band but many SMOS measurements are corrupted by unexpected man-made
83 Radio Frequency Interferences (RFI) (Oliva et al., 2012). SMOS SSS is also affected by the
84 presence of nearby landmasses up to several hundreds of kilometers into the ocean, likely an
85 effect of imperfect synthetic aperture image reconstruction in the present SMOS data

86 processing (more on limitations in the present SMOS image reconstruction is presented in
87 Anterrieu et al., 2015).

88 Other two satellite missions measuring SSS from space, Aquarius (Lagerloef et al., 2008)
89 (2011-2015) and SMAP (Piepmeier et al., 2017) (2015-present), are equipped with classical
90 L-band radiometers. Hence, they are expected to suffer less land-sea contamination than
91 SMOS. Aquarius and SMAP were launched subsequently to SMOS and have benefited from
92 a better RFI-protected onboard processing.

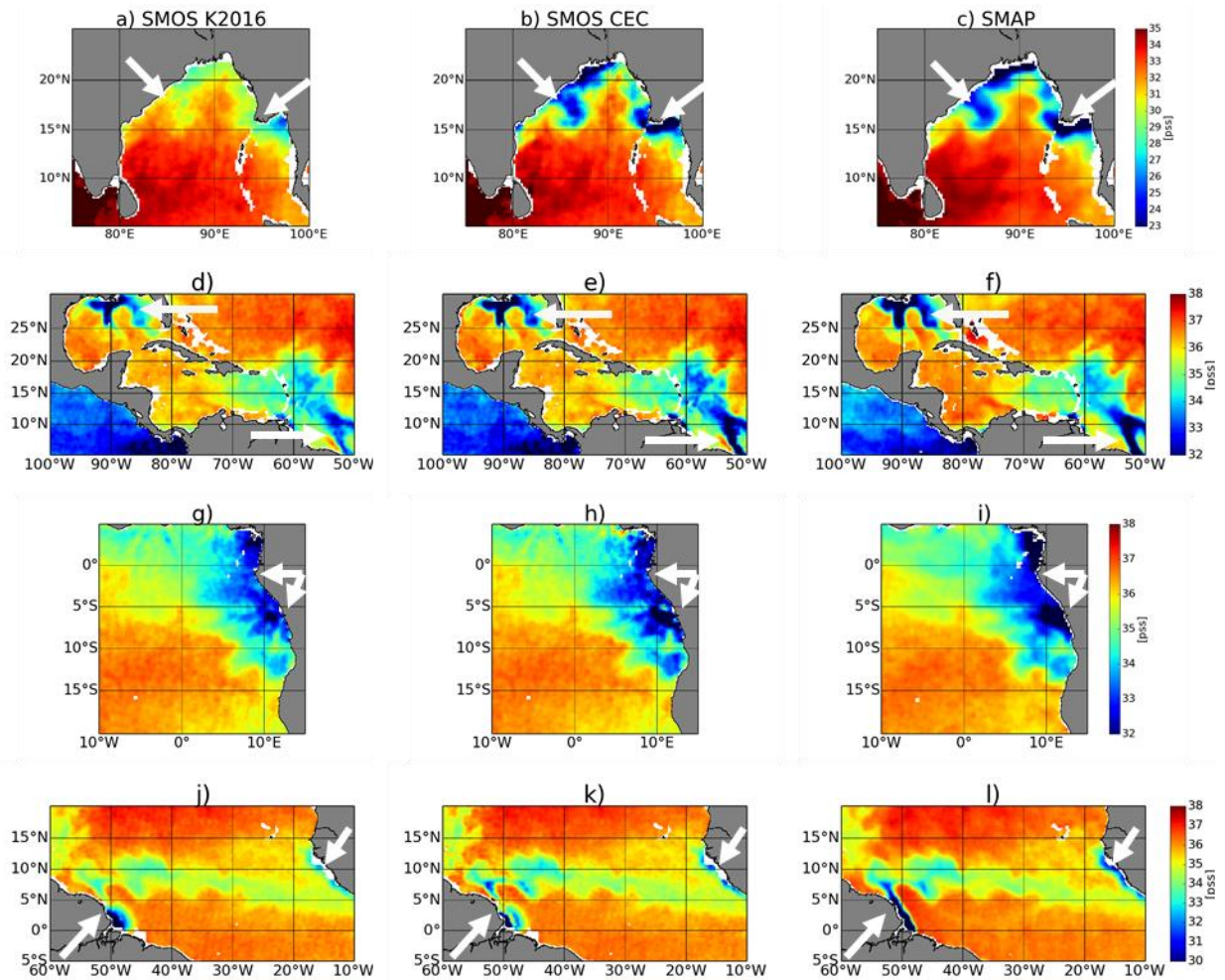
93 The unique length of SMOS record and its high spatio-temporal resolution (comparable to the
94 more recent SMAP mission) are strong motivations for improving its processing in order to
95 mitigate RFI and land-sea contaminations on the retrieved SSS. The validation of satellite
96 SSS using *in situ* SSS measurements is, however, very challenging in coastal areas where
97 contaminations are strong, *in situ* data are very sparse and variability is high, such as in river
98 plumes (Delcroix et al. 2005; Boutin et al. 2016). Hence, in addition to using *in situ* SSS, we
99 take advantage of SMAP SSS to assess corrections to the SMOS SSS.

100 Kolodziejczyk et al. (2016) (K2016 hereafter) have developed a Bayesian methodology to
101 mitigate SSS systematic errors due to land-sea contamination. The method is described in
102 detail in Section 3.3 of the present paper. It brings a clear improvement in most areas, with a
103 32% decrease of the RMSD globally with respect to ship measurements. Some examples
104 below, however, indicate much lower SSS values in SMAP than in K2016 SMOS retrievals,
105 in particular near river mouths. In the Bay of Bengal, for instance, fresh water originating
106 from the Ganges-Brahmaputra (GB) is transported southward by the East India Coastal
107 Current (EICC) after the monsoon, forming a ~200 km fresh water tongue along the Indian
108 coast, up to 10 pss fresher than in the central Bay of Bengal (Chaitanya et al. 2014). Fournier

109 et al. (2017) demonstrated the SMAP capacity to monitor the modulation of this freshwater
110 tongue extent by climate variability and mesoscale eddies stirring the freshwater plume away
111 from the coast. This peculiar pattern is more than 3 pss fresher in SMAP SSS than SMOS
112 K2016 SSS (Figure 1 a and c). Fournier et al. (2016) similarly used SMAP data to study an
113 unusual freshening associated with anomalous advection of the Mississippi River plume in
114 the Gulf of Mexico. While this freshening is also detected by SMOS K2016 (Figure 1 d), it is
115 saltier than in SMAP SSS (Figure 1 f). Such overestimation of K2016 SSS by SMAP relative
116 to SMOS in the low salinity regime also occurs in the eastern tropical Atlantic (Figure 1 g, i,
117 Congo and Niger river mouths, Reul et al. 2014a) and western tropical Atlantic (Amazon and
118 Orinoco, Figure 1 j, l). SMOS K2016 default in retrieving the freshest SSS of the major river
119 plumes illustrates the need of an improved processing in variable, low-salinity regions near
120 land.

121 The purpose of this paper is to present a revised version of the K2016 methodology. The
122 main changes aim at taking the SSS natural variability into consideration in the land-sea
123 contamination correction and at adding a correction for the seasonally-varying latitudinal
124 biases.

125 Ancillary datasets are detailed in section II. An overview of the SMOS SSS retrieval, of the
126 K2016 SMOS processing and a description of the revised methodology are given in section
127 III. Comparisons with ancillary data sets are presented in section IV and V. They are
128 summarized and discussed in section VI.



129

130 Figure 1: Satellite SSS: SMOS SSS corrected according to (a, d, g, j) K2016 methodology, (b, e, h, k)
 131 the method described in this paper (CEC); (c, f, i, l) SMAP SSS. 4 case study areas : (a, b, c) : Bay of
 132 Bengal - August 21st 2015; (d, e, f) : Gulf of Mexico – August 18th 2015 ; (g, h, i) : Eastern Tropical
 133 Atlantic Freshwater Pools – April 14th 2016; (j, k, l) : Amazon plume – October 21st 2015. SMOS and
 134 SMAP SSS is averaged over a SMOS repetitive orbit sub-cycle (18 days) and two SMAP repetitive
 135 orbit cycles (16 days) respectively. Striking fresh SSS features in better agreement with SMOS (new
 136 version) and SMAP are indicated with white arrows.

137

138 2. Data

139 Three types of ancillary data are used in this study. The *In situ* Analysis System (ISAS) SSS
 140 is used both to set the long term mean reference of our correction and to qualitatively indicate
 141 the most trustable SMOS SSS data in our correction process as described in Section 3. It is

142 also used to check the SMOS SSS variability. SMAP and ship SSS are used for independent
143 assessment.

144 **2.1 *In Situ* Analyzed SSS**

145 Monthly gridded fields of salinity derived from *in situ* measurements are obtained from the
146 ISAS (*In situ* Analysis System) v6 algorithm, an optimal interpolation (Bretherton, 1976) tool
147 developed for the synthesis of the Argo global dataset (Gaillard et al., 2016). We use the
148 fields reconstructed at 5 m depth on a half degree horizontal grid. The ISAS Near Real Time
149 (NRT) products are available since 2010. In addition, over the 2002-2012 period, ISAS13
150 (Gaillard, 2015) fields have been produced after a refined quality check of the Argo profiles.
151 Data are preprocessed for ISAS13 using a climatological test and followed by a visual control
152 of suspicious profiles. The interpolation is based on delayed mode Argo floats, TAO-
153 TRITON-PIRATA-RAMA moorings and MEMO (Marine Mammals) data.
154 The ISAS-NRT fields (2010-present) are used by the correction method whereas ISAS13 (till
155 2012) and ISAS-NRT (from 2013 to 2016) fields are used for the assessment presented
156 Section 4.

157 **2.2 SMAP SSS**

158 The SMAP mission (Piepmeier et al. 2017) provides L-band radiometric observations since
159 April 2015. While its main objective is the observation of soil moisture, the observed
160 brightness temperatures (Tb) are also used to retrieve SSS (Fore et al. 2016a). SMAP SSS
161 characteristics are quite close to those of SMOS in terms of spatio-temporal coverage and
162 spatial resolution (~50 km). In approximately 3 days, SMAP achieves global coverage and it
163 has an exact orbit repeat cycle of 8 days. The SMAP L-band microwave radiometer,
164 however, uses a conical scanning antenna instead of a synthetic aperture imaging antenna. As

165 stated in the introduction, a particular attention was put on filtering the RFI (Mohammed et
166 al. 2016) and their impact is expected to be limited compared to SMOS. SMAP also suffers
167 from land-sea contamination but, given that SMAP carries a real aperture antenna, the
168 contamination is not expected to be as spatially variable as with SMOS. We use level 3
169 SMAP SSS produced at the Jet Propulsion Laboratory using the Combined Active Passive
170 (CAP version 3) algorithm (Fore et al. 2016b). A complete description of the CAP v3
171 algorithm can be found in Fore et al. (2016a), but a brief description follows. The CAP
172 algorithm is only applied to passive measurement as the radar failed a few months after
173 launch. It includes specific Tb corrections for land and galactic noise contaminations, and a
174 global Tb bias adjustment (latitude and time-dependent). After correction, the rms difference
175 of SMAP retrieved SSS with respect to Hycom SSS in the vicinity to land is less than 1.5pss.
176 Level 2 SSS is retrieved from SMAP Tb measurements using a constrained objective
177 function minimization. Data are mapped on a 0.25° grid using a Gaussian weighting with a
178 search radius of approximately 45 km and a half-power radius of 30 km. They are
179 aggregated in level 3 maps produced daily with an 8-day running-average time window.
180 CAPv3 SMAP SSS agrees well with in situ SSS. Tang et al. 2017 found a rms difference of
181 0.26 pss between weekly SMAP SSS and buoy SSS. They also show that SMAP and SMOS
182 SSS depict salinity fluctuations very close to in situ SSS.

183 **2.3 Ship SSS**

184 Salinity data provided by thermosalinographs (TSG) installed on voluntary merchant ships
185 are used as ground truth. A full description of the data can be found in Alory et al. (2015).
186 They provide SSS estimates with an ~ 2.5 km resolution along the ship track and are
187 independent from the ISAS analyses. Samples are taken at a few meters depth. Noise on
188 individual ship SSS is estimated to be on the order of 0.08 pss (Alory et al. 2015). In the

189 presence of strong vertical stratification, TSG and satellite SSS are expected to differ as the
190 L-band radiometer skin depth is about 1 cm (Boutin et al. 2016). This may occur under heavy
191 rain conditions or in river plumes. Because of their singular spatio-temporal resolution, ship
192 measurements, however, provide invaluable information on the spatial variability of SSS
193 unresolved by Argo.

194 **3. SMOS data and processing methodology**

195 The SMOS mission (Kerr et al., 2010) provides SSS measurements from space since January
196 2010. The SMOS satellite is on a sun-synchronous circular orbit with a local equator-crossing
197 time at 6 AM on the ascending node and with a repeat sub-cycle of 18 days. It carries a 2-D
198 interferometric radiometer, the MIRAS instrument. This groundbreaking technology was
199 chosen as it involves much lighter antennas than real aperture antennas, and while getting
200 ground spatial resolution on the order of 50 km at L-band frequency requires a huge antenna.
201 The synthetic aperture antenna approach involves the reconstruction of an image using spatial
202 Fourier components as derived from the correlations between numerous antenna elements (69
203 in case of SMOS). The SMOS bi-dimensional multi-angular images of T_b are reconstructed
204 with a spatial resolution in the field of view ranging between about 35 km and 100 km (50
205 km on average). In this paper, we use the SSS retrieved within the center part of the field of
206 view that extends at +/-400 km away from the center of the satellite swath. Global ocean
207 coverage is then achieved after about 5 days. Individual T_b s are very noisy (1.6-3.2 K) and
208 lead to a typical noise on SSS of the order of 0.6 pss in tropical and subtropical regions on
209 pixel-wise SSS retrievals (Hernandez et al., 2015; Supply et al., 2017). However, owing to
210 the very good spatio-temporal coverage of SMOS, averaging SMOS SSS over typically one
211 month and $100 \times 100 \text{ km}^2$ results in an accuracy close to 0.2 pss in the open ocean, after
212 removing a climatological mean of SMOS systematic errors (Boutin et al., 2016).

213 In the following, before describing the new SSS correction methodology developed in the
 214 present paper, we recall in section 3.1, the principle of the along track (level 2, L2) SMOS
 215 SSS retrieval from Tb measurements, and, in section 3.2, the basis for the K2016 correction
 216 method applied to L2 SSS.

217 **3.1 SMOS SSS level 2 retrieval**

218 The SMOS L2 SSS is retrieved from Level 1 (L1) Tb through a maximum-likelihood
 219 Bayesian approach in which Tb measured in the antenna reference frame, Tb^{meas} , are
 220 compared with Tb simulated using a forward radiative transfer model, Tb^{mod} (see a general
 221 description of the retrieval algorithm in Zine et al. (2008)). The retrieved parameters, P_i , and
 222 their associated theoretical error, are estimated through the minimization of the χ^2 cost
 223 function:

$$224 \chi^2 = \sum_{n=1}^N \frac{[Tb_n^{meas} - Tb_n^{mod}(\theta_n, P_i \dots)]^2}{\sigma_{Tbn}^2} + \sum_{n=1}^M \frac{[P_i - P_{i0}]^2}{\sigma_{P_{i0}}^2}, \quad (1)$$

225 where N is the number of measurements available for retrievals in vertical and horizontal
 226 polarizations at different incidence angles θ_n . N is typically 120 to 240 within +/-400 km
 227 from the center of the track. σ_{An} is taken equal to the SMOS brightness temperature noise
 228 (between 1.6 and 3.2K depending on the location within the field of view) plus a small term
 229 that takes into account an error originating from the radiative transfer model error (see Zine et
 230 al. 2008 for more details). M is the number of physical parameters, P_i (SSS, wind, sea surface
 231 temperature and ionospheric total electronic content) that are adjusted by the retrieval; P_{i0} and
 232 $\sigma_{P_{i0}}$ are a priori values for P_i and their associated errors respectively.

233 In the present study, we use SSS produced at the Data Production Center (CPDC) of the
 234 Centre Aval de Traitement des Données SMOS (CATDS) in its RE05 version (Vergely and

235 Boutin, 2017). Daily SSS fields are provided on a 25-km resolution EASE 2 (Equal-Area
236 Scalable Earth 2) grid (Brodzik et al. 2012) for ascending and descending orbits separately
237 (CATDS, 2017a). L1 Tbs, radiative transfer models (roughness model 1) and retrieval
238 scheme used in CATDS CPDC RE05 are identical to the ones used in the European Space
239 Agency level 2 ocean salinity processor version 622 (ESA L2OS v622) (see a description in
240 SMOS-Ocean Expert Support Laboratories (2014)). The main difference between the
241 CATDS RE05 and the ESA v622 processing involves the Tb outlier filtering. No Tb outlier
242 filtering is applied when retrieving SSS with ESA L2 OS V622. The absence of Tb outlier
243 filtering enables an easier detection of RFI-polluted SSS through a larger χ^2 value (equation
244 1). This, however, removes pixels that are systematically contaminated by the presence of
245 nearby land, which could be mitigated by our correction. K2016 correction method was
246 indeed developed using ESA v5 processing in which an outlier filtering of Tb^{meas} was
247 performed and it was able to mitigate part of the RFI biases. In the CATDS RE05
248 processing, a $3 \sigma_{Tbn}$ filtering is applied to $(Tb^{meas} - Tb^{mod})$ before performing the SSS retrieval.
249 Some tests (not shown) performed on SSS retrieved from filtered and from non-filtered Tb
250 datasets confirm that the correction presented in this paper is more efficient when used in
251 conjunction with a Tb filtering.

252

253 **3.2 K2016 land-sea contamination correction**

254 In this section, we briefly review the K2016 methodology. The K2016 correction aims at
255 mitigating systematic errors constant with time and was shown to efficiently correct land-sea
256 contamination in many regions. Given the 18-day sub-cycle of SMOS, a given location over
257 the ocean is observed with the same SMOS measurement geometry every ~ 18 days; within

258 18 days, it is sampled by several SMOS SSS measurements which are located at various
 259 locations across the swath, x_{swath} . The K2016 methodology considers that the long term
 260 (2010-2014) SSS variability observed by SMOS has to be rather similar whatever x_{swath} and
 261 the orbit orientation x_{orb} . Relative biases, b_{land} , with respect to a reference SSS, SSS_{ref} , are
 262 derived from SMOS SSS through a least square minimization approach, and through a series
 263 of iterations that will be described below. A consistent set of SMOS SSS, $\text{SSS}_{\text{K2016}}$, is
 264 obtained as:

$$265 \text{SSS}_{\text{K2016}}(t, \phi, \lambda, x_{\text{swath}}, x_{\text{orb}}) = \text{SSS}_{\text{ref}}(t, \phi, \lambda) - b_{\text{land}}(\phi, \lambda, x_{\text{swath}}, x_{\text{orb}}) \quad (2)$$

266 where t is the time of the measurement, ϕ , and, λ , are respectively the latitude and the
 267 longitude of the considered location over the ocean. x_{swath} is sampled within 25 km wide bins.

268 b_{land} and SSS_{ref} are derived as follows. Defining $p = (\text{SSS}_{\text{ref}}, b_{\text{land}})^T$, p_0 the *a priori* values of p ,
 269 y_0 the SMOS SSS, the estimated values of p , p_{est} , are derived as:

$$270 p_{\text{est}} = p_0 + C_p \cdot G^T \cdot (G \cdot C_p \cdot G^T + R)^{-1} \cdot [y_0 - f(p_0)] \quad (3)$$

271 where G is the matrix of derivatives of observations with respect to the parameters (also
 272 called observational operator), R is the covariance matrix for the observation error, C_p is the
 273 covariance matrix for the *a priori* error on the parameters p . C_p is parametrized as a function
 274 of an acceptable standard deviation of SSS, σ_{SSSref} , over a correlation timescale τ .

275 The minimization is repeated four times, twice with $\tau=16$ days (corresponding to a 18-day
 276 Gaussian smoothing window), then twice with $\tau=8$ days (corresponding to a 9-day Gaussian
 277 smoothing window). At each iteration, a new set of *a priori* values for p and for σ_{SSSref} are
 278 computed. During the first iteration, the *a priori* values of SSS_{ref} , $\text{SSS}_{\text{ref}0}$, are taken as the
 279 median of SMOS SSS at the center of its swath over the 2010-2014 period, the *a priori* value

280 of b_{land} is equal to 0, σ_{SSSref} is taken equal to 0.3 pss, and the observation errors are taken
281 equal to the theoretical error associated with the L2 SMOS SSS retrieval, $E_{\text{SSS_L2}}$. SSS_{ref1} and
282 b_{land1} are computed from the p and σ_{SSSref} solutions of the first iteration. During the second
283 iteration, SSS outliers, linked primarily to RFI contamination, are detected using a 3-sigma
284 outlier detection: if the difference between the L2 SMOS SSS and $(\text{SSS}_{\text{ref1}} - b_{\text{land1}})$ is larger
285 than 3 times $E_{\text{SSS_L2}}$, the error on the measurement indicated in the matrix R is artificially
286 increased. SSS_{ref2} and b_{land2} , estimated at the end of step 2, are used to produce the 18 day
287 $\text{SSS}_{\text{K2016}}$ fields. The third and fourth iterations aims at optimizing SSS_{ref} and b_{land} at 9 day
288 resolution. During the third iteration, SSS_{ref2} and b_{land2} are taken as *a priori* parameters, τ is
289 reduced to 8 days and σ_{SSSref} is increased to 0.5 pss resulting in SSS_{ref3} and b_{land3} . The fourth
290 step leading to SSS_{ref4} and b_{land4} is similar to the second one using the same *a priori* values as
291 in step 3. At the end, an additional term is added to the estimated bias, to ensure that the 4-
292 year (2010-2014) median average of $\text{SSS}_{\text{K2016}}$ equals the 4-year median average of ISAS SSS
293 for each latitude and longitude:

$$294 \quad b_{\text{land}}(\phi, \lambda, x_{\text{swath}}, x_{\text{orb}}) = b_{\text{landx}}(\phi, \lambda, x_{\text{swath}}, x_{\text{orb}}) - (\text{med}(\text{SSS}_{\text{ref}}(t, \phi, \lambda)) - \text{med}(\text{SSS}_{\text{ISAS}}(t, \phi, \lambda))) \quad (4)$$

295 with b_{landx} equals to b_{land2} in the case of 18-day corrected field estimates, or to b_{land4} in the
296 case of 9-day corrected fields. Note that the last term of Equation (4) is the only external
297 information used in the entire correction process and does not modify the temporal variability
298 of the observed fields.

299 The K2016 methodology was developed based on SMOS SSS processed with ESA L2OS
300 version 550. In order to provide consistent comparison of the K2016 corrected SSS
301 ($\text{SSS}_{\text{K2016}}$) and the newly corrected dataset presented in this paper ($\text{SSS}_{\text{J2018}}$), $\text{SSS}_{\text{K2016}}$ was re-
302 computed using the L2 SMOS SSS version used for $\text{SSS}_{\text{J2018}}$ i.e. CATDS RE05.

303 3.3 New correction

304 In the present paper, we add a correction for seasonally-varying latitudinal biases, b_{lat} , and we
305 update the land-sea contamination correction, b_{land} , with respect to K2016. b_{lat} and b_{land} are
306 assumed to be additive, so that the corrected SSS, $\text{SSS}_{\text{J2018}}$, is expressed as:

$$307 \text{SSS}_{\text{J2018}}(t, \phi, \lambda, x_{\text{swath}}, x_{\text{orb}}) = \text{SSS}_{\text{ref}}(t, \phi, \lambda) - b_{\text{land}}(\phi, \lambda, x_{\text{swath}}, x_{\text{orb}}) - b_{\text{lat}}(\phi, x_{\text{swath}}, x_{\text{orb}}, m) \quad (5)$$

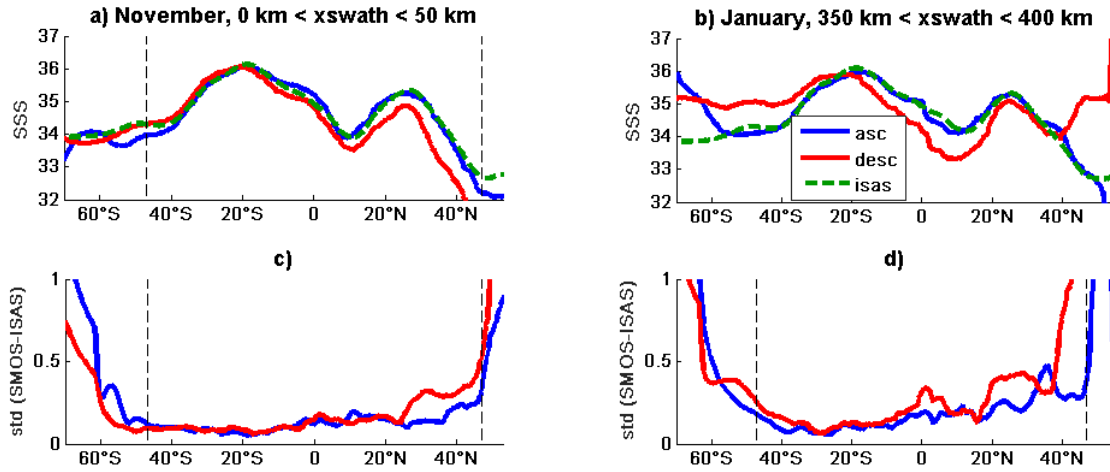
308 where m is the month of the SMOS pass. In a last step, similar to K2016 (equation 4), the 7-
309 year (2010-2016) median average of the corrected SSS is adjusted, for each latitude and
310 longitude, to the 7-year median average of ISAS SSS. The latter is the only quantitative
311 information external to SMOS data used in the correction process and does not modify the
312 temporal variability to the observed fields.

313 3.3.1 Observed seasonally-varying latitudinal biases

314 Further than 1000 km from the coastline, land-sea contamination is not detectable but
315 seasonally-varying latitudinal biases are observed. They mostly depend on x_{swath} , x_{orb} , and the
316 month of the year. The two examples on Figure 2 illustrate the behavior for two extreme
317 cases. In November (Figure 2 a-c), in the center of the swath, SMOS SSS latitudinal
318 variations are very close to ISAS SSS latitudinal variations on ascending orbits but not on
319 descending orbits. In January (Figure 2 b-d), descending orbits at the edge of the swath
320 display strong biases with respect to ISAS while ascending orbits do not. The systematic
321 errors are quite stable from year to year, as indicated by the standard deviation of the 2011 to
322 2016 monthly latitudinal SMOS minus ISAS SSS difference (Figure 2c and d). It is not true
323 at high latitudes where, in most cases, both the mean and standard deviation of the
324 differences are high. This is likely associated with an effect of ice contamination. Systematic
325 errors observed over other ocean basins are similar (see Appendix A1). These systematic

326 errors could originate from imperfect estimates of the sun or galactic noise contributions (Yin
 327 et al. 2013).

328



329 Figure 2 : Two examples of 2011-2016 latitudinal profiles of mean SSS (a; b) and of the standard
 330 deviation of the 2011-2016 monthly differences between SMOS SSS and ISAS SSS (c; d). The
 331 latitudinal means and standard deviations are computed over the Pacific Ocean further than 1200 km
 332 from any coast: green: ISAS, blue: SMOS ascending orbits; red: SMOS descending orbits; a;c)
 333 November; middle of the swath (0-50 km from the center of the swath); b; d) January; edge of the
 334 swath (350-400 km from the center of the swath). Dashed vertical lines indicate 47°N and 47°S.

335

336 3.3.2 Correction for seasonally-varying latitudinal biases

337 b_{lat} is determined separately for ascending and descending orbits, on a monthly basis, and is
 338 assumed to be independent of the longitude and of the year. We neglect interannual variations
 339 that could result from variation in sun activity, as they appear to be an order of magnitude
 340 smaller than the seasonal biases (see section 3.3.1). The correction is estimated from Pacific
 341 Ocean orbits further than 1200 km from continental coasts, in order to avoid land-sea
 342 contamination (b_{land} in Eqn 4 vanishes in this case) and because the northern latitudes in the
 343 Pacific Ocean are less affected by RFI than in the Atlantic Ocean. For x_{swath} locations and
 344 seasons not very affected by RFI at high latitudes, we checked that biases are similar in the

345 Pacific and Atlantic Ocean (see Appendix A1). For each x_{swath} and x_{orb} , twelve sets of
346 monthly latitudinal corrections are estimated by comparing SMOS SSS on contaminated and
347 non-contaminated x_{swath} intervals. The first step is to choose a set of non-contaminated x_{swath}
348 for each month and for each x_{orb} that is used as reference in our correction methodology. The
349 non-contaminated x_{swath} locations are identified from comparisons between 6-year averaged
350 (2011-2016) monthly latitudinal SSS profile at 0.25° resolution derived for each SMOS x_{swath}
351 location and from ISAS as described in Appendix A1. The 2010 year is not considered for the
352 correction estimate as the calibration of the MIRAS instrument was not very stable during the
353 SMOS commissioning period (January to June 2010). The latitudinal profiles of the unbiased
354 SMOS SSS at reference x_{swath} locations determined for a given month, are averaged together
355 to provide a reference SSS latitudinal profile. The latitudinal correction is then estimated as
356 the median difference, per 5° latitude, over the EASE2 grid latitudinal sampling, between the
357 latitudinal profiles of the SMOS SSS at contaminated x_{swath} and the reference SSS latitudinal
358 profile. The SMOS SSS latitudinal profiles differ from the ones based on ISAS SSS at high
359 latitudes (Figure 2). This difference may be explained by remaining RFI contamination in the
360 northern latitudes but also by sea-ice contamination extending equatorward to about 1000 km
361 from the ice edge. On ascending and on most descending latitudinal profiles, large
362 differences between SMOS and ISAS SSS are indeed found poleward of 47°N (see two
363 examples on Figure 2). Some degradation also occurs between 40° and 47°N (see a worse
364 case on Figure 2d). It concerns only a few x_{swath} and months on descending orbits and is
365 therefore rather limited. In the Southern Ocean, in Spring and Summer (Figure 2a-b), large
366 differences only appear way south of 47°S . However, in Winter, especially in the Atlantic
367 Ocean where the ice edge can be as north as 55°S , large differences can reach 47°S . As a

368 compromise, in the following, the correction is applied only to latitudes within 47°S-47°N
369 and results will be limited to this latitudinal range.

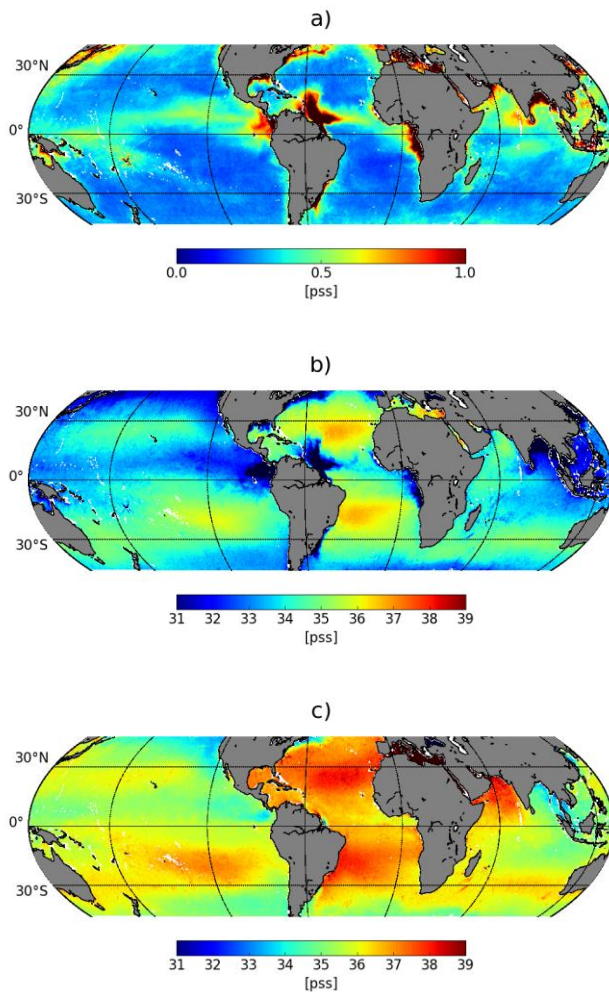
370 *3.3.3 Updated land-sea contamination correction*

371 Before estimating the land-sea contamination correction, we apply seasonally-varying
372 latitudinal corrections determined as described in the previous section. Actually, an imperfect
373 correction of sun and galactic noise effects is expected to generate systematic seasonal biases
374 whatever the distance to the coast.

375 With respect to K2016, we make the following changes:

- 376 • In K2016, the covariance matrix of observation error, R , was filled with
377 E_{SSS_L2} times the Identity matrix. With this approach, the observation errors
378 depend only on the Jacobian of the modelled Tbs with respect to the retrieved
379 parameters, on the a priori error on SMOS Tbs (equal to the SMOS
380 radiometric noise) and on the a priori errors on auxiliary parameters. It does
381 not take into account the actual differences between SMOS observed and
382 modelled Tbs. In most cases, this difference is very close to the radiometric
383 noise (e.g. Yin et al. 2012) and the associated χ (equation 1) normalized by the
384 root mean square of N , χ_N , is close to 1. However, in case of polluted areas
385 (e.g. RFI), χ_N becomes larger than 1. In the updated method, the errors
386 specified in R are set to $(E_{SSS_L2} \cdot \chi_N)$ in order to take observed mismatches
387 between SMOS measured and modelled Tbs into account. In case χ_N is greater
388 than 3, the particular SMOS SSS retrieval is not used in the correction
389 estimate.

- 390
- In K2016, $\sigma_{SSS_{ref}}$ was a fixed value (0.3 pss for $\tau=16$ days; 0.5 pss for $\tau=8$ days). $\sigma_{SSS_{ref}}$ now uses an estimate of the SSS natural variability standard deviation, $\sigma_{SSS_{nat}}$, as derived from SMOS measurements themselves. We derive $\sigma_{SSS_{nat}}$ using a two-step iterative procedure, in which we first compute debiased SSS using $\sigma_{SSS_{ref}}=0.3$ pss for each grid point over the whole period as before, then we recompute debiased SSS using $\sigma_{SSS_{ref}}$ equal to the standard deviation of the debiased SSS from step 1. $\sigma_{SSS_{nat}}$ is taken as the standard deviation of the debiased SSS obtained in step 2. In the open ocean $\sigma_{SSS_{nat}}$ is very close to the value we used in the previous version (0.3 pss) (Figure 3 a), but it is much larger in regions characterized by large inputs of freshwater, such as river plumes (e.g. Amazon plume, Bay of Bengal, Gulf of Mexico), rainy areas (e.g. Intertropical Convergence Zone, eastern and western tropical Pacific fresh pools) and areas characterized by numerous mesoscale features (e.g. Gulf Stream, south east of the Arabian Sea). With this variable $\sigma_{SSS_{ref}}$ we allow SSS_{ref} to vary more temporally in high variability regions through equation (3).
- The biases are derived from 7 years (2010-2016) of SMOS data instead of 4 years in K2016.
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413 Figure 3 : a) SSS variability ($\sigma_{SSS_{nat}}$) derived from 7 years of SMOS filtered and corrected SSS (after
 414 debiasing and filtering): large values are observed in river plumes and in rainy areas (ITCZ, SPCZ. b)
 415 Minimum and c) maximum of the SSS as derived from 18-day CEC LOCEAN that are used in the
 416 mapping of debiased near-real time products (see section 3.4).

417

418 3.4 Mapping methods

419 All SMOS level 3 maps shown in this paper include only SSS retrieved under moderate wind
 420 speed ($3-12 \text{ m s}^{-1}$) and within $\pm 400 \text{ km}$ from the center of the swath.

421 The non-bias corrected SMOS SSS is taken from the CATDS CPDC RE05 default
 422 processing. Daily SMOS SSS retrieved over ascending and descending orbits are combined
 423 to produce level 3 fields (L3P) (CATDS, 2017b). L3P fields over a $25 \times 25 \text{ km}^2$ EASE 2 grid

424 are obtained from SMOS SSS weighted by E_{SSSL2} and averaged within monthly and ~ 10
425 days $25 \times 25 \text{ km}^2$ bins. Measurements are filtered based on SSS retrieval quality flags and
426 avoiding regions suffering from major contaminations on Tb (e.g. galactic noise). A full
427 description of the procedure is available in Vergely and Boutin (2017).

428 Two sets of level 3 bias-corrected SMOS SSS fields are considered in this paper. The same
429 biases are applied (equation 5) but the filtering and mapping methods are different, partly due
430 to operational constraints in CATDS CPDC processing. One set, named L3Q, is processed in
431 near real time by the CATDS CPDC operational chain using a mapping procedure similar to
432 the one applied to L3P products. The other set, named CEC, is processed in delayed time by
433 the LOCEAN expertise center (CEC) of CATDS with a filtering and mapping procedure
434 similar to K2016. Hence, in the result section, changes brought by our new correction with
435 respect to non-corrected SSS will be evaluated by studying L3P and L3Q fields. Changes
436 with respect to K2016 methodology will be evaluated by studying K2016 and CEC fields.
437 The main characteristics of the L3P, K2016, CEC and L3Q processing are summarized in
438 Table 1.

439 Table 1: Summary of the main characteristics of the CATDS products and methods

	Original K2016	L3P	K2016 in this paper	CEC	L3Q
<i>References</i>					
CATDS Name	CEC LOCEAN debias_v0	CPDC L3P	-	CEC LOCEAN debias_v2	CPDC L3Q
Dataset reference	-	CATDS, 2017b	-	Boutin et al. 2017	CATDS, 2017c
<i>Input data processing</i>					
Level 1 data	ESA v5	ESA v6	ESA v6	ESA v6	ESA v6
Level 2 data	ESA v550	CATDS RE05 L2P	CATDS RE05 L2P	CATDS RE05 L2P	CATDS RE05 L2P
Tb outlier sorting	Yes	Yes	Yes	Yes	Yes
<i>Correction Methodology</i>					
Land-sea contamination correction	Yes	No	Yes	Yes	Yes
Latitudinal bias correction	No	No	No	Yes	Yes
Reference period	2010-2014	-	2010-2014	2010-2016	2010-2016
$\sigma_{SSS_{ref0}}$ (18-day)	0.3 pss	-	0.3 pss	$\sigma_{SSS_{nat}}$	$\sigma_{SSS_{nat}}$
Errors in R matrix	E_{SSS_L2}	-	E_{SSS_L2}	$E_{SSS_L2} \cdot \chi_N$	$E_{SSS_L2} \cdot \chi_N$
<i>L3 fields</i>					
Gridding method	Smoothing over R=50 km	Bin average (25 km grid)	Median nearest neighbors (25 km grid)	Median nearest neighbors (25 km grid)	Bin average (25 km grid)
Filtering	$SSS_{ref} \pm 3 \cdot E_{SSS_L2}$	L2 flags	$SSS_{ref} \pm 3 \cdot E_{SSS_L2}$	$SSS_{ref} \pm 3 \cdot E_{SSS_L2} \cdot \chi_N$	$SSS_{max} + 2 \cdot (E_{SSS_L2} \cdot \chi_N)$ & $SSS_{min} - 2 \cdot (E_{SSS_L2} \cdot \chi_N)$

440 *NB : The K2016 processing shown in the present paper has been recomputed from CATDS RE05 processing and using the same filtering as in
441 CEC product

442 We now describe in detail the mapping and filtering procedures for generating L3P and CEC
443 fields:

- 444 • At the CATDS CEC LOCEAN, SSS gridded fields at 25x25 km² resolution,
445 named CEC SSS in the rest of the paper, are built from the combination of
446 debiased SSS which have been filtered from outliers in the course of the biases
447 estimates (see description of steps 2 and 4 in K2016 methodology (section
448 3.2)). Debiased SSS are temporally averaged using a convolution with a
449 Gaussian kernel with a full width of either 9 or 18 days at half maximum. In
450 addition, a median filtering over nearest neighbors is applied to reduce
451 remaining noise. CEC fields are built every 4 days over the 2010-2016 period
452 (Boutin et al. 2017). From the 18-day CEC SSS fields over the 2010-2016
453 period, a minimum (SSSmin) and maximum (SSSmax) SSS is estimated at
454 each grid point (Figure 3b and c) and is used to filter the operational CATDS
455 CPDC products (see below).
- 456 • The CATDS CPDC operational chain provides near-real time data, at the
457 expense of a less-refined data filtering. Biases are estimated as described
458 previously and are applied (equation 4) to daily L3P SSS. For each orbit
459 orientation, we define upper and lower acceptable bounds for daily SSS, based
460 on acceptable absolute values and on SSS natural variability. The upper bound
461 is the minimum value between 40 pss and $SSS_{max} + 2 \cdot (E_{SSS_L2} \cdot \chi_N)$; the lower
462 bound is the maximum value between 5 pss and $SSS_{min} - 2 \cdot (E_{SSS_L2} \cdot \chi_N)$. SSS
463 with $(E_{SSS_L2} \cdot \chi_N)$ larger than 3 pss are filtered out. Level 3 SSS fields, named
464 L3Q in the rest of the paper, are then obtained using a simple average of the
465 SSS weighted by $(E_{SSS_L2} \cdot \chi_N)$ over one month or ~ 10-day. A full description

466 of the procedure is available in Vergely and Boutin (2017). Corrected fields
467 are produced in near-real time at various spatial resolution (CATDS, 2017c).
468 In this paper we use the 25 km resolution products.

469 **4. Comparison to ISAS**

470 Before assessing the new CEC and L3Q SSS fields with products which are not used in the
471 correction method, we compare the corrected and non-corrected SMOS SSS fields with ISAS
472 SSS fields. The comparison is restricted to L3P and L3Q SMOS SSS fields because these two
473 fields are mapped using the same methodology.

474 Even if ISAS SSS is used as a guide to choose the reference x_{swath} in the latitudinal
475 correction, we recall that the only quantitative ISAS information entering our method is the
476 7-year median average of the ISAS SSS fields. The amplitude of temporal variability is
477 independent of ISAS SSS variability. It is thus informative to compare the SSS temporal
478 variability detected by SMOS and ISAS.

479 By construction, the 7-year mean SMOS minus ISAS SSS difference is expected to be small.
480 It is nevertheless non-zero everywhere as we apply a more stringent filtering in the course of
481 the correction estimate than in the L3Q bin average computation. At less than 800 km from
482 coasts, the mean difference between SMOS SSS and ISAS SSS is reduced from -0.5 pss to -
483 0.07 pss (Table 2). The remaining -0.07 pss difference is likely due to the lack of *in situ*
484 measurement in very fresh areas in the vicinity of land (less than 2000m depth) and to non-
485 Gaussian short-scale SSS variability smoothed out by ISAS objective mapping. In addition,
486 SMOS samples the very near surface measurement ($\sim 1\text{cm}$) while most *in situ* measurements
487 used in ISAS analysis are performed close to 5m depth (Boutin et al. 2016). The standard

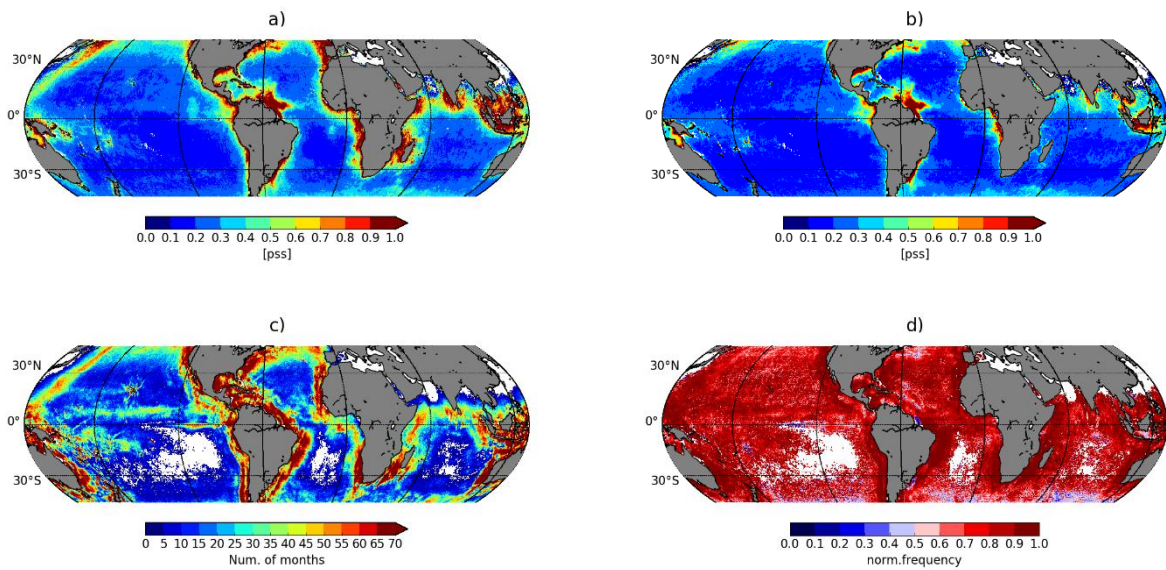
488 deviation of the differences (Figure 4 a & b) is much reduced in the vicinity of continents,
 489 except in river plumes areas but there, it could be an effect of ISAS smoothing.

490 Table 2: Statistics of monthly SMOS SSS (only pixels with more than 8 SMOS SSS retrievals in
 491 ascending and descending orbits are considered) minus ISAS SSS ; 2010-2016

	Number of pixels	Mean bias (SMOS – ISAS)	std(SMOS-ISAS)
45°S-45°N distance to coast <800 km			
SMOS without correction (L3P)	1542456	-0.53	0.63
SMOS with correction (L3Q)	1917346	-0.07	0.49
45°S-45°N distance to coast >800 km			
SMOS without correction (L3P)	5316809	-0.10	0.26
SMOS with correction (L3Q)	5429659	-0.02	0.20

492

493 In order to more precisely quantify the improvements between the L3Q and L3P SMOS SSS,
 494 we detect the number of months, N, between July 2010 and December 2016, for which the
 495 absolute value of the difference between the L3Q and the L3P SSS is larger than a threshold,
 496 T equal to 0.2 pss (Figure 4).



497 Figure 4 : Monthly SMOS SSS compared to monthly ISAS SSS from July 2010 to December 2016.
498 Standard deviation of the differences for a) L3P SMOS SSS; b) L3Q SMOS SSS. c) Number of
499 months with differences between L3P and L3Q SMOS SSS greater than 0.2 pss. d) Frequency with
500 which corrections identified on Figure c) correspond to decreased bias with respect to ISAS (i.e. L3Q
501 SMOS SSS closer to ISAS SSS than L3P SMOS SSS): red color means that the correction improves
502 most of the time; blue color means that the correction degrades most of the time. Blank colors in
503 figures c) and d) mean no change above the 0.2 pss threshold or no data in the L3P version (the
504 comparison is done only for valid L3P SSS).

505

506 As expected, the number of months affected by the correction in a given pixel is higher in the
507 vicinity of continents. In a next step we evaluate how frequently the changes correspond to
508 improvements. For these months significantly affected by the correction, we thus compute the
509 number of months with L3Q SSS closer to SSS_{isas} than to L3P SSS. In most areas, the
510 correction brings monthly SMOS SSS closer to monthly ISAS SSS in 60% to 100% of the
511 cases (Figure 4d). This is not true in the Gulf Stream region close to 40°N, probably because
512 ISAS is not able to reproduce SSS mesoscale variability recorded by SMOS (Reul et al.
513 2014b), nor close to 10°S in the western Pacific Ocean and in the middle Indian Ocean, two
514 regions strongly affected by RFI. It is nevertheless remarkable that other regions affected by
515 RFI such as the north-western Pacific Ocean are improved most of the time, suggesting that
516 the RFI disturbances there are sufficiently stable in time to be partly mitigated by our
517 correction.

518 **5. Assessment of the corrected fields**

519 **5.1 Comparison to SMAP SSS**

520 SMAP CAP SSS has a similar spatial resolution as SMOS CEC SSS, SMAP passes are at
521 6AM and 6PM local time like SMOS, so that the spatio-temporal sampling of SMOS and
522 SMAP are really comparable. SMAP SSS are much better filtered from RFI, hence providing
523 an unprecedented monitoring of main river plumes in the vicinity of continents. On the other

524 hand, SMAP Tb calibration is more challenging than for AQUARIUS (Fore et al. 2016a), so
525 that the absolute value of SMAP SSS may remain imprecise to about 0.2 pss in low to mid-
526 latitudes of the open ocean, but biases up to 0.45 pss, which origin remains unclear, have also
527 been reported during certain periods in the Bay of Bengal (Tang et al. 2017, their Figures 5
528 and 12 respectively). It is out of the scope of this paper to study SMAP CAP SSS biases. We
529 focus the investigation on the SSS variability measured by both sensors.

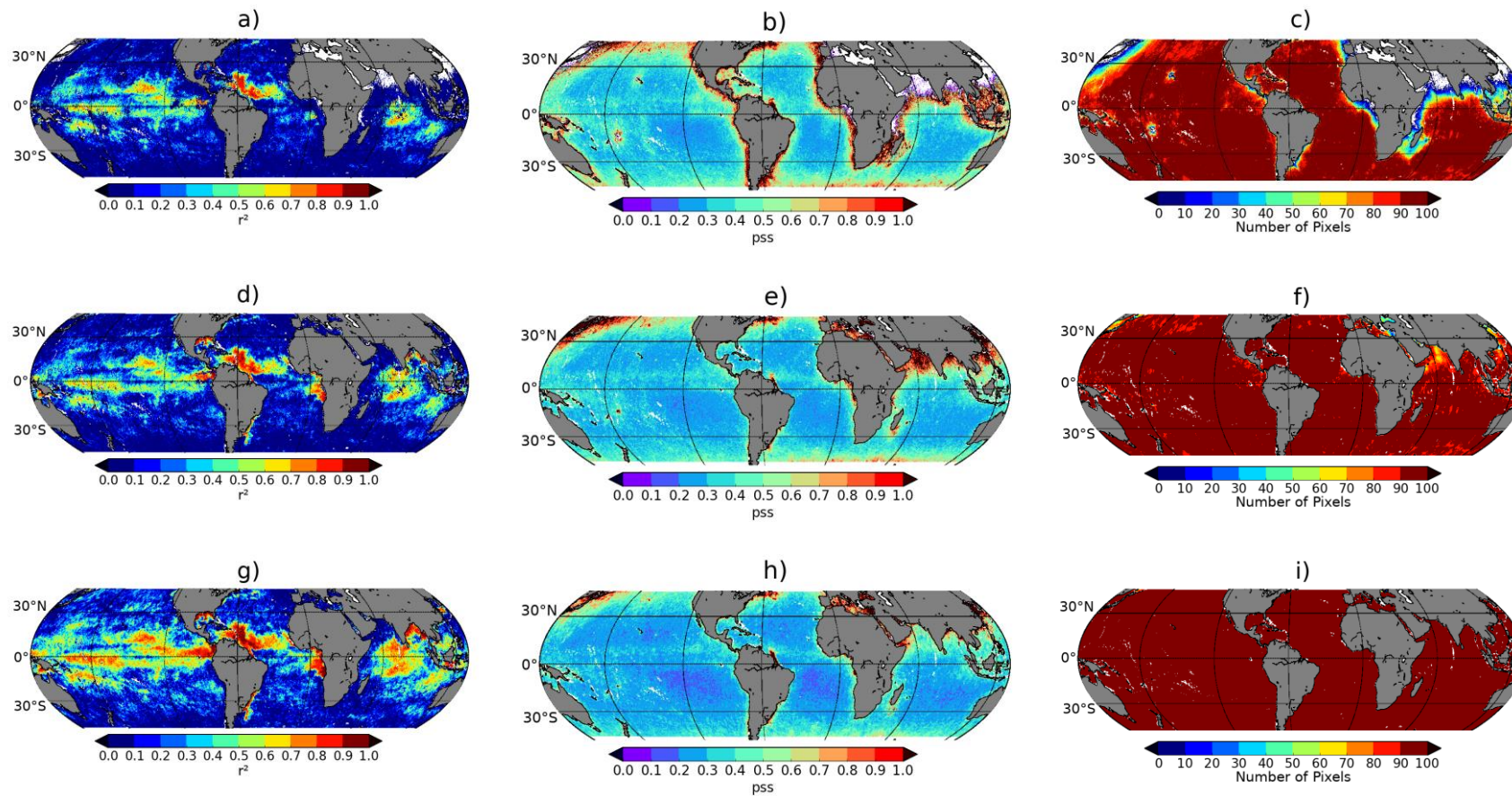
530 The various SMOS SSS fields are compared with SMAP SSS fields over the period between
531 April 2015 and December 2016. Two ranges of temporal resolutions are considered, one
532 close to one week, another one close to 18 days. The choices of the average durations are
533 guided by the satellite repetitive orbit cycle and sub-cycle in order to get, for each instrument,
534 the most even spatial coverage. In the following, for simplicity, 10-day L3P, L3Q and 9-day
535 CEC SMOS SSS fields compared with 8-day SMAP SSS fields are referred to as ‘weekly’
536 comparisons. Comparisons between 18-day SMOS SSS fields from K2016 and CEC
537 processing with 16-day SMAP SSS are referred to as ‘bi-weekly’ comparisons. We always
538 compare fields centered on the same time (at ± 12 hours), in order to minimize the effect of
539 the different durations.

540 At global scale and ‘weekly’ resolution (Figure 5), standard deviations of the SMOS minus
541 SMAP SSS differences are reduced in the vicinity of large continents and of RFI sources (e.g.
542 Fiji island, Hawaiï island, south of Madagascar) from more than 0.6 pss before correction
543 (L3P, Figure 5 b) to less than 0.4 pss after correction (L3Q, Figure 5 e; CEC, Figure 5 h)
544 becoming comparable to open ocean values. In addition, the number of valid pixels is
545 increased, especially in the vicinity of large continents (Figure 5 c, f and i). The improvement
546 is better with CEC fields than with L3Q fields due to the improved filtering. The square of
547 the Pearson correlation coefficient, r^2 , is as good or better when considering L3Q instead of

548 L3P SSS (Figure 5 d and a). r^2 indicates the proportion of variance contained in SMAP SSS
549 that is explained by SMOS SSS. Hence, if the natural SSS variability is low relatively to the
550 satellite SSS noise, r^2 is expected to remain small whereas if the natural variability is large
551 compared to the satellite SSS noise, r^2 is expected to increase. This is what is observed. r^2 is
552 in particular increased from less than 0.5 to above 0.5 in the north of the Gulf of Mexico, in
553 the Gulf of Guinea, in the Bay of Bengal (no valid measurements exist there in the L3P
554 processing) and to the north of the Amazon plume. The improvement is even larger when
555 considering CEC SSS (Figure 5 i) instead of L3Q SSS due to the different filtering and
556 mapping procedures: then, r^2 in the above-identified regions becomes higher than 0.8. These
557 large values of r^2 correspond to regions of large natural SSS variability, much larger than the
558 SSS noise, as will be shown below. On the other hand, in most regions of the open ocean
559 where SSS variability is on the same order or smaller than SSS noise, r^2 remains small. If
560 instead of considering all the available SMOS SSS pixels (Figure 5), the comparison is made
561 using only SSS pixels available in every SSS products (Appendix A2), the standard
562 deviations of the differences are comparable or slightly lower in regions polluted by RFI but
563 this is at the expense of many measurements which contain meaningful variability as
564 indicated by high r^2 on Figure 5.

565 Figure 5 indicates a clear improvement of L3Q and CEC fields with respect to L3P fields. In
566 comparison with K2016 (not shown), standard deviations of the SMOS CEC 18-day SSS
567 minus SMAP SSS differences are very similar (within +/-0.05 pss) in major parts of the
568 ocean, but in the regions identified above where r^2 became larger than 0.8, they are locally
569 improved by more than 0.5 pss; these regions are further studied below. We observe some
570 degradation (standard deviations of the SMOS minus SMAP SSS differences increase by up
571 to 0.3 pss) in some regions (the Mediterranean Sea, the Arabian Sea, the north-western part of

572 the Pacific Ocean) strongly affected by RFI and for which L3P fields do not provide valid
573 measurements. In these regions, however, r^2 obtained with both CEC and K2016 versions
574 remain less than 0.2.



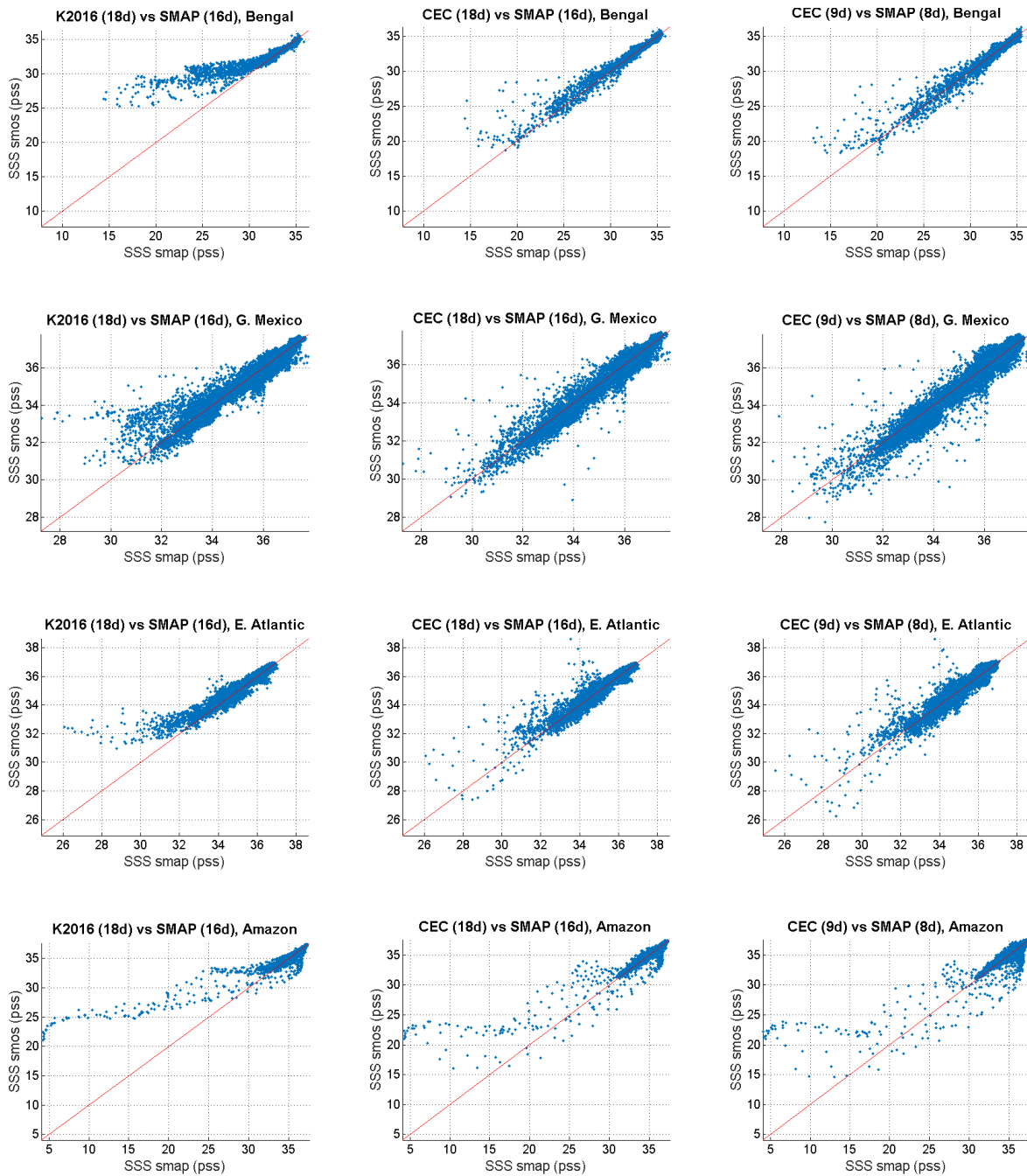
575 Figure 5: Comparison of SMOS and SMAP 'weekly' SSS: (a, d, g) r^2 , (b, e, h) standard deviation of the differences, (c, f, i) number of pixels used in the
 576 comparisons. (a, b, c) 10-day L3P SMOS SSS, (d, e, f) 10-day L3Q SMOS SSS, (g, h, i) 9-day CEC SMOS SSS. Same indicators but when considering only
 577 the pixels available in the four products are presented in Appendix A2.

578 We now detail more quantitatively the comparisons between SMAP and SMOS K2016 / CEC
579 SSS in four regions with very variable salinities (Bay of Bengal; Gulf of Mexico; Eastern
580 Tropical Atlantic Freshwater Pools; Amazon plume), identified on Figure 5 as having a high
581 r^2 after correction and already presented in the introduction. Contamination by RFI is very
582 strong in the Bay of Bengal and in the Eastern Tropical Atlantic Freshwater Pools (see very
583 small number of valid L3P measurements (Figure 5c)) and moderate in the two other regions.
584 The coast geometry is very different in these 4 regions: the Bay of Bengal and Gulf of
585 Mexico are semi-enclosed ocean areas so that land-sea contamination of an ocean pixel is
586 expected to come from more than 290° of different directions, while the other two regions are
587 surrounded in more than 180° around the points by the ocean.

588 As shown on the maps of Figure 1 and on the corresponding scatter plots (Figure 6, two left
589 columns), the new SMOS CEC SSS captures fresh SSS patterns much closer to the ones in
590 SMAP SSS and remains close to SMAP SSS in other SSS ranges. For instance, in the Bay of
591 Bengal (Figure 1 a-c), the comma-shaped fresh SSS around 85°E and 17°N corresponds to
592 fresh water originating from the Ganges-Brahmaputra trapped in an eddy (Fournier et al.
593 2017) and the one near 15°N , 95°E , to the Irrawady discharge. In the Gulf of Mexico (Figure
594 1 d-f), the horseshoe-shaped fresh SSS coming from Texas flooding and transported by ocean
595 currents (Fournier et al. 2016) is better captured, as well as the Eastern Tropical Atlantic
596 Freshwater Pools (Figure 1 g-i) and the Amazon and Orinoco plumes (Figure 1 j-l). The
597 statistics of the SMOS SSS minus SMAP SSS differences are reported in Table 3. The
598 median of the differences between SMOS and SMAP SSS and $\text{std}(\text{SMOS}-\text{SMAP})$ are
599 decreased in all regions. The L1 norm estimator std1 (equal to $\text{median}(\text{abs}(x-\text{median}$
600 $(x)))/0.67$, and that is less affected by the outliers than std), and r^2 are clearly improved in the
601 Bay of Bengal; the improvement is less in other regions because of the larger proportion of

602 higher SSS values, and less stringent noise filtering at moderate SSS. For SSS less than 25ps
603 in the Amazon plume and in the Bay of Bengal, SMOS SSS remains in some cases higher
604 than SMAP SSS.

605



606 Figure 6 : Scatter plots of SMOS corrected fields versus SMAP SSS on the 4 regions and fresh events
 607 periods illustrated on Figure 1: first line: Bay of Bengal; 2nd line: Gulf of Mexico; 3rd line : Eastern
 608 Tropical Atlantic Freshwater Pools; 4th line : Amazon plume. First column: SMOS K2016 SSS;
 609 second column: SMOS 18-day CEC SSS; last column: SMOS 9-day CEC SSS.

610 Table 3: Statistics of (SMOS SSS – SMAP SSS) corresponding to scatter plots of Figure 6

K2016 (18d) – SMAP (16d)				CEC (18d) - SMAP (16d)				CEC (9d) - SMAP (8d)			
median	std	std1	r ²	median	std	std1	r ²	median	std	std1	r ²
<i>Bay of Bengal</i>											
0.10	2.00	0.56	0.85	0.02	0.77	0.38	0.95	-0.03	0.81	0.41	0.95
<i>Gulf of Mexico</i>											
-0.02	0.50	0.29	0.90	-0.06	0.39	0.30	0.94	-0.06	0.45	0.37	0.93
<i>Eastern Tropical Atlantic Freshwater Pools</i>											
0.04	0.42	0.23	0.92	0.01	0.39	0.23	0.91	0.05	0.44	0.29	0.90
<i>Amazon Plume</i>											
-0.14	1.00	0.20	0.83	-0.13	0.82	0.20	0.85	-0.11	0.87	0.25	0.80

611

612 The time series of the indicators reported in Table 3 are plotted for each case study region on
 613 Figure 7 to Figure 10. ‘Bi-weekly’ indicators confirm that during periods with large SSS
 614 variability detected by SMAP (black line on top right figures) and low SSS (black line on top
 615 left figures), r² (bottom left figures) and std(SMOS-SMAP) (bottom right figures) are
 616 systematically improved for CEC with respect to K2016: r² becomes larger than 0.9 except in
 617 the Amazon plume (~0.8). This is not systematically the case during periods with low SSS
 618 variability and salty SSS when sometimes K2016 performs slightly better in term of r² and
 619 std(SMOS-SMAP): this is likely because our method neglects seasonal variation of $\sigma_{SSS^{nat}}$.
 620 Nevertheless, the worse r² obtained with CEC SSS relative to K2016 SSS correspond in
 621 reality to weak degradations of the corrected SSS, given the noise in both SMOS and SMAP
 622 SSS and the low SSS variability; on the contrary, the improved r² correspond to very
 623 significant improvements in the detection of fresh SSS in highly variable regions.

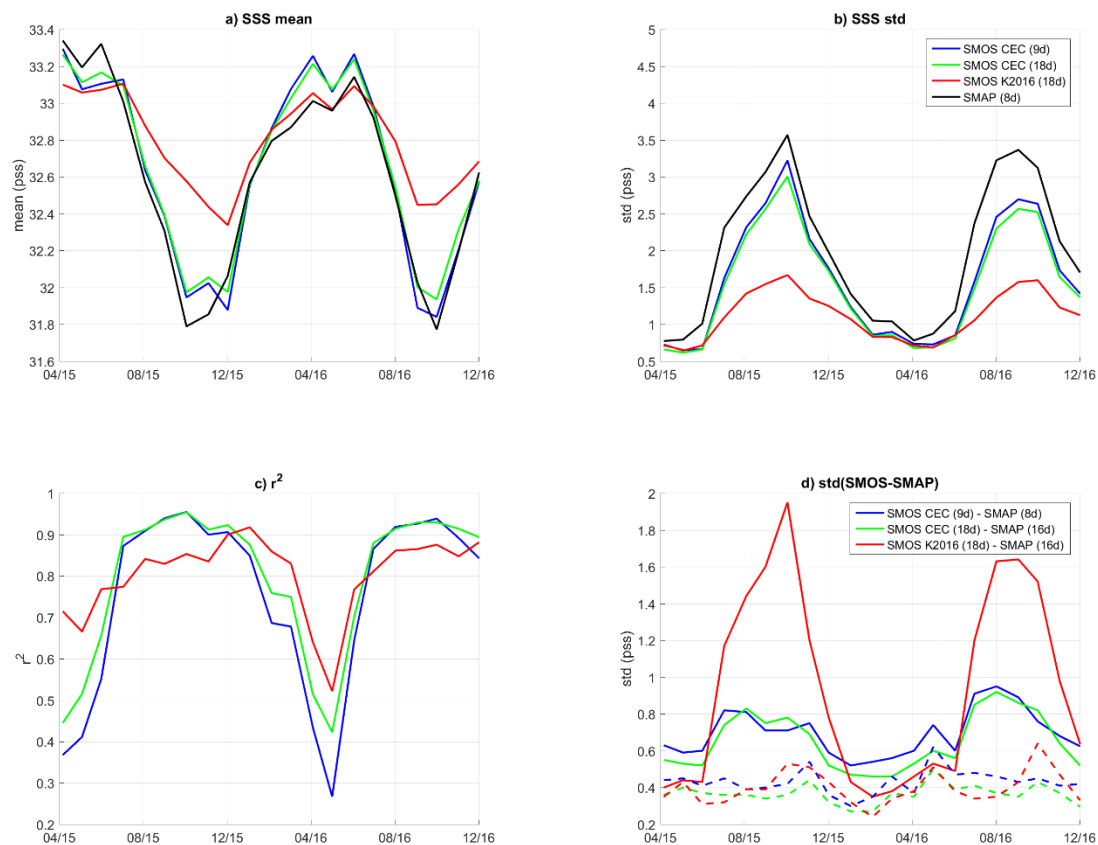
624 std1 (dashed lines on bottom right figures) is on the order of 0.3 pss, which is consistent with
625 a noise on each ‘bi-weekly’ satellite SSS product on the order of 0.2 pss. Tang et al. 2017
626 found a standard deviation of 0.17 pss between monthly SMAP and moorings SSS over the
627 open ocean, a value comparable to the one we find with monthly-100 km SMOS-ship
628 comparisons that will be described in section 5.2.

629 The standard deviations of the SSS (SSS std (top right figures)) obtained with CEC products
630 are much closer to the SSS std of the ‘weekly’ SMAP products than the ones obtained with
631 the ‘bi-weekly’ K2016 products during highly variable periods; during periods with low
632 variability all SSS std are very close to each other. Nevertheless, except in the Gulf of
633 Mexico, SSS std are slightly larger for SMAP SSS than for CEC SSS. This possibly indicates
634 that our method still underestimates SSS natural variability in some cases. This may also be
635 due to the adjustment to the 7-year median of ISAS SSS: for instance, the fresh water along
636 the Brazil coast at 50°W-5°N is observed as a continuous tongue in the SMAP SSS map
637 (Figure 1l), and as a discontinuous one in the SMOS SSS maps (Figure 1j - 1k) which is due
638 to a discontinuity in the 7-year median of ISAS SSS (not shown). Further validation with
639 external ground truth of SMOS and SMAP SSS would be necessary to confirm the origin of
640 this discrepancy.

641 It is also instructive to consider the statistics obtained with ‘weekly’ products (Figure 6, right
642 column and Figure 7 to Figure 10, blue lines) as SSS during periods with large freshwater
643 discharges can be very variable at short time scales. In most cases, r^2 and std(SMOS-SMAP)
644 obtained with ‘weekly’ products are slightly worse than the ones obtained with ‘bi-weekly’
645 products, because the noise is higher in the ‘weekly’ products but it nevertheless remains
646 small relative to the natural variability. It is only in Fall, in the Bay of Bengal, when the SSS
647 std is larger than 2.5 pss, that the r^2 and std(SMOS-SMAP) with the ‘weekly’ CEC product

648 are comparable to the r^2 and $\text{std}(\text{SMOS-SMAP})$ with ‘bi-weekly’ CEC product, the noise
 649 becoming negligible relative to the SSS natural variability. Hence, in very variable regions,
 650 the ‘weekly’ CEC maps could improve the monitoring of fresh spatial structures varying
 651 within 18 days.

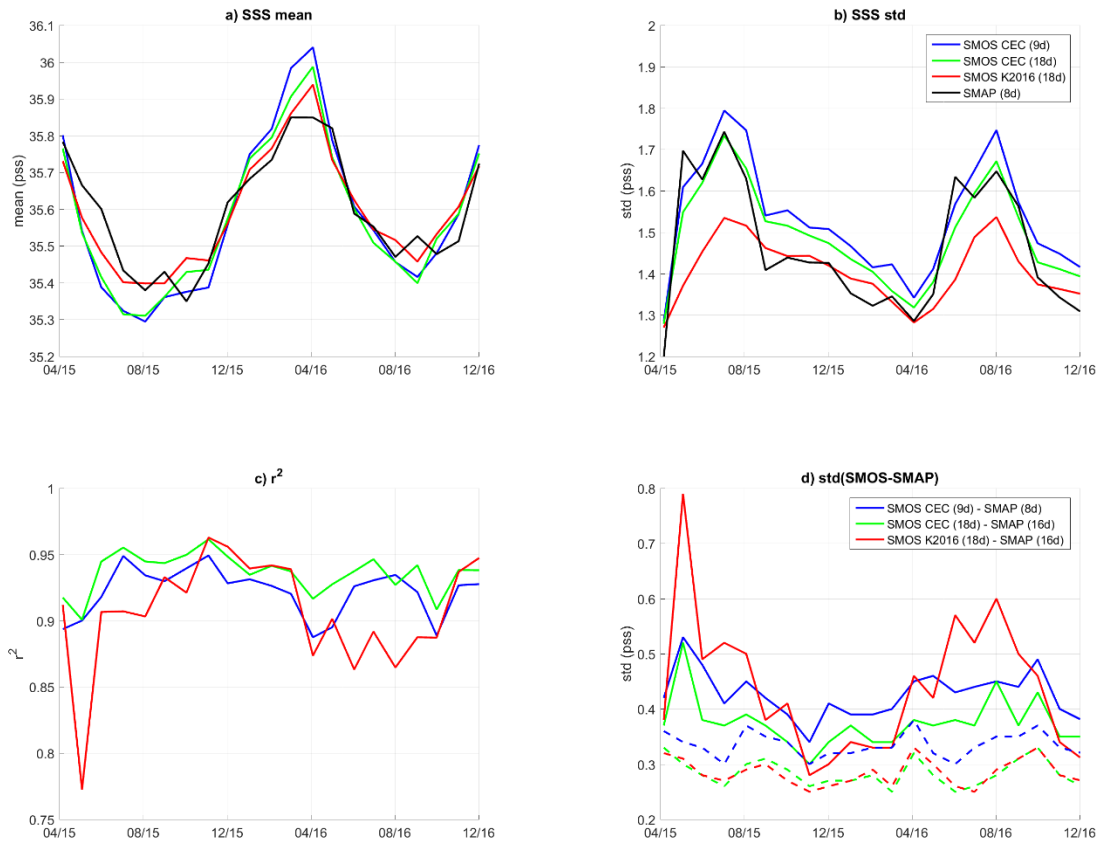
652



653 Figure 7: Time series of statistical parameters computed over the Bay of Bengal case study area, April
 654 2015 to December 2016: a) mean SSS; b) SSS standard deviation; c) square of the Pearson correlation
 655 coefficient (r^2) between SMOS and SMAP SSS; d) Standard deviation of the SMOS minus SMAP
 656 SSS differences (plain line) using L1 norm (dotted line). ‘Weekly’ SMOS CEC(blue), ‘bi-weekly’
 657 SMOS CEC (green), ‘bi-weekly’ SMOS K2016 (red), ‘weekly’ SMAP (black).

658

659

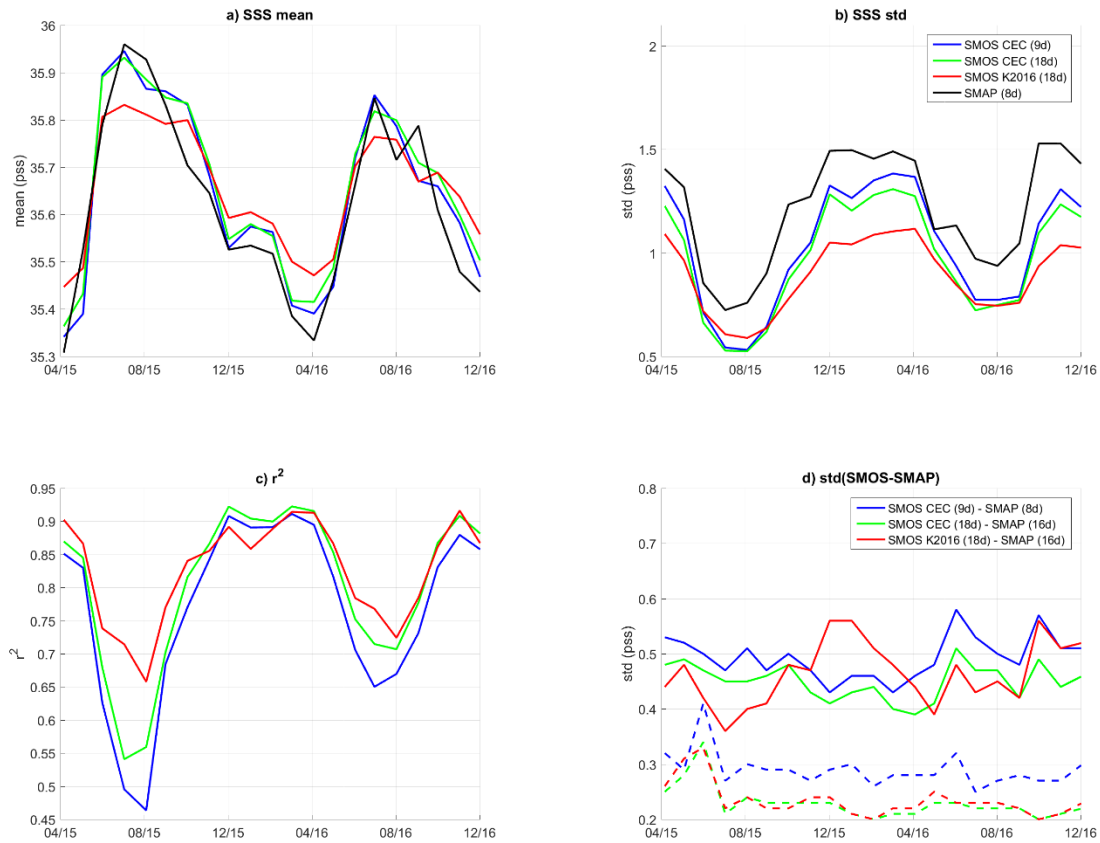


660

661 Figure 8: Time series of statistical parameters computed over the Gulf of Mexico case study area,
 662 April 2015 to December 2016: a) mean SSS; b) SSS standard deviation; c) square of the Pearson
 663 correlation coefficient (r^2) between SMOS and SMAP SSS; d) Standard deviation of the SMOS minus
 664 SMAP SSS differences (plain line) using L1 norm (dotted line). ‘Weekly’ SMOS CEC(blue), ‘bi-
 665 weekly’ SMOS CEC (green), ‘bi-weekly’ SMOS K2016 (red), ‘weekly’ SMAP (black).

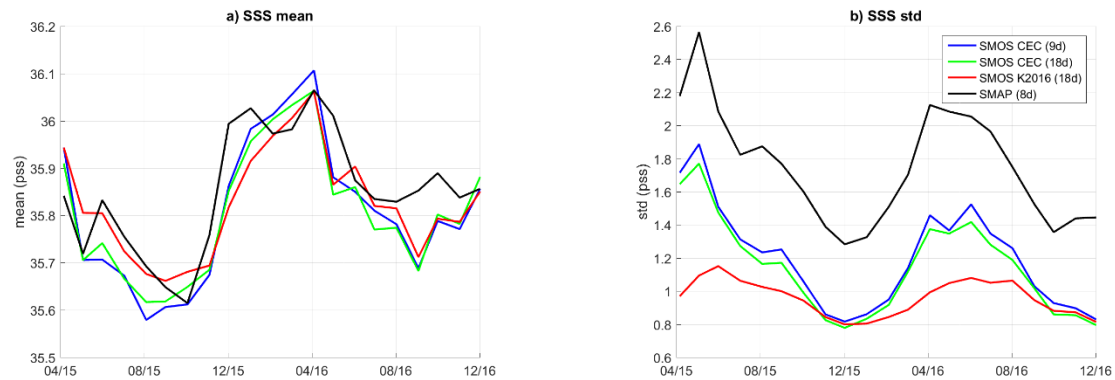
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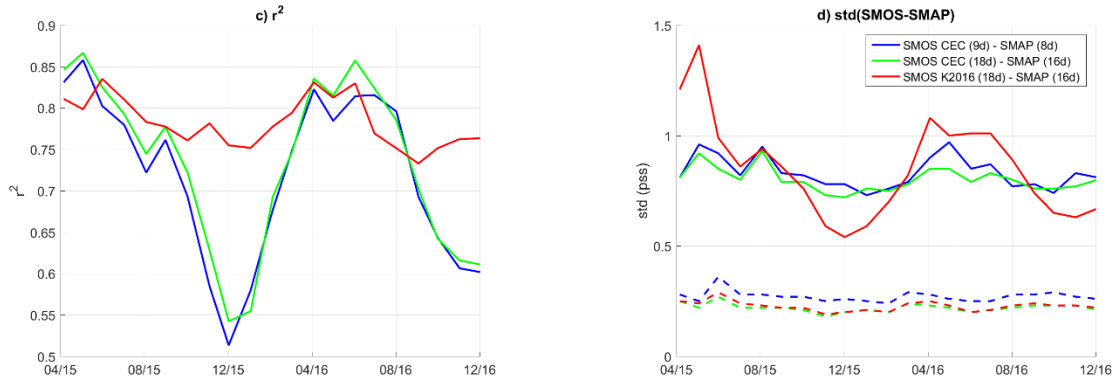
667



668 Figure 9: Time series of statistical parameters computed over the Eastern Tropical Atlantic Freshwater
 669 Pools case study area, April 2015 to December 2016: a) mean SSS; b) SSS standard deviation; c)
 670 square of the Pearson correlation coefficient (r^2) between SMOS and SMAP SSS; d) Standard
 671 deviation of the SMOS minus SMAP SSS differences (plain line) using L1 norm (dotted line).
 672 ‘Weekly’ SMOS CEC(blue), ‘bi-weekly’ SMOS CEC (green), ‘bi-weekly’ SMOS K2016 (red),
 673 ‘weekly’ SMAP (black).

674





675 Figure 10: Time series of statistical parameters over the Amazon plume case study area, April 2015 to
 676 December 2016: a) mean SSS; b) SSS standard deviation; c) square of the Pearson correlation
 677 coefficient (r^2) between SMOS and SMAP SSS; d) Standard deviation of the SMOS minus SMAP
 678 SSS differences (plain line) using L1 norm (dotted line). ‘Weekly’ SMOS CEC(blue), ‘bi-weekly’
 679 SMOS CEC (green), ‘bi-weekly’ SMOS K2016 (red), ‘weekly’ SMAP (black).

680

681 5.2 Comparison to ship SSS

682 Merchant ship transects are used to get ground-truth measurements at various distances from
 683 the coast. With respect to SMAP SSS, ship SSS is less uncertain but its spatio-temporal
 684 sampling and resolution is very different from SMOS SSS.

685 In a first step, we consider the scales of SSS variability captured by the various SMOS SSS
 686 versions and by the ship SSS far from coast. We focus on the subtropical region (50°W -
 687 20°W ; 15°N - 40°N) of the north Atlantic in 2013. This region is chosen because it is very
 688 well covered by regular ship tracks spaced by approximately one month, it is strongly
 689 impacted by the seasonally-varying latitudinal biases, it is characterized by mesoscale
 690 variability that is not resolved by the ISAS analysis (Kolodziejczyk et al. 2015; Sommer et al.
 691 2015), and it is not used for choosing the reference dwell lines of the seasonal latitudinal
 692 correction. We analyze below the density spectra (Figure 11, top) and the squared coherence
 693 (Figure 11, bottom) of ISAS, of 10-day L3P and L3Q, of 18-day CEC with ship SSS. Our
 694 analysis focuses on wavelengths between 1400 km and 150 km, in order to minimize the

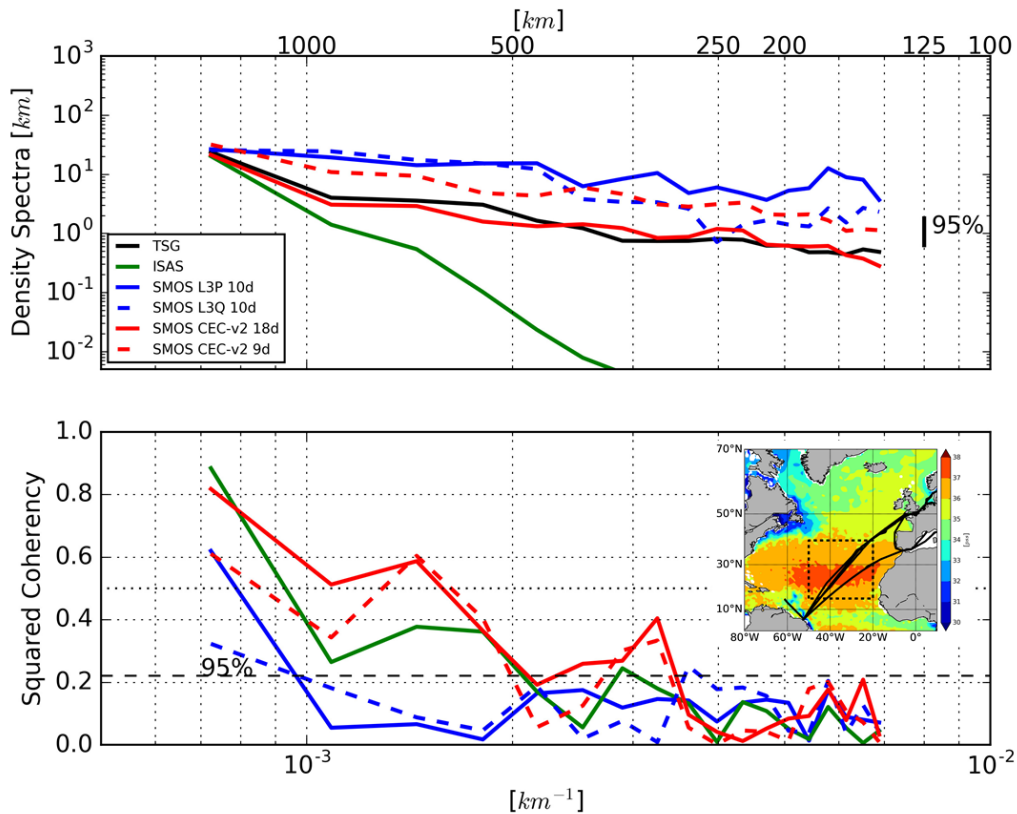
695 influence of the limited length of the selected ship tracks (about 2800 km) and of scales
696 resolved by SMOS (50 km). We recall here that coherence quantifies the correlation between
697 two quantities for a given wavenumber band. While at 1400 km wavelength ISAS and ship
698 SSS are very coherent, due to the subsampling of Argo measurements (1 profile per 10 days
699 per $3^\circ \times 3^\circ$) and to the horizontal scales of the optimal interpolation (~ 300 km), the ISAS
700 spectrum (Figure 11, top, green line) dramatically drops as well as its squared coherence
701 (Figure 11, bottom) for shorter wavelengths.

702 Whatever the wavelength, the density spectra (Figure 11 top) of the 18-day CEC SSS is
703 closer to the one of the ship SSS than the 10-day L3P and L3Q. The density spectrum of the
704 9-day CEC SSS is very similar to the one of the 10-day L3Q for spatial wavelengths between
705 150 and 330 km. For longer wavelengths, the density spectrum of 9-day CEC SSS is
706 intermediate between the 18-day CEC and the 10-day L3Q, indicating that at large scale,
707 where the temporal variability between 9 days and 18 days is expected to be small, the
708 different filtering and gaussian mapping applied to CEC products is more effective at
709 reducing the SMOS SSS noise than the min/max filtering and bin average mapping applied to
710 L3Q products. Up to 150 km, the density spectra of the 18-day CEC and ship SSS are in
711 remarkable agreement. This is in fact quite surprising because the MIRAS and TSG
712 instrumental noises are not expected to lead to the same SSS errors and because the temporal
713 sampling of SMOS (about 8 passes over 18 days) and of ship (\sim one transect per month) are
714 very different. Given the expected noise in level 2 SMOS retrieved SSS (0.6 pss), the median
715 filtering over nearest neighbor pixels at 25 km distance in the SMOS CEC product, and the
716 SMOS temporal sampling, the noise on the 18-day CEC SSS is expected to be on the order of
717 0.15 pss. Noise on individual ship SSS is estimated to be less, on the order of 0.08 pss (Alory
718 et al. 2015) but the temporal sampling is worse. Hence, the similarity in the two density

719 spectra suggests that the SSS error due to instrumental noise that is larger in SMOS than in
720 ship SSS, is compensated, over 18 days, by the better temporal sampling in SMOS than in the
721 ship data.

722 The squared coherence (Figure 11 bottom) of the 18-day CEC SSS is almost at the same level
723 (above 0.7) as the squared coherence of ISAS SSS at a 1400 km wavelength, and is always at
724 a higher and significant level for wavelengths up to 300 km. The 18-day CEC squared
725 coherence decreases with decreasing spatial wavelengths. This can be due to instrumental
726 noise, to the different temporal sampling of SMOS and ship and to spatially moving
727 structures within 18 days. The 18-day CEC squared coherence becomes not significant at
728 95% for wavelengths smaller than 300 km. Considering that at least 3 samples are necessary
729 to resolve a 300 km wavelength signal, this result indicates that 18-day CEC and ship SSS
730 capture similar scales of variability up to about 100 km. This is rather consistent with the
731 spatial integration of SMOS measurement (50 km) in addition to the median filtering over
732 nearest neighbor pixels at 25 km applied on CEC products.

733 The level of coherence is much less both with the 10-day L3P and L3Q products, due to a
734 lower signal to noise ratio.



735

736 Figure 11 : Top: Density spectra; Bottom: Coherence between ship SSS and SMOS or ISAS SSS. The
 737 spatial frequency (1/wavelength (km)) is indicated below the bottom plot, whereas the corresponding
 738 wavelengths (km) are indicated above the top plot. Vertical dashed lines correspond to spatial
 739 frequencies regularly spaced in logarithmic coordinates. Northern subtropical Atlantic (see box on the
 740 color map) in 2013. Ship SSS measured on regular merchant ships transects (14 regular transects in
 741 2013) (black), ISAS SSS (green), 10-day SMOS L3P (blue line), 10-day SMOS L3Q (dashed blue
 742 line), 18-day SMOS CEC (red line), 9-day SMOS CEC (red dashed line).

743

744 We will now investigate global statistics for the difference between SMOS and ship SSS.

745 Consistent with the weak coherence observed between the ship SSS and the 10-day L3P and

746 L3Q SSS, 9-day CEC and 10-day L3P or L3Q are of worse quality than the 18-day CEC and

747 monthly L3P and L3Q fields. Hence, in the following comparisons, we only consider

748 monthly L3P, L3Q and 18-day CEC fields. Ships provide within a few hours numerous

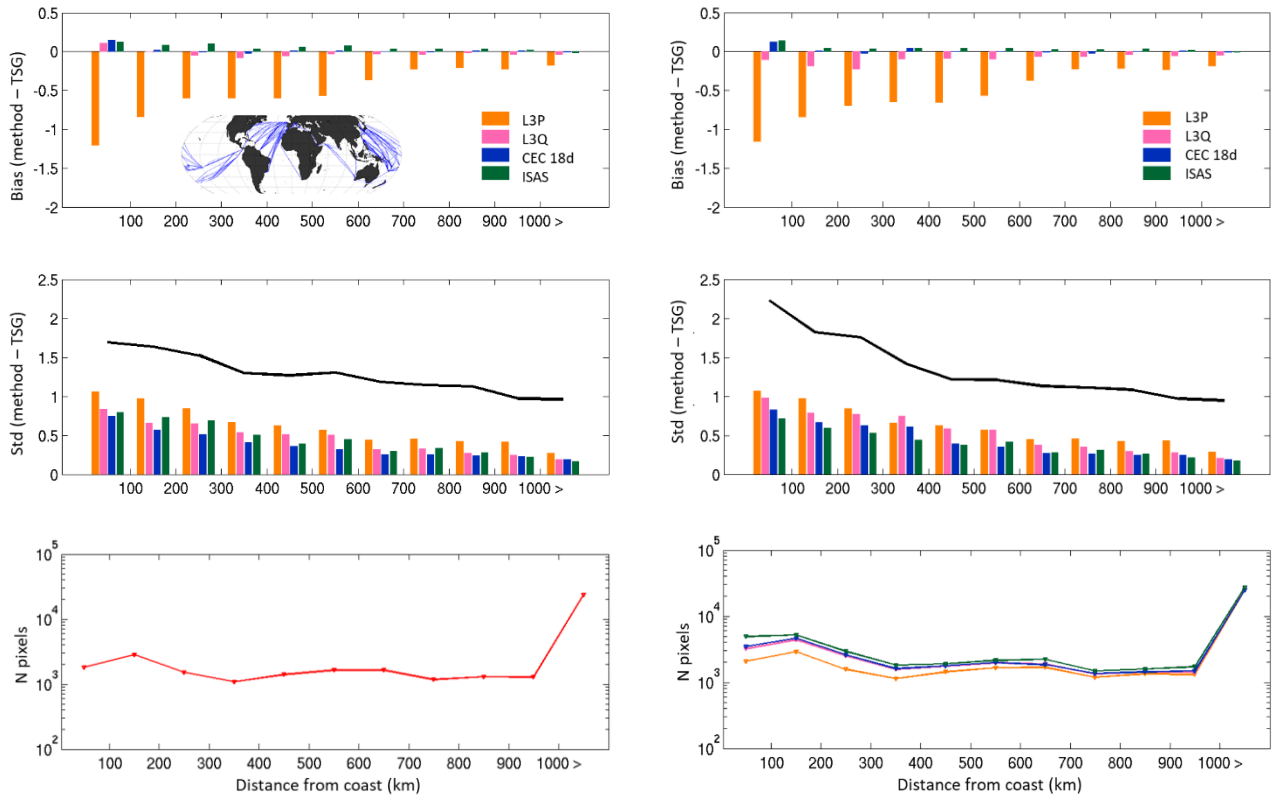
749 measurements within a satellite pixel. In the following, the SSS variability sampled by each

750 ship and by SMOS is smoothed over +/-50 km. This smoothing cannot be identical for the

751 two platforms because of their different spatio-temporal sampling. SMOS observes a surface
752 (two dimensions) whereas ship measurements are taken along a route (one dimension).
753 However, this method is expected to reduce the misfit between in situ and SMOS
754 observations coming from the spatial subsampling of SSS variability within a satellite pixel
755 by point measurements (Boutin et al. 2016). Mean differences and standard deviation of the
756 differences between SMOS SSS and ship SSS, named Std(SMOS-Ship) in the following, are
757 shown in Figure 12, as a function of the distance from the coast. Two sets of comparisons are
758 presented, involving either only SMOS pixels common to L3P fields (i.e. the ones the less
759 affected by RFI pollution) (Figure 12, left) or all valid pixels for each product (Figure 12,
760 right). The number of valid pixels is increased by nearly a factor 2 when approaching the
761 coast with L3Q and CEC fields with respect to L3P fields (Figure 12, bottom right). The
762 mean differences (Figure 12, top) obtained with monthly L3P are less than -0.5 pss up to 600
763 km from the coast. The mean differences with CEC fields are systematically less than 0.05
764 pss (in absolute value), further than 100 km from the coast, a very clear improvement with
765 respect to L3P. Similar improvement is observed with monthly L3Q when considering only
766 pixels common to L3P (Figure 12, left); the mean differences are, however, slightly more
767 negative when considering all valid pixels, indicating that the filtering is more efficient at
768 removing SSS outliers in CEC than in L3Q processing. At less than 100 km from the coast,
769 the mean difference with CEC product reaches 0.15 pss, a value close to the mean difference
770 between ISAS and ship SSS, consistent with local overestimate of the long term SSS mean by
771 ISAS, as suggested by SMOS and SMAP SSS comparisons in the Amazon plume along the
772 coast (Figure 1 and section 5.1). However, the scatter plot (not shown) between CEC and ship
773 SSS in the region of the Amazon plume is very scattered at low SSS and it was not possible
774 to identify a systematic bias.

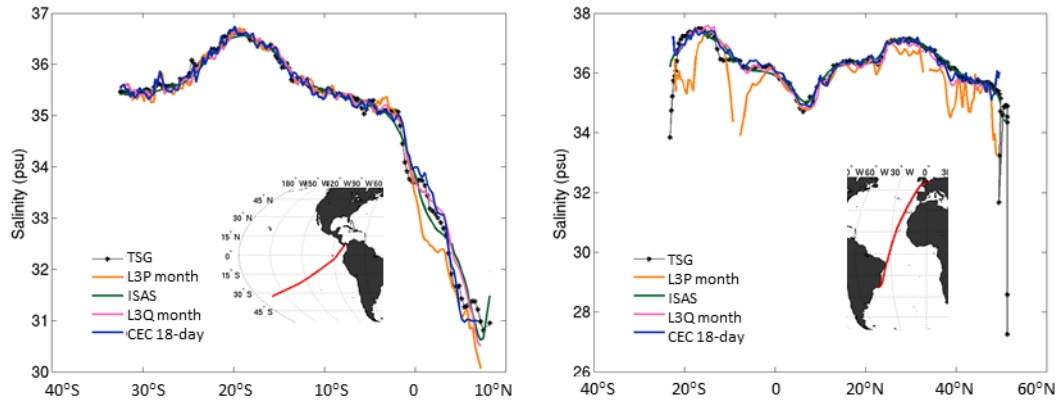
775 Std(SMOS-Ship) is clearly improved whatever the distance to the coast. Further than 1000
776 km from the coast, it is equal to 0.20 pss with CEC, 0.21 pss with L3Q while it is 0.24 pss
777 with L3P. It increases when approaching the coast: in the 100-200 km class and when
778 considering all valid pixels, it equals to 0.64 pss with CEC, 0.69 pss with L3Q, 0.78 pss with
779 L3P. When approaching the coast, the ship SSS variability is increased too (black lines on
780 Figure 12, middle right) and it is likely that part of the Std(SMOS-Ship) induced by the
781 different temporal sampling of SMOS and ships increases when approaching the coast.
782 Consequently, while Std(SMOS-Ship) is increased by a factor 3 between 100-200 km and
783 further than 1000 km from the coast, the signal to noise ratio is increased by only a factor 1.5
784 between these two classes. Similarly, Std(SMOS-Ship) and ship SSS std are lower when
785 considering only L3P pixels than when considering all valid pixels, so that the signal to noise
786 ratio in both cases remains similar. When considering all valid pixels (Figure 12, middle
787 right), the std difference obtained with ISAS remains slightly less than the ones obtained with
788 CEC and L3Q SSS in all the classes considered except for the range from 500 to 900 km
789 (Figure 12, middle right). On the contrary, when considering only pixels common to L3P,
790 (Figure 12, middle left), CEC SSS better captures SSS variability than ISAS in all the classes
791 up to 900 km from a coast. Two typical ship comparisons illustrate these features. On Figure
792 13 (left), a transect in the South Pacific is quite well sampled by L3P, except between the
793 equator and 4°N where the L3Q and CEC SSS is closer to ship SSS. ISAS SSS appears to be
794 smoother than SMOS SSS, as expected from the optimal interpolation. On Figure 13 (right) a
795 ship transect crosses the North Atlantic Ocean in September 2013, a period of moderate RFI.
796 The L3P SSS is very discontinuous due to RFI disturbances in the north and to land-sea
797 contamination south of the equator. The L3Q and CEC SSS are more numerous and closer to

798 ship SSS than L3P SSS, even though the L3Q SSS appears to be more affected by RFI than
 799 the 18-day CEC SSS north of 40°N.



800 Figure 12 : Statistics of ship comparisons (May 2010-August 2016) binned as a function of the
 801 distance from the nearest coast: top) mean difference; middle) standard deviation of the differences;
 802 the black line indicates the standard deviation of ship SSS in each class; bottom) number of pixels
 803 used in the comparisons. Left: considering only the SMOS pixels common to all versions; right:
 804 considering all pixels available in each version. Ship and SMOS SSS are integrated over 100 km.
 805 Orange: monthly SMOS L3P ; pink : monthly SMOS L3Q; light blue : 18-day SMOS CEC; green :
 806 ISAS.

807



808

809 Figure 13 : Examples of comparisons between ship SSS (black stars line) and SMOS SSS: orange:
 810 non corrected (L3P), purple: monthly L3Q corrected, light blue :18-day CEC corrected; green : ISAS.
 811 Left) from 2014-08-21 to 2014-09-03, Matisse ship. Right) from 2013-08-21 to 2013-09-03, Santa
 812 Cruz ship. All SSS products have been smoothed over +/-50 km.

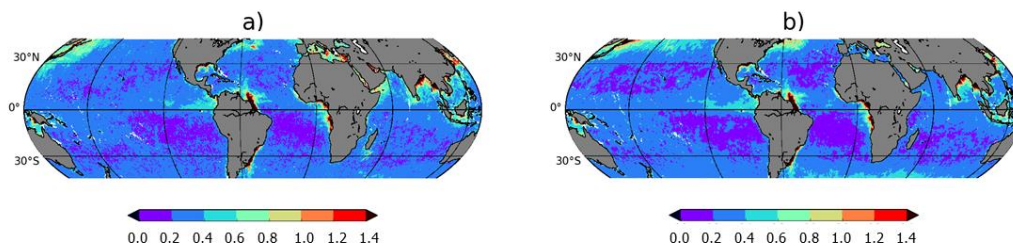
813

814 6. Discussion and Perspectives

815 Retrieving accurate SSS from SMOS measurements in the vicinity of continents is very
 816 challenging. The land-sea brightness temperature contrasts induce a contamination of the
 817 retrieved SSS signal, up to about 1000 km from the coast. This contamination is very variable
 818 across the SMOS swath. The origin of this pollution is very complex. It is likely related to an
 819 imprecise characterization of the 69 individual antenna patterns constituting the SMOS
 820 synthetic antenna, preventing a reliable theoretical modelling of the correction in the current
 821 SMOS image reconstruction process. The land-sea contamination has thus to be mitigated
 822 empirically. When doing so, the main difficulty is to distinguish the SMOS signal resulting
 823 from natural SSS variability from ones contaminated by RFI, whose sources are often located
 824 near coasts. To make matters worse, the typical RFI signature yields low SSS, and the largest
 825 SSS natural variability often occurs in low SSS regions, e.g. from river plumes or high rain
 826 regime. The K2016 methodology developed for correcting SSS affected by land-sea
 827 contamination was very efficient in many areas, but not in those characterized by strong

828 natural variability, as it implicitly assumed that natural SSS variability was negligible relative
829 to SMOS SSS noise. The revised correction methodology presented in this paper includes
830 information on the amplitude of natural SSS variability inferred from SMOS measurements.
831 We further add a seasonally- and latitudinally-dependent bias correction.

832 The SMOS corrected SSS is much more consistent to the independent SMAP SSS than
833 K2016, both in terms of SSS patterns and amplitude (Table 3). The SMOS SSS is, however,
834 slightly noisier than SMAP: in the open ocean (Pacific ITCZ region), Supply et al. 2017
835 found an error of 0.6 pss on L2 SMOS SSS and of 0.5 pss on L2 SMAP SSS. This difference
836 is explained by the radiometric accuracy of the respective instruments and by the SMAP
837 flight hardware that allows efficient detection and filtering of most RFI (Mohammed et al.
838 2016) unlike SMOS. Nevertheless, both satellite missions record very similar SSS variability
839 at weekly time scale that is not resolved by mapped Argo data (Figure 14). On average over
840 47°N-47°S, the standard deviation of the difference between SMOS CEC and ISAS SSS
841 (Figure 14a) is 0.33 pss while the standard deviation of the difference between SMAP and
842 ISAS SSS (Figure 14b) is 0.31 pss. The geographical distribution of this variability is very
843 consistent with the small-scale variability of SSS observed by ship measurements (see Figure
844 6 of Boutin et al. 2016) with minima in the subtropics and maxima in coastal areas, in the
845 vicinity of river plumes or in regions characterized by strong mesoscale fronts, such as the
846 Gulf Stream.



847

848 Figure 14 : Standard deviation of ‘weekly’ satellite SSS minus ISAS SSS between 47°N and 47°S,
849 over the year 2016. a) SMOS CEC, b) SMAP CAP.

850

851 The only quantitative external information entered in the correction algorithm is the 7-year
852 median of ISAS SSS that fixes the absolute calibration of the SMOS SSS in each pixel but
853 does not influence its variability. In seasonally-varying latitudinal biases correction, ISAS
854 SSS serves only in a qualitative way for choosing the SMOS cross-swath locations used as
855 reference. The implemented correction removes most of the systematic errors and brings
856 clear improvement when compared with *in situ* ground truths measurement or with SMAP
857 SSS. Nevertheless, some refinements could still be envisioned. The absolute calibration based
858 on ISAS median SSS leads to some inaccuracies in very near coastal pixels. This issue could
859 probably be improved in the future by analyzing to what extent the absolute calibration is
860 sensitive to the time period under consideration for computing the median and by merging
861 information coming from ISAS SSS with other SSS fields. A further step could be taken by
862 merging SMOS and SMAP information in order to build a level 4 product taking advantage
863 of synoptic spatio-temporal coverage of satellite data for monitoring SSS variability and
864 using *in situ* SSS for the absolute calibration of SSS fields. Future studies should also pay
865 more attention to the bias seasonal and interannual variability as a function of sun activity
866 and of land Tb variability which have been neglected in our study.

867 Our method corrects SMOS SSS retrieved with a Bayesian approach at level 2, as described
868 in Zine et al. 2008 and as implemented in ESA and CATDS operational processors. Such a
869 retrieval method takes advantage of the expected consistency between the various Tbs
870 measured at various incidence angles at a given distance across the swath and takes the
871 radiometric accuracy of each Tb into account. The land-sea contamination is expected to add
872 variability and biases on the SMOS Tbs at a given distance across the swath, so that the

873 quality of the Bayesian retrieval is downgraded. In order to cope with this caveat, a
874 systematic correction at Tb level has been implemented in ESA L2 OS processor v662,
875 before the retrieval of SSS. The biases in the vicinity of land and the standard deviation of the
876 difference with respect to ISAS are much reduced (Spurgeon and SMOS-Ocean Expert
877 Support Laboratories, 2017), but flagged SSS (poor quality retrieval) remain in many coastal
878 areas. Thus, the accuracy of the retrieved SSS is in general not as good as the one obtained
879 with our correction at the SSS level (Level-3). The better performance of our methodology is
880 likely due to the fact that we account for SSS variability. Given all the non-SSS geophysical
881 effects affecting Tbs (roughness effect, galactic noise etc...), it is very difficult to account for
882 SSS variability when dealing with Tbs measured at different angles within the field of view.
883 Nevertheless, future work should explore a two-step correction, first performed at Tb level to
884 improve the Bayesian L2 retrieval and second performed at SSS level.

885 An alternative debiasing method from a non-Bayesian approach has also been proposed by
886 Olmedo et al (2017). Contrary to our approach, Olmedo et al. (2017) retrieve SSS from single
887 angular Tb measurements, they filter SSS outliers using statistical indicators of the 3-year
888 SSS histogram per incidence angle classes. They adjust the absolute value of SMOS SSS by
889 adding the World Ocean Atlas climatology. An analysis (not shown) of the 9-day De-biased
890 non-Bayesian SMOS SSS fields available from the Barcelona Expertise Center which have
891 been obtained with an objective analysis in the regions and periods shown in Figure 1
892 indicates that the striking fresh features are captured at a similar level as what was obtained
893 with K2016 methodology, consistent with the fact that the statistical indicators used to filter
894 outliers do not depend on the SSS natural variability.

895 While SMAP SSS is expected to be much less affected by RFI, some disturbances remain in
896 some regions (Mohammed et al. 2016) and the calibration of SMAP data is also challenging

897 (Fore et al. 2016b, Meissner and Wentz, 2016). Hence, when dealing with a local scientific
898 study, dedicated comparisons with *in situ* ground truth are highly recommended in order to
899 precisely estimate the validity of satellite SSS in a given region and period with respect to the
900 natural variability that is considered. This should be facilitated in the future with the
901 development of the SMOS Pilot Mission Exploitation Platform (PI-MEP).

902 The CATDS/CPDC L3Q SSS is currently limited to 47°S-47°N as we could not define
903 unbiased SMOS reference dwell lines poleward of this latitude. This is likely because of
904 imperfect correction for surface roughness and ice contamination which can extend up to
905 1000 km from the ice edge and which is much more difficult to mitigate than land-sea
906 contamination as the ice edge is moving. Future studies should focus at correcting the ice
907 contamination and improving roughness correction. In addition, in regions contaminated with
908 highly variable RFI over the 7-year period, such as the northernmost parts of the Atlantic and
909 Pacific Oceans, the land-sea contamination correction becomes very tricky. In our study, RFI
910 affected Tbs are filtered out using a three-sigma filtering applied on SMOS Tbs before
911 retrieving SSS and using a Chi filtering applied on L2 SSS. Future studies should look at
912 improving this filtering.

913 **7. Acknowledgements**

914 We thank Stéphane Tarot for his very reactive support at CATDS CPDC. This work was
915 supported by CNES-CATDS and CNES-TOSCA SMOS-Ocean projects. SMOS CATDS
916 CEC data (also named L3_DEBIAS_LOCEAN_v2) have been produced by LOCEAN/IPSL
917 (UMR CNRS/UPMC/IRD/MNHN) laboratory and ACRI-st company. CATDS-CPDC data
918 (freely available at the CATDS) were operated for the "Centre National d'Etudes Spatiales"
919 (CNES, France) by IFREMER (Brest, France). Both products are available at www.catds.fr.

920 SMAP CAP SSS is produced at Jet Propulsion Laboratory. It is available on [ftp://podaac-](ftp://podaac-ftp.jpl.nasa.gov/allData/smap/)
921 [ftp.jpl.nasa.gov/allData/smap/](ftp://podaac-ftp.jpl.nasa.gov/allData/smap/). ISAS 13 analysis fields are made freely available by
922 Laboratoire d'Océanographie Physique et Spatiale (LOPS) ([http://www.umr-lops.fr/SNO-](http://www.umr-lops.fr/SNO-Argo/Products/ISAS-T-S-fields)
923 [Argo/Products/ISAS-T-S-fields](http://www.umr-lops.fr/SNO-Argo/Products/ISAS-T-S-fields)). Near real time ISAS analysis are produced by the Coriolis
924 data center and are freely available via CMEMS web site CMEMS-Copernicus Services:
925 <http://marine.copernicus.eu/>. SSS data derived from thermosalinograph instruments installed
926 onboard voluntary observing ships were collected, validated, archived, and made freely
927 available by the French Sea Surface Salinity Observation Service ([http://www.legos.obs-](http://www.legos.obs-mip.fr/observations/sss/)
928 [mip.fr/observations/sss/](http://www.legos.obs-mip.fr/observations/sss/)). We thank anonymous reviewers for their comments which helped
929 to improve the manuscript.

930

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1088

1089 **List of Figure Captions:**

1090 Figure 1 : Satellite SSS: SMOS SSS corrected according to (a, d, g, j) K2016 methodology, (b, e, h, k)
 1091 the method described in this paper (CEC); (c, f, i, l) SMAP SSS. 4 case study areas : (a, b, c) : Bay of
 1092 Bengal - August 21st 2015; (d, e, f) : Gulf of Mexico – August 18th 2015 ; (g, h, i) : Eastern Tropical
 1093 Atlantic Freshwater Pools – April 14th 2016; (j, k, l) : Amazon plume – October 21st 2015. SMOS and
 1094 SMAP SSS are averaged over respectively a SMOS repetitive orbit sub-cycle (18 days) and two
 1095 SMAP repetitive orbit cycles (16 days). Striking fresh SSS features in better agreement with SMOS
 1096 (new version) and SMAP are indicated with black arrows.

1097 Figure 2: Two examples of 2011-2016 latitudinal profiles of mean SSS (a; b) and of the
 1098 standard deviation of the 2011-2016 monthly differences between SMOS SSS and ISAS SSS
 1099 (c; d). The latitudinal means and standard deviations are computed over the Pacific Ocean

1100 further than 1200 km from any coast: green: ISAS, blue: SMOS ascending orbits; red: SMOS
1101 descending orbits; a;c) November; middle of the swath (0-50 km from the center of the
1102 swath); b; d) January; edge of the swath (350-400 km from the center of the swath). Dashed
1103 vertical lines indicate 47°N and 47°S.

1104 Figure 3: a) SSS variability ($\sigma_{SSS_{nat}}$) derived from 7 years of SMOS filtered and corrected
1105 SSS (after debiasing and filtering): large values are observed in river plumes and in rainy
1106 areas (ITCZ, SPCZ. b) Minimum and c) maximum of the SSS as derived from 18-day CEC
1107 LOCEAN that are used in the mapping of debiased near-real time products (see section 3.4).

1108 Figure 4: Monthly SMOS SSS compared to monthly ISAS SSS from July 2010 to December 2016.
1109 Standard deviation of the differences for a) L3P SMOS SSS; b) L3Q SMOS SSS. c) Number of
1110 months with differences between L3P and L3Q SMOS SSS greater than 0.2pss. d) Frequency with
1111 which corrections identified on Figure c) correspond to decreased bias with respect to ISAS (i.e. L3Q
1112 SMOS SSS closer to ISAS SSS than L3P SMOS SSS): red color means that the correction improves
1113 most of the time; blue color means that the correction degrades most of the time. Blank colors in
1114 figures c) and d) mean no change above the 0.2 pss threshold or no data in the L3P version (the
1115 comparison is done only for valid L3P SSS).

1116 Figure 5: Comparison of SMOS and SMAP ‘weekly’ SSS: (a, d, g) r^2 , (b, e, h) standard
1117 deviation of the differences, (c, f, i) number of pixels used in the comparisons. (a, b, c) 10-
1118 day L3P SMOS SSS, (d, e, f) 10-day L3Q SMOS SSS, (g, h, i) 9-day CEC SMOS SSS.
1119 Same indicators but when considering only the pixels available in the four products are
1120 presented in Appendix A2.

1121 Figure 6: Scatter plots of SMOS corrected fields versus SMAP SSS on the 4 regions and
1122 fresh events periods illustrated on Figure 1: first line: Bay of Bengal; 2nd line: Gulf of
1123 Mexico; 3rd line : Eastern Tropical Atlantic Freshwater Pools; 4th line : Amazon plume. First

1124 column: SMOS K2016 SSS; second column: SMOS 18-day CEC SSS; last column: SMOS 9-
1125 day CEC SSS.

1126 Figure 7: Time series of statistical parameters computed over the Bay of Bengal case study
1127 area, April 2015 to December 2016: a) mean SSS; b) SSS standard deviation; c) square of the
1128 Pearson correlation coefficient (r^2) between SMOS and SMAP SSS; d) Standard deviation of
1129 the SMOS minus SMAP SSS differences (plain line) using L1 norm (dotted line). ‘Weekly’
1130 SMOS CEC(blue), ‘bi-weekly’ SMOS CEC (green), ‘bi-weekly’ SMOS K2016 (red),
1131 ‘weekly’ SMAP (black).

1132 Figure 8: Time series of statistical parameters computed over the Gulf of Mexico case study area,
1133 April 2015 to December 2016: a) mean SSS; b) SSS standard deviation; c) square of the Pearson
1134 correlation coefficient (r^2) between SMOS and SMAP SSS; d) Standard deviation of the SMOS
1135 minus SMAP SSS differences (plain line) using L1 norm (dotted line). ‘Weekly’ SMOS CEC(blue),
1136 ‘bi-weekly’ SMOS CEC (green), ‘bi-weekly’ SMOS K2016 (red), ‘weekly’ SMAP (black).

1137 Figure 9: Time series of statistical parameters computed over the Eastern Tropical Atlantic Freshwater
1138 Pools case study area, April 2015 to December 2016: a) mean SSS; b) SSS standard deviation; c)
1139 square of the Pearson correlation coefficient (r^2) between SMOS and SMAP SSS; d) Standard
1140 deviation of the SMOS minus SMAP SSS differences (plain line) using L1 norm (dotted line).
1141 ‘Weekly’ SMOS CEC(blue), ‘bi-weekly’ SMOS CEC (green), ‘bi-weekly’ SMOS K2016 (red),
1142 ‘weekly’ SMAP (black).

1143 Figure 10: Time series of statistical parameters over the Amazon plume case study area, April 2015 to
1144 December 2016: a) mean SSS; b) SSS standard deviation; c) square of the Pearson correlation
1145 coefficient (r^2) between SMOS and SMAP SSS; d) Standard deviation of the SMOS minus SMAP
1146 SSS differences (plain line) using L1 norm (dotted line). ‘Weekly’ SMOS CEC(blue), ‘bi-weekly’
1147 SMOS CEC (green), ‘bi-weekly’ SMOS K2016 (red), ‘weekly’ SMAP (black).

1148 Figure 11: Top: Density spectra; Bottom: Coherence between ship SSS and SMOS or ISAS SSS. The
1149 spatial frequency (1/wavelength (km)) is indicated below the bottom plot, whereas the corresponding
1150 wavelengths (km) are indicated above the top plot. Vertical dashed lines correspond to spatial
1151 frequencies regularly spaced in logarithmic coordinates. Northern subtropical Atlantic (see box on the
1152 color map) in 2013. Ship SSS measured on regular merchant ships transects (14 regular transects in
1153 2013) (black), ISAS SSS (green), 10-day SMOS L3P (blue line), 10-day SMOS L3Q (dashed blue
1154 line), 18-day SMOS CEC (red line), 9-day SMOS CEC (red dashed line).

1155 Figure 12: Statistics of ship comparisons (May 2010-August 2016) binned as a function of
1156 the distance from the nearest coast: top) mean difference; middle) standard deviation of the
1157 differences; the black line indicates the standard deviation of ship SSS in each class; bottom)
1158 number of pixels used in the comparisons. Left: considering only the SMOS pixels common
1159 to all versions; right: considering all pixels available in each version. Ship and SMOS SSS
1160 are integrated over 100 km. Orange: monthly SMOS L3P ; pink : monthly SMOS L3Q; light
1161 blue : 18-day SMOS CEC; green : ISAS.

1162 Figure 13: Examples of comparisons between ship SSS (black stars line) and SMOS SSS: orange: non
1163 corrected (L3P), purple: monthly L3Q corrected, light blue :18-day CEC corrected; green : ISAS.
1164 Left) from 2014-08-21 to 2014-09-03, Matisse ship. Right) from 2013-08-21 to 2013-09-03, Santa
1165 Cruz ship. All SSS products have been smoothed over +/-50 km.

1166 Figure 14: Standard deviation of 'weekly' satellite SSS minus ISAS SSS between 47°N and
1167 47°S, over the year 2016. a) SMOS CEC, b) SMAP CAP.

1168 Figure 15: SSS latitudinal profiles in December 2011(top left), 2012 (top right), 2013 (bottom
1169 left), 2014 (bottom right) in the Atlantic Ocean (1200 km from continents)- SMOS ascending
1170 orbits (blue), descending orbits (red), ISAS(green).

1171 Figure 16: SSS latitudinal profiles in December 2011(top left), 2012 (top right), 2013 (bottom
1172 left), 2014 (bottom right) in the Pacific Ocean (1200 km from continents)- SMOS ascending
1173 orbits (blue), descending orbits (red), ISAS(green).

1174 Figure 17: Median of SMOS minus ISAS SSS absolute differences as a function of dwell line
1175 location and year, for the month of January (left), May (middle) and September (right), for
1176 ascending (top) and descending (bottom) orbits. The black lines indicate the range of selected
1177 x_{swath} .

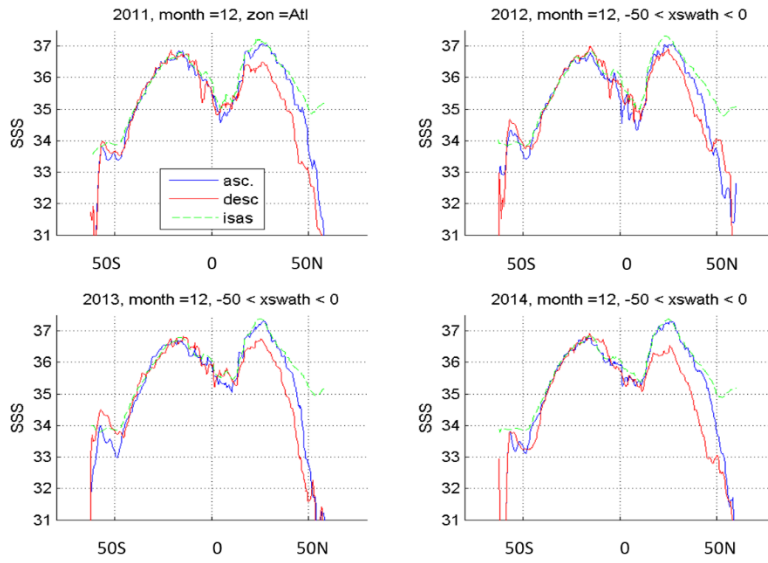
1178 Figure 18: ‘Weekly’ comparison of SMOS and SMAP SSS: (a, c, e) square of the Pearson
1179 correlation coefficient (r^2), (b, d, f) standard deviation of the difference. (a, b) L3P SMOS
1180 SSS, (c, d) L3Q SMOS SSS, (e, f) CEC SMOS SSS. Only pixels common to the four
1181 products are considered in the comparisons.

1182

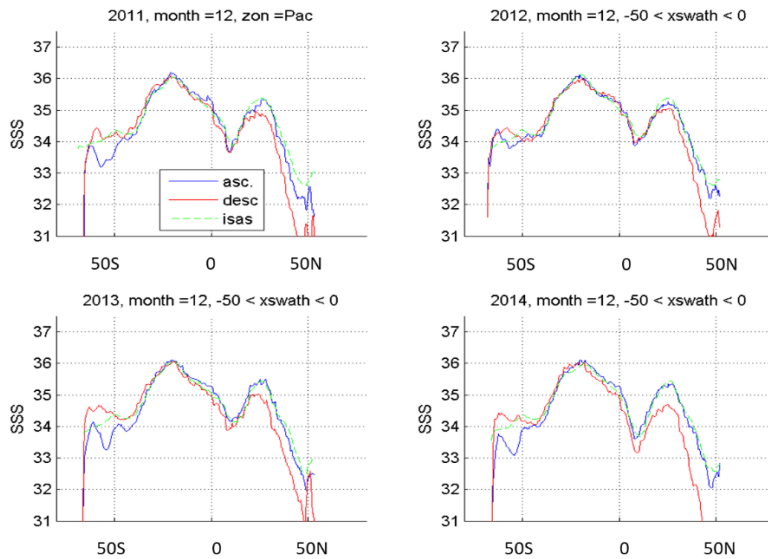
1183

1184 **Appendix A1: Selection of the region and of the reference x_{swath} to be used for**
1185 **the seasonal latitudinal correction:**

1186 Given the high RFI contamination in the northern latitudes of the Atlantic Ocean and given
1187 the relatively small area further than 1000 km from the continents in the Atlantic Ocean, we
1188 choose to estimate the seasonally-varying latitudinal biases from Pacific Ocean orbits only.
1189 Nevertheless, before doing this choice, we checked, on x_{swath} and periods not very affected by
1190 RFI at high latitudes, that biases are similar in the Pacific and Atlantic Ocean. We observe
1191 that the differences between ocean basins are on the same order of magnitude as the
1192 interannual variability of the biases as illustrated with a few examples on Figure 15 and on
1193 Figure 16.



1195
 1196 Figure 15: SSS latitudinal profiles in December 2011(top left), 2012 (top right), 2013 (bottom left), 2014
 1197 (bottom right) in the Atlantic Ocean (1200 km from continents)- SMOS ascending orbits (blue), descending
 1198 orbits (red), ISAS(green).

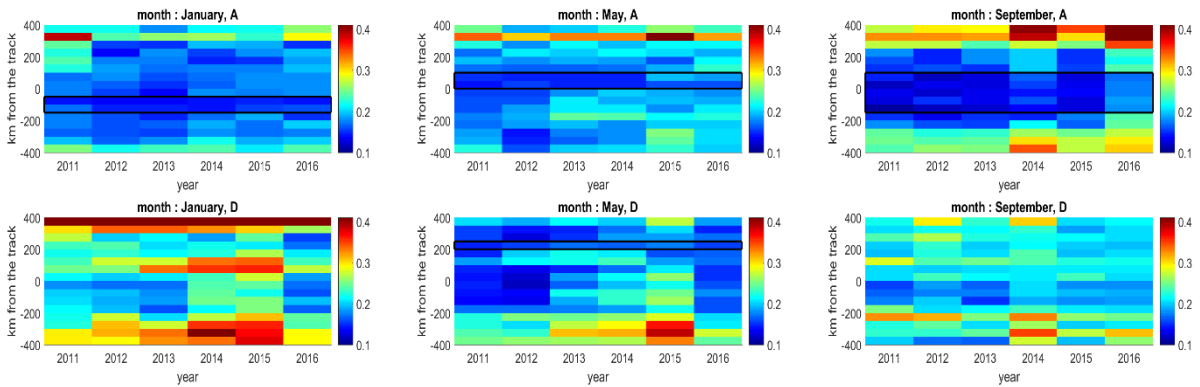


1199
 1200 Figure 16: SSS latitudinal profiles in December 2011(top left), 2012 (top right), 2013 (bottom left), 2014
 1201 (bottom right) in the Pacific Ocean (1200 km from continents)- SMOS ascending orbits (blue), descending
 1202 orbits (red), ISAS(green).

1203

1204 Over the 2011-2016 period, for each x_{swath} , each month and each x_{orb} , reference x_{swath} are
 1205 chosen as the ones having relatively weak and stable (from one year to another) SMOS minus
 1206 ISAS SSS differences (DIFF) over the 45°S-45°N latitudinal range. We did not define a

1207 quantitative criterion for this selection because the patterns of DIFF strongly vary from one
 1208 month to another, from ascending to descending orbits and as a function of latitude (not
 1209 shown). During most months, reference x_{swath} are located on ascending orbits only. We
 1210 illustrate the location of the reference x_{swath} with respect to the median of SMOS minus ISAS
 1211 SSS absolute differences for the months of January, May and September (Figure 17). The
 1212 locations of all the selected reference x_{swath} are reported in Table 4.



1213 Figure 17: Median of SMOS minus ISAS SSS absolute differences as a function of dwell line location
 1214 and year, for the month of January (left), May (middle) and September (right), for ascending (top) and
 1215 descending (bottom) orbits. The black lines indicate the range of selected x_{swath} .

1216

1217 Table 4: Reference x_{swath} locations

	Ascending orbits	Descending orbits
January	[-150 -50] km	-
February	[-250 -100] km	-
March	[-250 -100] km	-
April	[0 100] km	[150 200] km
May	[0 100] km	[200 250] km
June	[50 100] km	[50 100] km

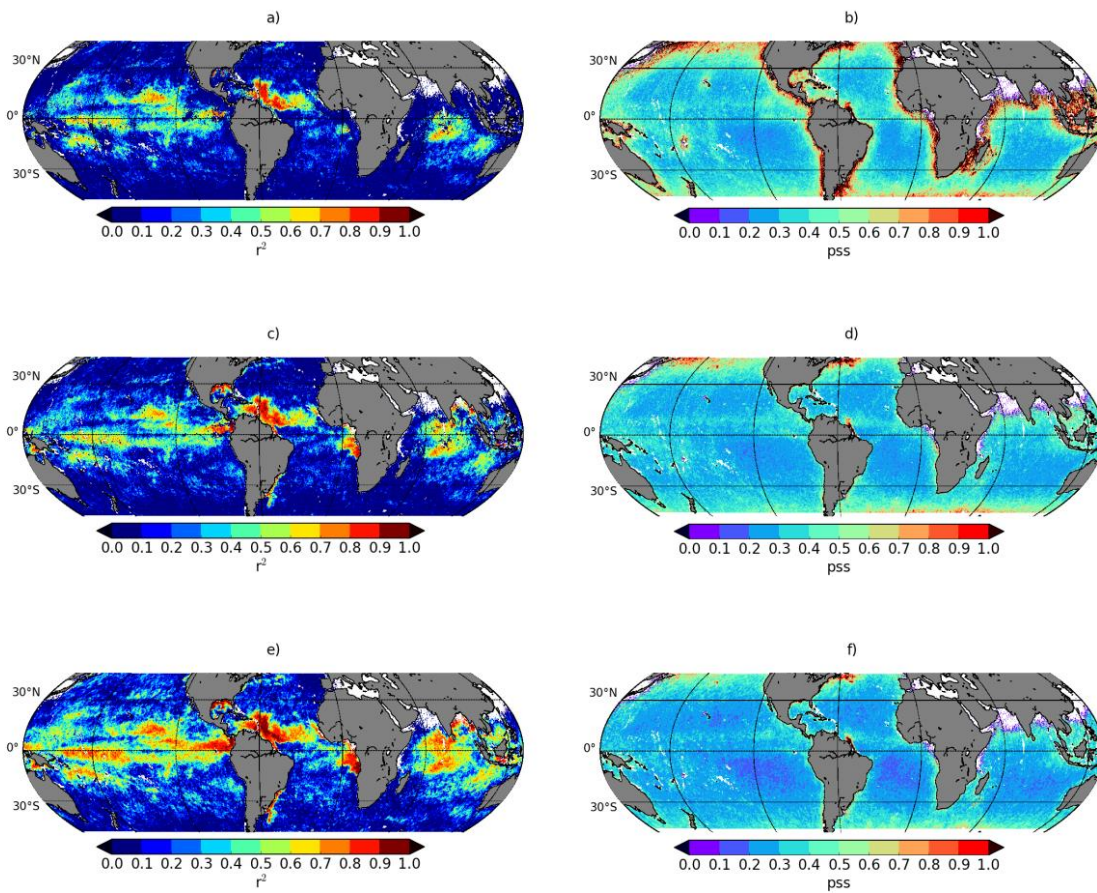
July	[-150 50] km	[50 100] km
August	[-250 250] km	[-50 100] km
September	[-150 100] km	-
October	[-50 100] km	-
November	[-250 -100] km	-
December	[-100 -50] km	-

1218

1219

1220 **Appendix A2: SMOS-SMAP SSS comparison considering only pixels common**

1221 **to all SSS fields:**



1222 Figure 18: ‘Weekly’ comparison of SMOS and SMAP SSS: (a, c, e) square of the Pearson
1223 correlation coefficient (r^2), (b, d, f) standard deviation of the difference. (a, b) L3P SMOS
1224 SSS, (c, d) L3Q SMOS SSS, (e, f) CEC SMOS SSS. Only pixels common to the four
1225 products are considered in the comparisons.